University of Glasgow

BUILDING A CIRCULAR FUTURE FOR ELECTRONICS THROUGH RESPONSIBLE INNOVATION: INSIGHTS FROM REACT

Drawing on insights from keynotes, expert panels, interviews with the companies, and roundtables.

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EXECUTIVE SUMMARY

Electronics are at the heart of the digital transformation, powering advances in healthcare, mobility, communications, and clean energy. They are also indispensable to achieving global net-zero goals, driving renewable energy, digital infrastructure, and enabling circular economy solutions.

However, the sector faces a critical paradox: while enabling progress, it also generates escalating risks. Electronics produce substantial waste, rely on scarce and geopolitically sensitive raw materials, and operate within fragile global supply chains that are difficult to regulate and vulnerable to disruption. Rising e-waste, high emissions, and raw material scarcity underscore the urgency of rethinking how electronics are designed, produced, used, and recovered.

To address these challenges, circular economy approaches are essential but not sufficient. Extending product lifecycles, improving repairability, and recovering materials can reduce waste. However, the transition is shaped by trade-offs: modularity may weaken durability, automation may displace jobs, and IP protection may limit repair. These dilemmas cut across technology, industry, and society and require careful navigation.

This white paper proposes Responsible Innovation (RI) as a framework to guide this transition. RI emphasises anticipation, inclusivity, reflexivity, responsiveness, transparency, and equity — principles that enable decision-makers to balance economic, environmental, and social priorities while building trust and resilience.

The REACT project, a £6M+ UKRI-funded Green Economy Centre, is leading this agenda by supporting the electronics, ICT, semiconductor, quantum, and photonics industries in transitioning to circular and low-carbon futures. Through expert talks, interviews, panels, and roundtables, REACT has convened diverse stakeholders to identify opportunities, barriers, and best practices.

KEY MESSAGES

- **Electronics are indispensable yet unsustainable**: urgent action is required to address rising e-waste, supply-chain emissions, and critical material scarcity.
- **Circular economy is necessary but not sufficient**: trade-offs and dilemmas must be addressed holistically.
- **Responsible Innovation provides the governance lens**: embedding RI ensures solutions are environmentally sound, socially equitable, and economically viable.
- **REACT is driving change**: by connecting industry, academia, and policymakers, REACT delivers actionable insights, fosters cross-sector collaboration, and positions the UK as a leader in responsible and circular electronics.

CALL TO ACTION

This white paper provides practical insights for policymakers, industry leaders, researchers, and practitioners to accelerate the shift towards responsible and circular electronics. It highlights pathways for innovation, collaboration, and governance that will not only reduce risks but also unlock opportunities for long-term competitiveness, resilience, and global leadership.

REACT | UKRI Engineering and Physical Sciences Research Council | UKRI UK Research and Innovation | University of Glasgow Adam Smith Business School

INTRODUCTION

Electronics are indispensable to modern society and central to achieving Net Zero goals. They power renewable energy systems, enable digital infrastructure, and provide the backbone for innovations in health, mobility, and communication. However, the sector also generates significant environmental and social risks. It is one of the fastest-growing sources of waste, depends heavily on scarce and geopolitically sensitive raw materials, and operates within opaque global supply chains that are both fragile and difficult to regulate. This paradox underscores the urgency of rethinking how electronics are designed, produced, used, and recovered.

Circular economy approaches have been widely promoted as a response, aiming to extend product lifecycles, recover valuable resources, and reduce waste. However, circularity on its own is not sufficient. The transition comes with tough trade-offs. For example, making products easier to repair can clash with intellectual property rules, modular designs may reduce product durability, and automation can boost efficiency but also put jobs at risk. These are not just technical issues — they are bigger dilemmas that cut across business models, policy, and society.

To address these dilemmas, this white paper adopts the Adam Smith Responsible Innovation Framework, developed by researchers at the University of Glasgow. The framework translates responsible innovation into six actionable principles:

- **Anticipation** – Identify potential risks, opportunities, and long-term impacts early.
- **Inclusivity** – Engage diverse stakeholders in shaping solutions.
- **Reflexivity** – Critically reflect on assumptions, values, and possible unintended effects.
- **Responsiveness** – Adapt strategies to emerging evidence and changing expectations.
- **Transparency** – Communicate processes, decisions, and trade-offs openly.
- **Equity** – Ensure fair distribution of benefits and prevent inequalities.

By applying this framework, we look not only at the challenges facing the electronics sector — such as e-waste, emissions, material scarcity, and supply chain fragility — but also at the opportunities to reimagine electronics for circularity in ways that are socially just, environmentally sound, and economically viable. The framework serves as a practical guide for policymakers, industry leaders, and practitioners to align circular economy strategies with responsible innovation principles, ensuring that solutions reduce risks while creating long-term societal value.

