Implications of the Circular Economy for Electronic Products

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Abstract

The Circular Economy concept of the European Union aims to save energy and material resources while minimizing resource risks while giving the EU a competitive advantage in economic terms. This paper explores the implications of the circular economy for electronic products by analyzing design aspects such as durability, reparability, reusability, remanufacturing, as well as plastics recycling and the application of recycled plastics in new products. This involves both reviewing how those aspects are finding their way into new requirements under the EU Ecodesign directive as well as select activities in the research landscape and on company level.

Keywords:

Circular Economy, electronic products, design strategies, material efficiency, Ecodesign directive

1 INTRODUCTION

The European Commission has set the goal for the European Union to transition to a circular economy, in which linear production and consumption patterns of ‘take, make, dispose’ are replaced by a circular approach, in which the value of products, components and resources is maintained for as long as possible and the generation of waste is minimized.

To enable the transition to a circular economy, the Circular Economy Action Plan of the European Commission [1] proposes actions aimed at supporting each step along the value chain – from production to consumption, repair and remanufacturing, waste management, and secondary raw materials to be fed back into the economy. The Action Plan explicitly mentions the significance of electronic products for their content of valuable resources. Plastics and critical raw materials, as defined by the European Commission [2], are identified as priority areas which face specific challenges in the context of the circular economy.

There is a wide consensus that the design of products needs to be changed and that design is pivotal to the transition to a circular economy. Yet few examples are available in the electronics industry, and of those a majority could be characterized to address niche markets or experimental stages. Specific examples start with something as simple as choosing materials with an established end-of-life (EOL) strategy and including post-consumer recycled plastics (PCR) during the production stage. More complex examples are design trade-off decisions between more robust designs (extending the first use cycle of a product) and more modular design to accommodate better material recycling, repair, reuse, refurbishment, upgrading, etc.

This paper explores the following themes and questions: What are the key elements of the Circular Economy Action plan with relevance to electronic products? How can reparability, upgradability, reusability, durability and recyclability be integrated into the design of electronic products? How can remanufacturing of products and stimulating a market for secondary raw materials such as plastics be addressed? For each of these themes, the paper explores which aspects are currently discussed for new requirements under the European Ecodesign directive and what approaches research activities and companies currently address.

2 RELEVANT KEY ELEMENTS OF THE CIRCULAR ECONOMY ACTION PLAN

The Circular Economy Action Plan acknowledges the significance of the product design phase, in which the environmental impacts of the product life cycle are largely predetermined. Better design can make products more durable or easier to repair, upgrade, remanufacture, or recycle, and thus help to save resources. Consequently, it is foreseen to promote better design by emphasizing circular economy aspects in future product requirements under the European Ecodesign directive [3]. The objective of the Ecodesign directive is to improve the efficiency and environmental performance of energy-related products. To date, requirements have mostly focused on improving the energy efficiency of electric and electronic products in scope of the directive. However, the Action Plan explicitly states the goal to emphasize issues related to material efficiency, such as reparability, durability, upgradability, and recyclability. The provision of economic incentives to manufacturers whose products are easier to recycle, based on the end-of-life costs of their products, is suggested as another instrument to guide design decisions.

Material and energy efficiency aspects of production processes are foreseen to be addressed by promoting the socially and environmentally sustainable sourcing of raw materials through various tools and measures. Further, remanufacturing is highlighted as a high-potential area to be funded via the EU's Horizon 2020 program, among others.

The Circular Economy Action Plan also puts emphasis on the importance of consumption and the role of consumers in the transition to a circular economy. To this end, the communication of sustainability aspects of products towards consumer will be improved, e.g. by including information on the durability of products on the existing energy efficiency labels. Additionally, shared economy concepts and selling and consuming services rather than products are mentioned as viable approaches. With regard to material recycling at EOL, the need for quality standards to enable the increased use of secondary raw materials in the production process, particularly plastics, is addressed. Furthermore, the need to stimulate sufficient demand for recycled materials is mentioned.

In summary it can be said that the Circular Economy Action Plan takes the entire life cycle of products and possible loops for their components and materials into account rather than focusing on EOL activities only. However, in a survey of EU Member States, the EEA found that the majority of policy approaches employed to closing material loops across different life cycle stages has this far focused mostly on waste-related aspects and recycling [4]. Product design and measures aiming to enable reuse, repair, refurbishment, and remanufacturing activities, were not found to be extensively reflected in policy approaches (Fig. 1).

