FAIRPHONE

Fairphone's Report on Recyclability

Does modularity contribute to better recovery of materials?

Table of Contents

Introduction

From the dawn of the industrial era up to today, many of our products have been created according to the principles of a linear economy: we find resources, make a product, and then dispose of it when we're done using it. But in recent years, there's been a growing awareness of the need to move to a circular economy, an approach that aims to maximize the usefulness of products, components and materials across the entire lifecycle. In terms of recycling, this means achieving maximum recovery of materials once products reach the end of their usable life.

Improving material recovery in the electronics sector will require brands, manufacturers and recyclers to take a product-centered approach, as defined by Reuter and Van Schaik[1,2,3] to understand the complete lifecycle, where the inefficiencies occur in the system and which frameworks can offer solutions. To take the first step in this direction, Fairphone is starting by examining the end-of-life phase of its latest smartphone, the Fairphone 2.

Eventually, when our phones are no longer (re)usable or repairable, they will make the transition from constant companion to electronic waste. When that time comes, the findings of this recyclability study will help to guide our decisions in order to recover the greatest percentage of materials from the Fairphone 2.

1) M.A. Reuter, C. Hudson, A. van Schaik, K. Heiskanen, C. Meskers, C. Hagelüken (2013):United Nations Environmental Protection (UNEP) Report "Metal Recycling: Opportunities Limits Infrastructure" report: http://www.unep.org/resourcepanel/Publications/MetalRecycling/tabid/106143/Default.aspx]

2) M.A. Reuter, A. van Schaik (2015): Product-Centric Simulation-Based Design for Recycling: Case of LED lamp recycling, Journal of Sustainable Metallurgy 1(1), 4-28.

3) M.A. Reuter, A. van Schaik, J. Gediga (2015): Simulation-based design for resource efficiency of metal production and recycling systems, Cases: Copper production and recycling, eWaste (LED Lamps), Nickel pig iron, International Journal of Life Cycle Assessment, 20(5), 671-693.

Acknowledgements

We would like to acknowledge the help of Dr. Antoinette van Schaik (MARAS B.V.) and Prof. Dr. Dr. h.c. Markus A. Reuter (Freiberg, Germany) who performed the recyclability study commissioned by Fairphone and supported us in the writing of this report.

Problem Definition

Recycling has long been viewed as the panacea of sustainability. Once you're done using something, you just have to recycle it (instead of throwing it away) and the problem is solved, right? But it's not that simple, of course. What happens to products after you put them in the recycling bin? How does recycling actually work?

For products that are made of a single material (like glass), the process can be as simple as melting it down to reusing it. But complex consumer products are much trickier. Recycling electronic devices requires a combination of steps, including dismantling, size reduction (shredding), physical sorting and further metallurgical and other final treatment processing. Materials are inevitably lost at every phase of the process, and the overall recycling efficiency also depends on the design of the products, the properties of the materials they are made of, how well the waste is collected and sorted, and more. In addition, recycling consumes energy, meaning recovered materials still come at a cost to the environment.

Here we want to highlight the fundamental difference between material and product-centric recycling. While the approach used in this report shows the effect that all materials have on each other and on the quality of the final output, a material-centric approach would focus on the output of separate materials and often neglect the influence of the process on all other materials. We believe through this product-centric approach we can provide a fully fundamental basis to estimate resource efficiency in the circular economy[4].

With this complexity in mind, part one of our recyclability study specifically addresses materials recovery by focusing on two key questions:

1. What is the exact composition of the Fairphone 2 and how do the materials behave in different recycling routes via physical separation, process metallurgy, plastics processing as well as energy recovery?

2. How can modularity (in terms of easy disassembly) help increase the recovery rate of materials during the recycling process?

Part two of the recyclability study looks at the environmental footprint of various recycling approaches. These results will be published in a future report and blog post (www.fairphone.com/en/blog).

4) A. van Schaik, M.A. Reuter (2016): Recycling indices visualizing the performance of the circular economy, World of Metallurgy – ERZMETALL, 69(4), 201-216.

Set Up of the Recyclability Study

To conduct this study, we turned to Dr. Antoinette van Schaik (MARAS B.V.) and Prof. Dr. Dr. h.c. Markus A. Reuter (Freiberg, Germany), both renowned experts in recycling, sustainable technologies for metallurgy and digitalizing the circular economy. We asked them to investigate the recyclability of the Fairphone 2 using the Recyclability Index and Materials Flower as developed by Van Schaik and Reuter.