CIRCULARITY IN ELECTRONICS: CONTEXT AND POTENTIAL

Electronics play a pivotal role in driving decarbonisation—from enabling smart grids and IoT, to supporting renewable energy systems and digital infrastructure. Paradoxically, they are among the most resource-intensive and waste-generating sectors, owing to rapid product turnover, complex material composition, and limited recovery systems. Globally, e-waste is accelerating: in 2022, the world produced a record 62 million tonnes of electronic waste, yet only around 22.3 % was formally collected and recycled.[1] In the UK, households are estimated to hoard some 880 million unused electrical items, while more than 100,000 tonnes of electrical items are discarded in bins annually.[2]

[1] https://ewastemonitor.info/the-global-e-waste-monitor-2024/

[2] https://www.circularonline.co.uk/news/households-hoarding-880-million-unused-electrical-items-material-focus-says/

Circularity in electronics offers an alternative to the dominant linear model of "take-make-dispose." It emphasises lifecycle extension via repair, refurbishment, and reuse; product redesign for disassembly; remanufacturing; and material recovery through recycling. However, the industry is finding this transition extremely challenging. Many electronic devices incorporate dozens of materials, including plastics, rare earth metals, flame retardants, and adhesives, that resist cost-effective separation and recycling. The complexity of composite materials means that recycling often becomes technically cumbersome or economically unattractive. Moreover, fluctuating commodity prices, limited scale economies, and the absence of reliable reverse logistics infrastructure compound the difficulty of closing material loops.[3]

In many cases, manufacturers continue to design products with short lifespans, replacing modularity or disassembly features in favour of compactness, performance, or cost minimisation. This practice reinforces the linear model by making devices more difficult to repair or upgrade. At the same time, the supply chains underpinning electronics remain global and opaque, creating challenges in tracing materials, enforcing accountability, and ensuring that recovered components return to useful manufacture.[4]

Nevertheless, circularity is not purely a technical transition; it also demands shifts in business models, consumer practices, supply-chain governance, and institutional support. Without rethinking how products are monetised (for example, via leasing or product-as-a-service), supporting repair and refurbishment markets, embedding transparency in sourcing, and coordinating industry actors across reverse logistics chains, many of the theoretical gains of circularity remain unrealised in practice.

To be robust, circular strategies must be guided by responsible innovation (RI). Without anticipation of risks, reflexive adjustment, or stakeholder inclusivity, circular approaches risk unintended outcomes, such as exacerbating inequality (e.g. favouring consumers in high-income regions), reducing product reliability (if repair mechanisms degrade performance), or trapping firms in unsustainable cost structures (if circular operations remain more expensive than linear models). Embedding RI ensures that circular transformations are socially equitable, environmentally sound, and commercially viable.

Thus, circular electronics holds two intertwined potentials. First, it can reduce waste, conserve scarce materials, and lower environmental impact across product lifecycles. Second, it can catalyse systemic change, redefining how products are designed, how value is shared, and how innovation is governed in the electronics sector. These are the foundations upon which the opportunities, challenges, and dilemmas in the next section were built.

[3] https://www.sktes.com/news/the-journey-of-electronics-recycling-navigating-towards-a-circular-economy

[4] https://www.weforum.org/stories/2021/05/electronics-can-trigger-a-more-circular-sustainable-world-heres-how/

Key facts

The electronics industry faces mounting pressures as it struggles to align with circular economy goals:

- In 2022, the world generated 62 million tonnes of e-waste, of which only 22.3% was formally collected and recycled.[5]
- The UK alone is estimated to have 880 million unused electrical items stored in homes, while more than 100,000 tonnes of electronics are discarded in bins each year.[6][7]
- Electronic devices often contain 40–60 different elements, including critical raw materials that are rarely recovered at scale due to complex design and low economic incentives. [8]
- Global demand for critical minerals such as lithium, cobalt, and rare earth elements is expected to quadruple by 2040, driven by electronics and clean energy technologies.[9]

These figures underline the scale of the challenge: without systemic change, the very sector enabling the Net Zero transition risks undermining its own sustainability.

A CASE IN POINT: THE SMARTPHONE DILEMMA

Smartphones are a prime example of the tensions at the heart of circular electronics. On the one hand, they are indispensable tools for communication, commerce, and health services. On the other hand, they represent one of the fastest-growing categories of e-waste, often discarded within 2–3 years of purchase. Efforts to make devices more repairable or modular face resistance from manufacturers, citing intellectual property and performance concerns. Meanwhile, the demand for rare earth metals embedded in phones drives environmental degradation and geopolitical risk.