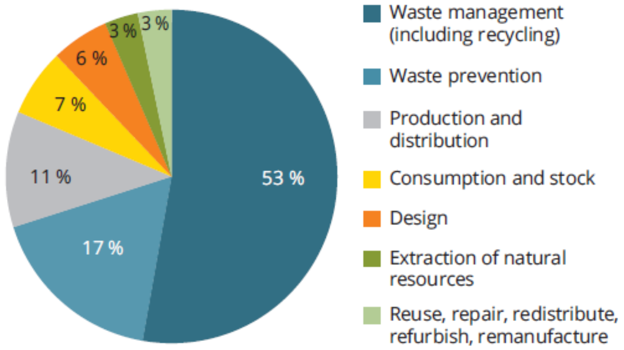

Fig. 1: Distribution of responses on policy approaches to closing material loops in a survey of Member States conducted by the European Environment Agency [4]

Considering that WEEE is one of the fastest growing waste streams worldwide [5], focusing on waste management and recycling is essential, but may not be the only approach to effectively address material efficiency of electronic products. It has been shown that for some products, the environmental impacts embedded through production and resource extraction are much higher than the impact of all other life cycle phases. This is especially true for mobile ICT products, such as smartphones, tablets and laptops, which are frequently highly energy efficient in the use phase [6]. Typically, the life cycle profiles of such devices show that the clear majority of environmental burden is associated with the manufacturing activities, while EOL processes only contribute minor shares and often recover minor shares of the complex material mixtures found in those products. This is illustrated via the example of a Life Cycle Assessment of the Fairphone 2, a smartphone that follows a modular approach, and which emphasizes social and environmental values in their products and production processes. It has been found that extending the time the product stays in the use phase, e.g. through design for reparability, is an effective path to mitigate environmental burden caused by the production [7].

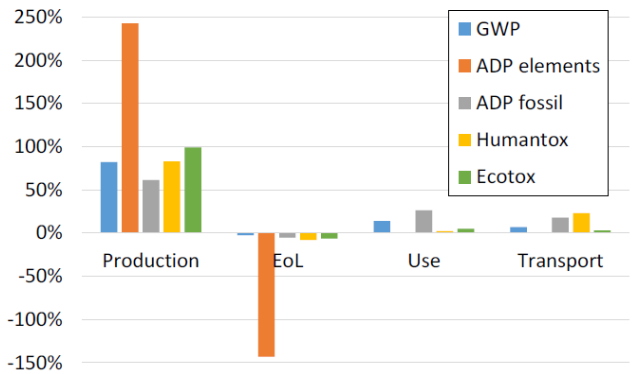

Fig. 2: Relative impacts of the different life cycle phases per impact category for the Fairphone 2 smartphone [7]

3 REPARABILITY, UPGRADABILITY, AND REUSABILITY OF ELECTRONIC PRODUCTS

For some product categories, particularly for mobile ICT devices such as smartphones, tablets and notebooks, the trend in product design in the past years has been towards slimmer and more integrated devices. One of the most extensively discussed components in this context are device batteries, as their functionality inevitably degrades over time and for their content of valuable materials such as cobalt, lithium and graphite. For the product groups mentioned above, it has become commonplace to integrate batteries into the products as opposed to designs which allow the user to easily remove and replace the battery without the use of tools. Depending on the design approach chosen by the manufacturer, this practice has the potential to considerably complicate the repair process once the battery needs replacement, in addition to removal of the battery at EOL for separate recycling. Determining factors for the ease of repair are mostly the joining technique for the device and for the battery itself (e.g. use of screws, clips, or adhesive).

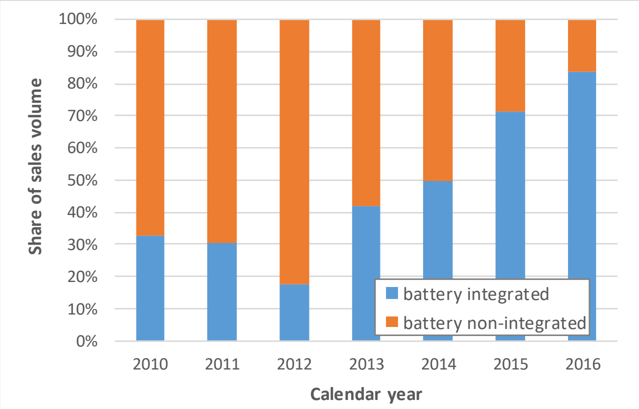

Fig. 3 : Share of sales volume of best-selling smartphone models in Europe with integrated batteries and non-integrated batteries in the years 2010 to 2016 [8]

While RAM and mass storage units are typically soldered directly onto the mainboard in smartphones and tablets, the same design choice can recently also be observed in the case of notebooks. This trend further extends to notebook CPUs and GPUs, which are moving away from technology that reversibly joins those components to the PCB, such as pin grid array (PGA) fitted into a socket, towards permanently joining techniques using soldering, such as ball grid array (BGA) technology. This approach may significantly complicate upgrade and repair activities for those components and can potentially be considered counterproductive to the ambitions of the circular economy. On the other hand, more integrated solutions often also require less material, such as copper and gold for electrical connections between components.