Applying the Adam Smith Responsible Innovation Framework to this dilemma highlights the need to anticipate downstream impacts of design choices, include both consumers and repair communities in the discussion, and ensure equity by avoiding models that limit access or exacerbate global inequalities. This case illustrates why balancing circularity with responsibility is essential.

Drawing on insights from expert talks, panels, interviews, and roundtable discussions hosted by the REACT project, this white paper maps the opportunities and constraints shaping circular electronics, identifies the key dilemmas that must be navigated, and highlights best practices and pathways for action. The aim is to provide actionable insights for policymakers, industry leaders, researchers, and wider stakeholders, positioning REACT as a thought leader in shaping responsible and circular futures for electronics.

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[5] https://ewastemonitor.info/the-global-e-waste-monitor-2024/

[6] https://www.circularonline.co.uk/news/households-hoarding-880-million-unused-electrical-items-material-focus-says/

[7] https://www.theguardian.com/environment/2023/oct/12/half-a-billion-cheap-electrical-items-go-to-uk-landfills-in-a-year-research-finds

[8] https://www.weforum.org/stories/2021/05/electronics-can-trigger-a-more-circular-sustainable-world-here-s-how/

[9] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

OPPORTUNITIES, CHALLENGES, AND DILEMMAS IN RESPONSIBLE ELECTRONICS

A dynamic interplay of opportunities, challenges, and dilemmas shapes the shift toward circular and sustainable electronics. On one side, emerging business models, technological advances, ecosystem collaborations, and changing consumer preferences create new possibilities for reducing waste and recovering value. On the other hand, systemic barriers such as fragile supply chains, material losses, entrenched consumerism, and uneven policy frameworks constrain progress and complicate adoption. Between these two extremes lie innovation dilemmas—tensions that cannot be resolved by simple fixes but must be navigated responsibly—as each path carries implications for environmental integrity, social equity, and economic viability. Understanding this landscape is essential for developing governance approaches that enable the sector to deliver on its potential for Net Zero while addressing the risks it generates. Insights for the challenges and opportunities for responsible electronics were drawn from responsible innovation principles.

CHALLENGES

The transition to circular and responsible electronics faces a series of entrenched challenges that shape the pace and direction of innovation. These challenges extend beyond technical hurdles to include political tensions, systemic material and waste issues, persistent consumerist behaviours, and gaps in knowledge and capacity. Taken together, they reveal that achieving sustainability in electronics is not only a matter of redesigning products but also of addressing wider economic, cultural, and policy conditions that constrain progress.

POLITICAL TENSION IMPACTING POLICY

- Current frameworks are inconsistent and reactive, often retrofitting sustainability onto outdated systems. History also shows that poorly conceived regulations (e.g., the ban on a specific chemical in LCD manufacturing) can have the unintended consequence of destroying an entire industry in Europe, offshoring production and its associated environmental footprint.

- Roundtable noted bans on Chinese tech (e.g., Huawei) as politically motivated, limiting collaboration and access to advanced technology. This could be a form of as a form of protectionism that risks leaving Western economies with inferior technology and widening the innovation gap, rather than solving the core problem.

MATERIAL AND WASTE CHALLENGES: SYSTEMATIC PROBLEM OF THE PROCESS

- Over 8.3 billion tons of polymers have been produced since the 1950s, with 60% discarded.
- Design Flaw: Products are designed for performance, not end-of-life. The use of permanent, high-bonding adhesives makes modern devices nearly impossible to disassemble for recycling, unlike older, screw-based designs. Low recycling rates in electronics are due to complex materials and flame retardants. 800 million electrical items are hoarded in UK homes; 100,000 tonnes are discarded in bins annually.
- Infrastructure Gap: The recycling infrastructure is underdeveloped and vulnerable. The loss of a single plant (e.g., the fire at Shore Recycling in Perth) can disrupt the national waste processing system for large electronics, exposing a critical systemic weakness.
- Linear Lock-in: The entire system is built on a linear model. There is a significant cost disparity between using recycled materials and cheaper virgin materials, and business models are based on

selling new units rather than maintaining value in a circular system. Critical material losses (e.g., copper, gallium, germanium) due to poor recovery and illegal exports.

- The complexity of managing sustainability within a global supply chain. For example, while STMicroelectronics can control its internal operations—such as wafer manufacturing, testing, and packaging—it has limited influence over customer specifications and end-of-life product handling. As a supplier of components rather than finished consumer products, the company must comply with customer demands, which often restrict opportunities for sustainable design changes. This disconnect between production and consumption highlights the difficulty of influencing broader environmental outcomes without regulatory support.

CONSUMERISM CULTURE DOMINANCE

- The prevailing economic model prioritises high sales volume and short product lifecycles (e.g., an 18-month lifecycle for a mobile phone).
- Consumer preferences exacerbate this; people are willing to pay a premium for status items like designer trainers but demand cheap, new, large appliances, demonstrating a cultural undervaluing of longevity and repair.
- There is a strong stated preference for owning new products rather than leasing or renting, which is a barrier to product-as-a-service circular models.
- Market Forces and Innovation: Speakers highlighted that technological development is often shaped more by commercial pressures than genuine consumer needs. For example, STMicroelectronics noted that features such as augmented reality and AI demand greater computing power and data transfer, which complicates device design and recycling. Integrating these advanced technologies into mobile platforms creates new sustainability challenges, particularly around material recovery and energy efficiency. The company questioned whether market evolution is truly customer-driven or primarily guided by corporate strategies to maximise profit.

KNOWLEDGE GAPS AND AWARENESS

- Many businesses are unaware of the economic and environmental benefits of circular models, as they have never been presented with a viable case for their specific products. There is some consensus that circular models are only designed for resource-intensive companies and find no advantages in smaller businesses.
- A specific knowledge gap exists in how to strategically manage the New Product Development process with circular principles in mind, especially among SMEs who lack structured stage-gate processes.

OPPORTUNITIES

While challenges highlight barriers that must be overcome, innovation dilemmas expose the tensions that arise when opportunities collide with existing constraints. Dilemmas are not simply obstacles but paradoxes where advancing one goal risks undermining another — for example, extending product lifecycles through repair while safeguarding intellectual property. These tensions illustrate that circular electronics cannot be achieved through technical fixes alone but demand careful navigation of trade-offs across economic, social, and environmental priorities.

CIRCULAR BUSINESS MODELS

- **Lifecycle extension**: WEEE Scotland's refurbishment of Costa Coffee machines saves the company £5.1 million annually, with parts tested and repaired up to three times before reuse. This is not a simple recycling contract but a sophisticated, integrated service model. Weee Scotland takes ownership of the repair process for Costa's espresso machines, handling an estimated 70-80 components. Their process involves a rigorous quality assurance protocol: receiving a defective part, confirming the fault in their own workshops, repairing it to an agreed standard, and testing it in a working machine before placing it on a shelf as "good stock." This model is financially compelling, saving Costa Coffee a conservative estimate of £5.1 million annually. It demonstrates that circularity is not a cost centre but a significant profit lever for both the service provider and the client, creating local skilled jobs in the process.

- **Harnessing Digital Product Passports for Circular Electronics:** Digital product passports and related tools are emerging as powerful enablers of circularity in electronics. Current pilots show how tracking provenance, repairs, and lifecycle information for refurbished devices can help build consumer trust and demonstrate value. When combined with design strategies for durability, repairability, and recyclability—and supported by robotics and AI for advanced sorting and tracking—these tools can significantly improve sustainability outcomes. Beyond traceability, big data and non-invasive modelling offer new opportunities to optimise waste management and material recovery, while predictive maintenance systems can enhance resource efficiency and extend product lifespans. Together, these innovations point to a future where digital tools strengthen sustainable sourcing and accelerate the transition to a more circular electronics sector.

- **Capturing Value from 'Urban Mining' and Material Recovery**: Circular business models also apply to advanced material recovery. The collaboration between the Royal Mint and a Canadian company to extract precious metals from PCB boards, with Weee Scotland as an industry partner, is a prime example. This moves beyond shredding and downcycling into high-value "urban mining," where waste electronics are treated as a concentrated ore of valuable metals. For this to be economically sustainable, it requires a consistent and high-quality feedstock, which circular models like the one with Costa Coffee help provide by first extracting maximum value from repair before directing end-of-life components to this final stage. This creates a multi-tiered revenue stream from a single product.

TECHNOLOGICAL INNOVATION AND ADVANCEMENTS

- **Debonding technologies:** Innovation in materials science, such as developing adhesives that can be deactivated on demand, could revolutionise disassembly and recycling.
- **Bio-based materials:** Rapid advancement in creating polymers from bio-sources like glucose (e.g., bio-polypropylene) offers a path to decouple plastic production from fossil fuels.
- **Advanced recycling:** Biotechnology presents an opportunity to break down and valorise the complex legacy of plastic waste sitting in landfills.

ECOSYSTEM-ENABLED COLLABORATION

- **Supply chain leadership**: Large corporations like Apple are proving that change is possible by using their influence to drive the adoption of recycled content (recycled rare earths, copper, lithium) across their entire global supply chain, creating a powerful pull effect.
- **Strategic partnerships:** Cross-sector collaboration is key (e.g., Impact Solutions partnering with universities to open a Biodegradation Innovation Hub). The REACT project itself is a prime example of creating a collaborative ecosystem to tackle shared challenges.