Fig. 4 : Examples for ICs on a notebook mainboard connected to the mainboard via PGA fitted into a socket (left) and directly soldered onto the mainboard (right)

The Ecodesign directive has been identified in the Circular Economy Action Plan to address such design aspects which influence the reparability, upgradability, and reusability of products, among others. To this end, current preparatory studies and revisions of existing regulation under the Ecodesign directive are introducing corresponding measures. Specifically, product groups in scope of such studies are electronic displays, including television sets [9], computers, including notebooks and tablets [10], and enterprise servers and network equipment [11]. For example, several draft requirements prohibit the use of welding (soldering) and gluing for certain components. In the case of desktop and notebook computers, the following components are explicitly mentioned: batteries, internal power supply units, display, mass storage system, memory, keyboard, trackpad, network interface board, and wireless LAN board. For tablets, soldering and gluing is not eligible for batteries and display. However, the use of adhesive tapes to adhere batteries is exempted from this requirement. The draft requirements further suggest making the provision of accompanying repair information by manufacturer mandatory. This includes, among others, exploded diagrams showing the location of listed components in a product and documentation of disassembly and re-assembly operations.

The Fairphone 2 smartphone can serve as an example of an ICT product that employs a modular approach for improved reparability: The fact that the consumer can easily replace individual modules significantly lowers the barrier for do-it-yourself repairs and thus the barrier to keep the products longer in use. A Life Cycle Assessment of the Fairphone 2 demonstrated that although modularity implies a slightly higher impact of the production phase, the enhanced reparability very likely leads to significantly lower total life cycle impacts over an extended product lifetime [7].

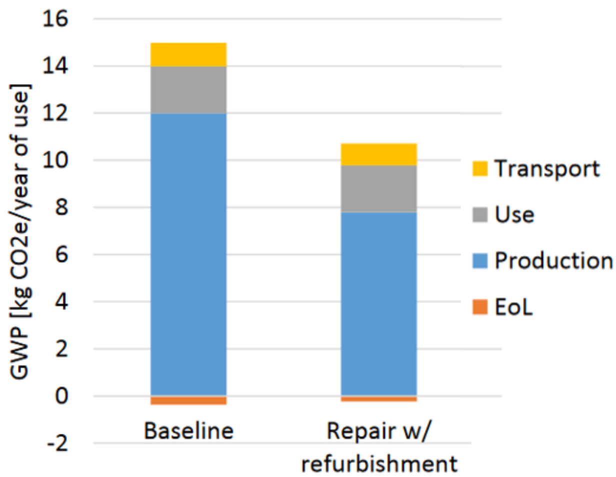

Fig. 5 : Global Warming Potential of the Fairphone 2 life cycle per year of use (left: baseline scenario in which only the battery is replaced once in the use time of 3 years; right: repair scenario in which further components are replaced to extend the use phase to 5 years) [7]

The benefits of modular design in environmental terms in the end depend on the way the user makes use of it. The design strategy only fully pays off if the use period is indeed extended, e.g. by swapping broken parts or upgrading components to be able to longer use a device, or if components are separated at the EOL to enter dedicated recycling paths.

4 DURABILITY OF ELECTRONIC PRODUCTS

Product longevity may be increased by the above-mentioned design strategies for reparability, upgradability and reusability, but manufacturers may also choose to design their devices for maximum robustness and reliability to extend the technical lifetime. For smartphones, tablets and notebooks, this may mean constructing a compact device designed to withstand adverse events such as drops by the user and minimizing the risk of ingress of foreign matter such as dust and liquids. As is well known, certification for international protection (IP) according to the international standard IEC 60529 [12] is increasingly employed for smartphones and other devices to warrant ingress protection. However, constructing devices in such a way may mean further integration of components into devices, as discussed in section 3, potentially hampering the ability to repair and upgrade. Hence, certain conflicts between different design strategies can be observed, which may require manufacturers to prioritize one strategy over another.

The Ecodesign directive currently has only a limited number of requirement in place which aim at product durability. The approach is to target components in products that are considered to fail most frequently. In the case of vacuum cleaners for instance, the hose is required to still be usable after 40,000 oscillations under strain and the operational motor lifetime is required to be greater than or equal 500 hours [13]. New durability requirements have also been suggested in the above-mentioned draft requirements for computers [10] regarding the device battery: It is suggested that manufacturers communicate the remaining capacity the device battery can hold after withstanding 500 charge/discharge cycles carried out according to the relevant IEC standard. While this is an information requirement rather than a specific threshold value for minimum durability, it is designed as an intermediate step towards a more concrete future requirement, as data can be collected to be used in setting a specific threshold in the future. Additionally, based on a draft technical report by the Joint Research Centre [14], it is suggested that manufacturers pre-install a software on notebooks which allows the users to limit the maximum state of charge of the battery to reduce the negative impact a high state of charge has on battery durability.

These examples show that the durability of devices needs to be evaluated on a case-by-case basis, as each product category may have different components which fail most frequently, either due to technical reasons (battery) or due to common use patterns (shattered displays with smartphones and tablets). Whether this is an efficient approach to product durability, or whether other instruments, such as extended producer warranties, may proof more practical, remains to be seen.

5 REMANUFACTURING AND CASCADE REUSE OF ELECTRONIC COMPONENTS

Keeping products in the use phase for as long as possible has been identified as a priority on the path towards a circular economy. However, it can be assumed that virtually all products will eventually be disposed of. Many organizations involved with collecting and recycling of WEEE assess the potential for repair of devices to maintain its highest possible economical value. If repair is not economically viable, components may still be harvested for spare parts. Keeping in mind the fast pace of technological development, especially in the ICT sector, another application of functional components from EOL electronics may be cascade reuse in less demanding applications. Again, the viability of component harvesting depends on the joining technique applied, and soldered or adhered components may make this process considerably more complex, as the effect of subjecting ICs and printed wiring boards to additional soldering processes are not planned for in the original product design stage and may be detrimental to the product's functional integrity.

Nevertheless, de-soldering of flash memory components from smartphones for a cascaded reuse in applications such as USB sticks are currently under investigation in the EU project sustainablySMART [15]. Desoldering of such BGA components is challenging as there is the trend to use increasingly underfillers for these packages, which enhances reliability of the assembly, but results in residues at the point of desoldering. This is actually a good example of trade-offs in a Circular Economy: Better reliability of assemblies is good for an extended first product life. However, repair and a second component life faces an additional barrier through the use of underfillers.

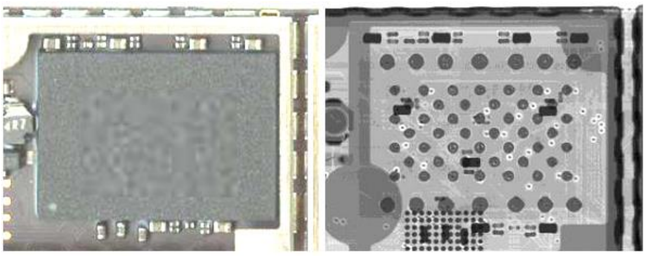

Fig. 6 : Flash memory BGA (left: photo with underfill meniscus visible on the left side, right: X-ray image with solder balls visible underneath the component) [15]

Under these conditions a Circular Economy strategy has to define whether a longer first life or a component second life has to be prioritized. Another challenge is the number of reflow cycles a BGA component might go through: Typically, BGA components are qualified for a limited number of reflow cycles, which corresponds to first production and already a component rework in first production might go beyond the number of soldering cycles the component is meant to go through. For a second life another sequence of desoldering, reballing, and resoldering processes are required, which leads to additional stress on the component. Sitek et al [15] at least report that investigated memory BGA packages withstand numerous reflow cycles and still pass quality and functional tests.

Another aspect of concern is data erasure from memory components for a second life. Recently cases were reported in which data could be retrieved from newly manufactured USB sticks and it was found that the storage units stemmed from discarded smartphones [16]. The project sustainablySMART therefore also investigates data erasure routines to reliably erase data from BGA Flash memory components. The challenge is that eMMC technology used for smartphone Flash memory is based on an integrated memory controller in the memory package. This controller governs the access to the actual memory and any data deletion process has to be adapted to the internal memory controller.