CONSUMER AWARENESS SHIFT

- There is a growing opportunity to educate and shift consumer perception. Evidence-based communication of the benefits (cost savings, quality, environmental impact) of circular models can build trust in refurbished products.
- Raising awareness of the true environmental and social cost of cheap, disposable electronics can help consumers make more informed values-based purchasing decisions, creating market demand for circular products..

INNOVATION DILEMMAS

Innovation dilemmas emerge when efforts to advance sustainability and circularity in electronics encounter competing priorities or trade-offs. Unlike simple barriers, dilemmas are not problems to be "solved" once and for all, but tensions that must be navigated responsibly. They reflect situations where pursuing one desirable outcome can undermine another, for example, empowering consumers with the right to repair while safeguarding intellectual property. Addressing these dilemmas requires governance approaches, such as Responsible Innovation (RI), that foster inclusive dialogue, anticipate unintended consequences, and ensure balanced outcomes across economic, social, and environmental dimensions.

RIGHT TO REPAIR VERSUS INTELLECTUAL PROPERTY PROTECTION

This dilemma grows directly from the opportunity of circular business models and the challenge of consumerism culture. Expanding repairability empowers consumers, reduces waste, and encourages product longevity, aligning with new opportunities such as refurbishment models and digital product passports. However, these initiatives challenge manufacturers' ability to protect proprietary technologies and safeguard revenue streams from controlled after-sales services. The dilemma reflects a wider tension between empowering users to extend lifecycles and preserving incentives for innovation and brand protection.

MODULARITY VERSUS DURABILITY

The tension between modularity and durability links the opportunity of eco-design and circular product innovation with the challenge of material waste and complex manufacturing processes. Modularity supports disassembly, repair, and component replacement, offering a pathway to higher recycling rates. However, modular designs can reduce product robustness or performance, potentially increasing failure rates and contributing to more waste rather than less. The dilemma centres on whether modularity enhances or undermines overall sustainability once durability and longevity are taken into account.

ETHICAL SOURCING VERSUS COST COMPETITIVENESS

This dilemma arises from the challenge of global material dependence and critical resource losses, combined with the opportunity to develop responsible supply chains and bio-based alternatives. Ethically sourced or recycled inputs reduce environmental harm and mitigate social risks in mining. However, they often increase costs, creating competitive disadvantages in markets dominated by consumerism culture and price sensitivity. The tension is between meeting rising societal expectations for responsible products and maintaining affordability and market access.

AUTOMATION VERSUS EMPLOYMENT

Here, the opportunity of technological innovation, particularly robotics, AI, and big data for recycling, encounters the challenge of existing labour structures and informal recycling practices. Automation promises efficiency and improved recovery rates for scarce materials but risks displacing jobs in low-skill sectors, including communities reliant on manual recycling for livelihoods. The dilemma lies in how to embrace technological advances without exacerbating social inequalities, making workforce transitions and retraining central to any responsible solution.

OPEN COLLABORATION VERSUS GEOPOLITICAL COMPETITION

This dilemma emerges at the crossroads of the opportunity for ecosystem collaboration and the challenge of political and policy tensions. Circular electronics require global supply chain transparency, harmonised standards, and cooperation across borders. However, increasing geopolitical competition, trade restrictions, and bans on specific technologies fragment ecosystems and restrict the trust needed for collaboration. The dilemma reflects the difficulty of scaling circularity in an environment where international cooperation is increasingly undermined by political rivalry.

Why dilemmas matter

The dilemmas outlined above highlight that the transition to circular electronics is not simply a matter of overcoming technical barriers or seizing emerging opportunities. Instead, progress unfolds within a web of tensions where each potential solution carries risks of unintended consequences. Opportunities such as new business models, eco-design, advanced recycling technologies, or global collaboration are continually shaped—and sometimes constrained—by challenges of consumer behaviour, material scarcity, political instability, and knowledge gaps.

These dilemmas matter because they show that innovation is never a neutral process. Every design choice, policy decision, or business model experiment redistributes costs and benefits across consumers, industry, workers, and wider society. Failing to recognise these tensions risks pushing circularity strategies that succeed in one dimension, for example, efficiency or affordability, but fail in others, such as social equity or long-term resilience.

Rather than being resolved once and for all, dilemmas must be navigated responsibly, with attention to inclusivity, anticipation of impacts, and a willingness to adapt as contexts evolve. This is precisely where Responsible Innovation provides value: as a governance lens that helps stakeholders balance competing priorities, mitigate risks, and ensure that circular electronics deliver not just technical and commercial gains, but also environmental integrity and social fairness.