Another step forward is to consider reuse scenarios as early as in the product design stage. Circular Devices for instance, the company behind the PuzzlePhone, has thought up several ways in which components can be used if they are no longer fit to satisfy the demands of users. These include the integration of the "brain module", containing the main computing elements, into a supercomputer-like cluster [17].

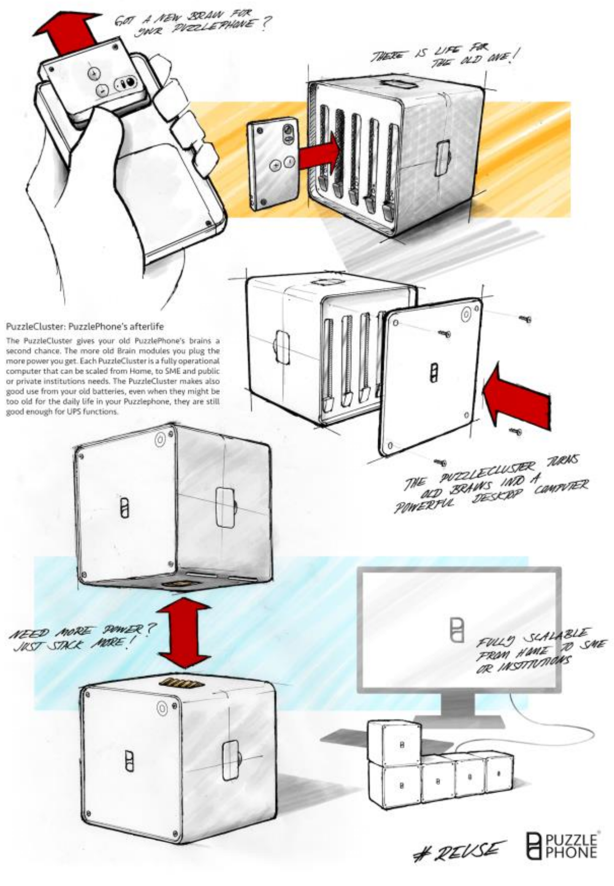

Fig. 7 : Design concept showing re-use of compute modules enabled through high integration technologies [17]

Conclusively, reuse approaches have a great potential to maximize the efficiency of resources incorporated into products and components, however, there seems to be a long way ahead before the practice can become commonplace. Compatibility of components between different products and product generations is an issue that could be addressed by modularity as well as standardization, e.g. in terms of form factors, electrical connectors, and software.

6 PLASTICS IN A CIRCULAR ECONOMY

Of the estimated 20-50 million tons annual Waste of Electric and Electronic Equipment (WEEE), an average of 21 % by weight are plastics [18]. While valuable metals from WEEE are frequently recovered at high rates, the same cannot be said about plastics. For one, the economic value of plastics from WEEE is orders of magnitude below the value of metals such as gold, silver, platinum, and well below metals such as copper, cobalt and gallium [5]. Additionally, the variety of available combinations of polymers and polymer blends, as well as additives such as flame retardants, plasticizers, and reinforcing agents, among others, makes an efficient and effective separation and recovery challenging. The dominating approach to separating polymers from shredded WEEE fractions is the sink and float method. One or several sequential salt-containing solutions keep materials below a defined density afloat, while materials with a higher density will sink to the ground. Density separation is usually designed to keep the polymers most commonly found in WEEE afloat, i.e. ABS, PS and PP, while other materials, such as glass, and plastics containing flame-retardants, sink [19]. Other solutions to separate different plastics include optical techniques such as NIR and MIR or selective solvent extraction, such as Fraunhofer IVV's CreaSolv® process. The latter can even separate additives, such as brominated flame retardants or antimony trioxide, which are typically lost in electronics recycling processes despite the fact that antimony is on the European Commission's Critical Raw Materials agenda. The process is under research in the Horizon 2020 project CloseWEEE [20].

One barrier to closing the loop for plastics in EEE is the use of materials that are currently not recyclable from a technical or economic point of view, such as polymers reinforced with glass fibers and carbon fibers. Co-molded plastics parts are also of concern. The Circular Economy particularly in the case of post-consumer recycled (PCR) plastics also has a conflict to solve between high recycling rates and getting potentially hazardous substances out of the material cycle: Thresholds under European RoHS, POP and other directives are usually defined on the basis of detection limits and that if no hazardous substance is intentionally added concentration should be close to zero. In the case of recycled polymers from post-consumer plastics there is always a share of historic waste, which still contains banned materials. Although no hazardous materials are intentionally added to the recycled polymers, concentration will be higher than among virgin polymers, which never have been brought in contact with these substances. Furthermore, not all brominated flame retardants are banned or regulated, but NGOs and industry frequently requires "halogen-free" material – which, depending on the defined threshold – is definitely a barrier to use recycled plastics in new products.

Another gap to closing the loop has been stated to be the demand side of recycled polymers [1]. While several manufacturers of EEE have incorporated recycled plastics in their devices for many years, large scale integration of PCR plastic is not commonplace. Manufacturers require materials with reliable and consistent quality and a stable supply at reasonable prices. The latter implies recycled materials should be available at equal or below the cost of virgin materials. As recycled polymers are not necessarily equal to virgin materials in terms of material purity – ABS can reportedly be separated with 99 % and PS with 98.5 % purity [19] – virgin materials may be regarded by manufacturers as the more reliable choice. Consequently, an absence of incentives may be the reason for the lack of large-scale implementation of WEEE PCR plastics in new EEE.

The use of recycled plastics in new applications on large scale is an endeavour with high complexity and influenced by many different yet interlinked factors - not only the quality, but also a guaranteed availability and stable price of recycled plastics influence the decision whether or not the final user will select PCR plastics over virgin materials. In an economic system, where recycling is a for-profit activity, product design and material choices can result in favourable or unfavourable economics of the recycling processes and final material price. Even if a product is technically recyclable, but the process of material liberation and recycling does not result in positive economic value, products are unlikely to be recycled [21]. Mindful material selection paired with product design, linked to disassembly, materials liberation and economically running sorting and recycling processes could contribute positively to increased yields of high quality recycled plastic and overall improvement of the economics across the value chain.

Several voluntary schemes currently list PCR plastics content in their criteria. For example, EPEAT lists the declaration of post-consumer recycled plastic content as a required criterion and the actual implementation of PCR plastics in products in ranges of either 5 % to 10 % or above 25 % as optional criterion for imaging equipment [22]. TCO criteria for displays require a minimum of 85 % post-consumer recycled plastic for cutting edge products [23]. However, in terms of European legislation, obligatory requirements are currently not in place. Preliminary suggestions for revised requirements under the Ecodesign directive for printers suggest a tiered approach, requiring the use of PCR plastics from WEEE in printers starting with a low percentage to be increased over time [8], in order to stimulate a growing market for PCR plastics and ultimately close the loop.

7 CONCLUSIONS AND OUTLOOK

The EU's Circular Economy Action Plan sets the goal of transitioning from a linear to a circular economy and identifies concrete actions to facilitate this transition. Some of the identified actions have already been taken up in defining new product-level requirements under the European Ecodesign directive. This approach will in the future be supported by a set of standards, which has been commissioned to the EU's standardization organizations under standardization request M/543. This work will produce calculation and test methods with reference to product durability, upgradability, reparability, and re-use and remanufacturing [24]. However, the efficiency and effectiveness of prohibiting or prescribing certain technologies for specific product categories in the scope of the Ecodesign may be questioned. Moving to an approach in which the goal is prescribed, but the process to get there is left to manufacturers and product designers may eventually yield better solutions. For instance, if extended producer warranties were to be prescribed, the technical solutions to achieve the target value may be left to the manufacturers. A further step may be to set performance indicators on company level with goals to lower the primary material input per unit of product produced and thus pushing the market to new solutions for material efficiency.

What's more, changing product design and enhancing the recycling rates is just one puzzle piece in the big picture. To truly transition from a linear to a circular economy, the way we do business eventually needs to change. New and innovative business models are needed that generate benefits for the company, the prosumer and other stakeholders while minimizing negative impacts on the environment. The guiding principle is to preserve the highest possibly integrity of the product to retain its possibly highest value. In order to retain this value for as long as possible implies moving away from selling a product, towards providing the product as a service for as long as possible, including repair and refurbishment activities. Furthermore, products should be used more efficiently through multiple use by different users (sharing) or (cascade) re-use of the product (in different applications). In such circular economy business models, revenue is generated through pay-per-service, lending or contracting models, rather than selling as many units as possible. The idea behind this is that, all things considered, following the efficiency, sufficiency and consistency strategy will be better for the people, the planet, and for business alike.

Until this vision of a circular economy becomes a reality, technological solutions can be expected to be incrementally implemented by frontrunning companies, such as Fairphone and others, and via new requirements set out by political instruments such as the Ecodesign directive. The path towards a circular economy has been set, and the implications on electronic products are undeniably taking shape.

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