RESPONSIBLE INNOVATION AS A GOVERNANCE LENS

The dilemmas outlined in the previous section illustrate that the transition to circular electronics is not a linear process but one characterised by competing priorities, contested values, and uncertain consequences. These dynamics highlight the need for a governance approach that goes beyond technical problem-solving or economic optimisation. Responsible Innovation (RI) provides such a lens. By embedding ethical reflection, stakeholder engagement, and adaptive decision-making into innovation processes, RI enables policymakers, industry, and researchers to navigate dilemmas in ways that balance economic viability with environmental sustainability and social fairness.

PRINCIPLES OF RESPONSIBLE INNOVATION

RI rests on six core principles that guide responsible practice across sectors: anticipation, inclusivity, reflexivity, responsiveness, transparency, and equitability.[10]

- *Anticipation* encourages innovators to explore possible future consequences of technologies before they become entrenched.
- *Inclusivity* ensures that diverse stakeholders, from consumers and workers to policymakers and recyclers, have a voice in shaping innovation.
- *Reflexivity* asks organisations to critically examine their own assumptions, values, and roles in shaping outcomes.
- *Responsiveness* emphasises the need to adapt when new knowledge or societal expectations emerge.
- *Transparency* supports openness about risks, impacts, and trade-offs.
- *Equitability* underlines the importance of fair distribution of both the benefits and burdens of innovation.

Together, these principles offer a structured way of addressing the dilemmas identified, ensuring that innovation in electronics serves not only technical or commercial goals but also wider societal interests.

EMBEDDING RI IN BUSINESS MODEL INNOVATION

Circular business models, such as product-as-a-service, repair economies, and digital product passports, offer promising opportunities but also raise dilemmas around costs, durability, and consumer engagement. Embedding RI in business model design ensures that these tensions are considered explicitly, enabling solutions that anticipate risks, include affected stakeholders, and balance short-term viability with long-term sustainability. For example, repair models shaped by RI would involve dialogue between manufacturers, consumers, and regulators to design ecosystems that protect both user rights and intellectual property.

APPLYING RI TO TECHNOLOGICAL DEVELOPMENT

Technological advances in robotics, AI, and new materials can significantly enhance recycling efficiency and resource recovery, yet they also generate dilemmas around employment and affordability. RI encourages innovators to anticipate these impacts early in development, explore options for just transitions, and co-create pathways that maximise benefits while mitigating harms. This could involve pairing automation with

[10] https://ieeexplore.ieee.org/document/10738489

targeted reskilling programmes or aligning material innovation with affordability strategies to avoid excluding low-income markets.

GOVERNANCE FRAMEWORKS AND TOOLS

The integration of RI into circular electronics is not only conceptual but also practical. Frameworks such as the Adam Smith Responsible Innovation Framework (AS-RIF) provide structured approaches for aligning innovation with societal values.[11] In parallel, the field increasingly recognises the need for maturity models and diagnostic tools that can help organisations assess how well they are embedding RI in practice. A hypothetical measuring scale, for instance, could allow firms to benchmark their level of responsible innovation maturity, identify gaps, and plan improvements over time. When combined with circular economy indicators, such a scale would enable more consistent evaluation of progress and provide decision-makers with clearer evidence to guide responsible pathways for innovation.

THE ROLE OF RI IN NAVIGATING DILEMMAS

By embedding RI across business models, technologies, and governance systems, stakeholders can move beyond viewing dilemmas as obstacles and instead treat them as navigational challenges. RI does not eliminate trade-offs, but it equips organisations to handle them with foresight, inclusivity, and adaptability. In practice, this means creating innovation pathways where circularity strategies do not come at the expense of durability, where automation is paired with social safeguards, and where collaboration can be maintained despite political tensions.

[11] https://ieeexplore.ieee.org/document/10738489

CASE STUDIES AND BEST PRACTICES

To make the discussion concrete and credible, this section presents selected case studies from industry and public entities that exemplify circular electronics practices—some with explicit alignment to responsible innovation principles. These cases show how organisations have navigated real trade-offs, deployed new technologies or business models, and pushed systemic change.

APPLE: DISASSEMBLY, REFURBISHMENT, AND CIRCULAR SUPPLY CHAINS

Apple's efforts in circular electronics span a range of initiatives—from automated disassembly to refurbished product lines and supply chain traceability. One prominent example is Liam, a robotic system designed to disassemble iPhones into modules, thereby facilitating component recovery and material reuse.[12] Apple also operates Daisy, a successor disassembly robot, and promotes device trade-in and refurbishment programmes that feed components back into new devices or secondary markets.[13]

In addition to mechanical innovation, Apple has worked with McKinsey to deepen its understanding of circular value chains across materials like copper, aluminium, and rare earths, aiming to scale material recovery globally.[14] Its recycled materials strategy and claims of a closed-loop supply chain provide instructive lessons in transparency, material traceability, and the challenges of scaling circular metrics.

This case illustrates several dilemmas: enabling repair and component recovery without compromising IP, balancing performance with disassembly requirements, and navigating disclosure obligations in competitive markets.

ROYAL MINT: RECLAIMING PRECIOUS METALS FROM E-WASTE

The Royal Mint, Britain's long-standing coin producer, has launched a pioneering gold and precious-metal recovery facility to process printed circuit boards (PCBs) from discarded electronics. Rather than shipping e-waste overseas or relying on high-temperature smelting, the Mint is deploying a patented chemical extraction technology from Canadian clean tech firm Excir, capable of recovering over 99 % of gold at ambient temperatures.[15]

In partnership with automation provider Rockwell, it uses a PlantPAx Distributed Control System (DCS) to integrate and optimise the chemical extraction workflows at scale.[16] The facility is designed to process up to 4,000 tonnes of PCBs per year.[17]

This project illustrates the convergence of circular innovation, ecosystem collaboration, and governance challenges. It shows how an established institution can pivot into e-waste recovery, but also surfaces dilemmas around cost, scaling, regulatory oversight, and material traceability.

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[12] https://www.apple.com/environment/pdf/Liam_white_paper_Sept2016.pdf

[13] https://medium.com/%40dixitjigar/apples-supply-chain-innovation-resilience-and-sustainability-in-the-digital-age-c8f0eb951042

[14] https://www.mckinsey.com/about-us/case-studies/how-apple-is-helping-unearth-a-path-toward-increasing-the-global-use-of-circular-materials

[15] https://www.royalmint.com/aboutus/press-centre/turning-electronic-waste-into-gold/

[16] https://www.rockwellautomation.com/en-us/company/news/press-releases/Rockwell-Automation-Helps-the-Royal-Mint-Reduce-E-Waste-in-Precious-Metal-Recovery-Facility.html

[17] https://www.royalmint.com/aboutus/press-centre/new-factory-extracting-gold-from-e-waste-unveiled-by-the-royal-mint/

BLOCKCHAIN FOR TRACEABILITY IN REVERSE LOGISTICS OF MOBILE PHONES

In the academic domain, a notable initiative demonstrates how distributed ledger technology (DLT) can be used to enhance traceability in reverse logistics of mobile phones. A proposed framework uses blockchain and smart contracts to record the remanufacturing or refurbishing stages, maintain immutable audit trails, and facilitate trust among multiple actors in the circular supply chain.[18]

Though still largely conceptual or pilot-level, this case is instructive in how digital technologies can support transparency, stakeholder inclusion, and accountability—key principles of RI. It also raises practical questions about privacy, scalability, and adoption across fragmented value chains.

EMERGING RESEARCH: RECYCLABLE VITRIMER-BASED PCBS

In the research frontier, new material innovations show promise for improving circularity at the component level. For instance, researchers have developed vitrimer-based printed circuit boards (vPCBs) that allow for selective reversible decomposition, repair, and remanufacture. These boards can be depolymerised in a controlled fashion, facilitating nearly full recovery of polymers, fibres, and metals without destructive processing.[19] This case illustrates how advanced material science can mitigate core technical constraints—especially those around mixed materials, irreversibility, and harmful processing. However, it also surfaces the dilemma of scaling novel materials in existing manufacturing ecosystems and assessing trade-offs (e.g. cost, compatibility, performance).

Lessons across the cases

The case studies presented highlight several cross-cutting lessons about what it takes to advance circularity in electronics. They show that technical solutions alone are insufficient; progress depends on governance, collaboration, and the ability to manage trade-offs in practice. From questions of scale and transparency to the role of institutional leadership, these lessons illustrate both the potential of circular approaches and the conditions required for them to deliver lasting impact. From these cases, several key lessons emerge for advancing circular and responsible electronics:

- **Alignment of circular and RI principles:** All cases reveal how circular practices do not occur in isolation—they need governance, stakeholder engagement, and foresight (e.g. in supply chain transparency or material traceability).
- **Scaling is hard:** From Apple's robotics to the Royal Mint's chemical processes, moving from prototype to industrial scale often exposes hidden costs, regulatory barriers, and integration challenges.
- **Dilemmas surface in practice:** Whether between repairability vs IP, novel materials vs manufacturing fit, or collaboration vs competition, real-world cases show that trade-offs are inevitable.
- **Transparency and traceability are foundational:** Digital tools and rigorous systems are key to building trust and enabling circular flows.
- **Institutional leadership matters:** Established players (like the Royal Mint) or global brands (Apple) have the reach, capital, and legitimacy to experiment with circular transitions in ways that smaller firms might struggle to replicate immediately.

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[18] https://arxiv.org/abs/2005.11556

[19] https://arxiv.org/abs/2308.12496

PATHWAYS AND RECOMMENDATIONS FOR ACTION

The lessons from expert insights and case studies point to a common conclusion: circularity in electronics cannot be achieved by technology or market forces alone. It requires coordinated action across policy, industry, research, and society, guided by principles of Responsible Innovation. This section sets out pathways for embedding circularity and responsibility into practice, offering targeted recommendations that translate broad ambitions into actionable steps for different stakeholder groups.

The transition to responsible and circular electronics requires both a clear set of overarching priorities and targeted actions across key stakeholder groups. Building on expert insights, case studies, and roundtable discussions, the following framework brings these strands together.

TOP 5 PRIORITIES FOR SYSTEMIC CHANGE

1. **Strengthen circular practices**
   Reimagine how electronics are designed, used, and recovered—embedding repair, reuse, and recovery into business models.
2. **Advance innovation for sustainability**
   Prioritise breakthroughs in areas like battery technology and green materials that can deliver significant environmental gains.
3. **Build skills and capacity**
   Invest in talent pipelines, specialised training, and knowledge exchange to keep pace with rapid technological change.
4. **Enable responsible markets**
   Use policy, funding, and regulation to make sustainable options economically viable, while shifting consumer perceptions of refurbished products.
5. **Foster collaboration and responsible innovation**
   Strengthen academic–industry partnerships, leverage initiatives like REACT, and adopt the principle of "think globally, act locally" to accelerate systemic change.

Stakeholder-specific actions

Policy

- Harmonise right-to-repair regulations across markets.
- Strengthen and extend Extended Producer Responsibility (EPR) schemes.
- Develop and align critical minerals strategies.
- Support international standards for transparency and traceability.

Industry

- Integrate eco-design and modularity principles into product development.
- Pilot and scale circular business models (leasing, repair-as-a-service, device trade-ins).
- Adopt digital product passports and transparent supply chain reporting.
- Build cross-sector partnerships for material recovery and secondary markets.

Research and Innovation

- Apply Responsible Innovation frameworks (e.g., AS-RIF) in research programmes.
- Develop maturity scales and metrics for assessing responsible innovation.
- Advance materials science for recyclability and safe disassembly.
- Create toolkits for SMEs to adopt circular and responsible practices.

Consumers and Society

- Incentivise repair and reuse behaviours through fiscal and policy levers.
- Support repair cafés, community initiatives, and refurbishment schemes.
- Raise awareness of e-waste impacts and resource scarcity through campaigns.
- Encourage citizen participation in shaping circular policy and innovation agendas.

Coordinated Pathways

- Establish multi-stakeholder platforms to align actions and share best practices.
- Position initiatives such as REACT as conveners and thought leaders in responsible electronics.
- Emphasise that systemic progress depends on joint commitment across policy, industry, research, and society.

CONCLUSION: TOWARDS RESPONSIBLE CIRCULAR ELECTRONICS

Electronics will remain central to the pursuit of digital transformation and global Net Zero goals, but the sector's current trajectory is unsustainable. Rising e-waste, supply chain fragility, and critical material dependence highlight that technological advances alone will not deliver the necessary transition. Circular economy strategies provide an essential foundation, but without a guiding framework, they risk reproducing trade-offs and inequities rather than overcoming them.

The Adam Smith Responsible Innovation Framework offers a pathway to navigate these dilemmas by embedding anticipation, inclusivity, reflexivity, responsiveness, transparency, and equity into practice. By aligning circular economy strategies with responsible innovation, stakeholders can not only reduce environmental harms but also ensure that solutions deliver long-term societal value.

The recommendations outlined in this white paper emphasise that progress depends on coordinated action across policy, industry, research, and society. Policymakers must harmonise regulations and incentivise transparency; industry must adopt eco-design and circular business models; researchers must embed responsibility into innovation programmes; and citizens must be empowered to participate in shaping the future of electronics. Crucially, multi-stakeholder platforms such as REACT can convene and align these efforts, positioning the UK and its partners as leaders in responsible and circular electronics.

The way forward demands not only new technologies but also new forms of governance, collaboration, and responsibility. By embedding responsible innovation at the heart of circular strategies, the electronics sector has the opportunity to move from being a driver of risk to a cornerstone of resilience, competitiveness, and sustainability.

KEY TAKEAWAYS

- **Electronics are essential but unsustainable**: urgent action is needed to address e-waste, emissions, material scarcity, and fragile supply chains.
- **Circular economy is necessary but not sufficient**: without governance, trade-offs and unintended impacts can undermine sustainability goals.
- **Responsible Innovation is the missing lens**: the Adam Smith Responsible Innovation Framework helps balance environmental, social, and economic priorities.
- **Systemic change requires coordination**: progress depends on joint commitment from policymakers, industry, researchers, and society, with initiatives like **REACT** convening and leading the agenda.