Using rigorous process models that simulate the behavior of the materials in Fairphone 2 in the recycling stream, the Recyclability Index indicates to what extent the various materials are recoverable. The potential recovery rates are based on using the current best available techniques (BAT), taking into consideration the limits of the product's design and what the laws of thermodynamics and physics allow when it comes to separating materials into usable recyclates. In this Recycling Index, recovery rates are calculated for both the overall product as well as each individual material present in the Fairphone 2.

To perform this study, the consultants completed the following steps:

- Practical investigation of the construction of the Fairphone 2.
- Collection and processing of all material composition information from the product's material declarations together with Fairphone value chain team members.
- Definition of three different recycling routes that combine industrial BAT (best available techniques) recycling routes representative of the typical processes used for consumer electronics, based on the consultant's extensive industrial expertise. Accompanied by flowsheets to visualize the three routes.
- Modeling the Fairphone 2 recycling process following the three chosen routes, using metallurgical and physical separation process simulation software HSC Chemistry/Sim ® (Outotec). This was done considering the composition, connections, materials and compounds of the Fairphone and the separation performance and efficiency of each of the processes within the different recycling routes based on physics and thermodynamics, physical material properties (e.g. magnetism, density, colour, etc.), and liberation behavior to determine particle quality (mono or multi-material composition).
- List of the outputs (recyclates & metal products and recycling/recovery rates) by element and by recycling route and highlight where the main material losses occur.
- Assessment of the environmental footprint of the different recycling routes expressed in Global Warming Potential (i.e. CO_2 emissions) (results shared in a future report).
- Providing advice on design for recycling (available in a future blog post).

Results of the Recyclability Study

The study identified and analyzed three different potential recycling routes for the Fairphone 2. These routes are based on combinations of the best techniques currently available, with the goal of understanding which methods could optimize the recovery of materials. The study also looked at the environmental impact of different processes, but those findings will be included in a future report.

To be able to understand the balance between physical processing and metallurgical/plastics processing as well as energy recovery, a complete particle and thermochemistry based flowsheet model was developed as shown in Figures 1 and 2. This applies to the full complexity of all material combinations and simulates which processes are used to recycle them. As the authors have worked in industry these flowsheets are realistic and the parameterization is based on many years of industrial and academic experience.

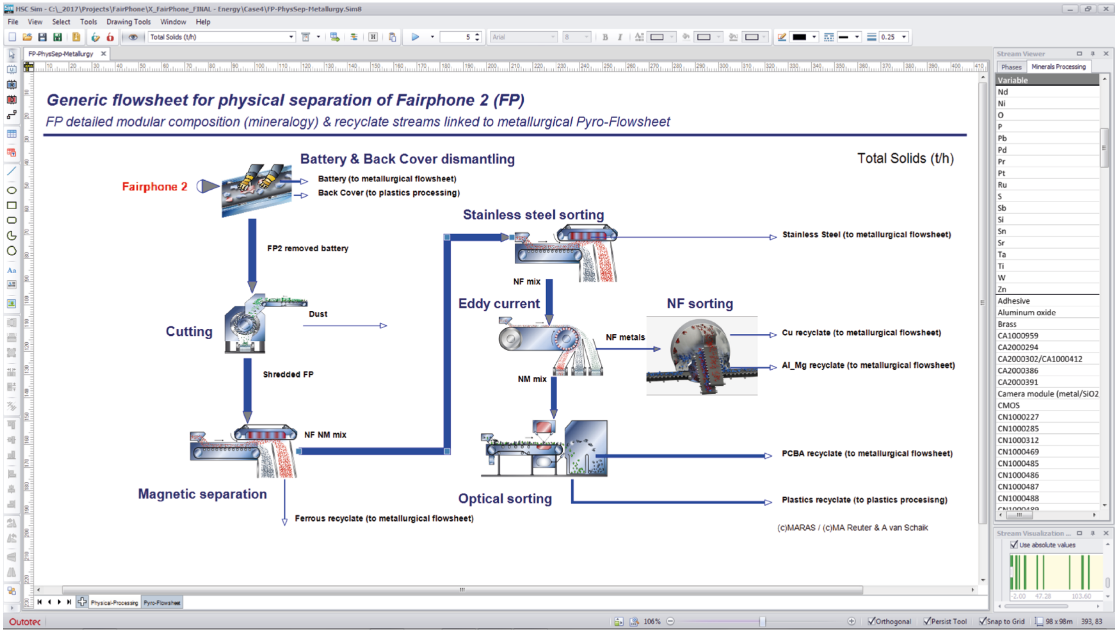

Figure 1: Shows the physical separation based on a full particle model (mono and multi-material particles) of the bill of materials and full material declarations of the Fairphone 2. Then tracks all particles through the system (keeping track of recyclate quality/composition) and routes them to the appropriate processing unit operations and plants as shown in Figure 2.

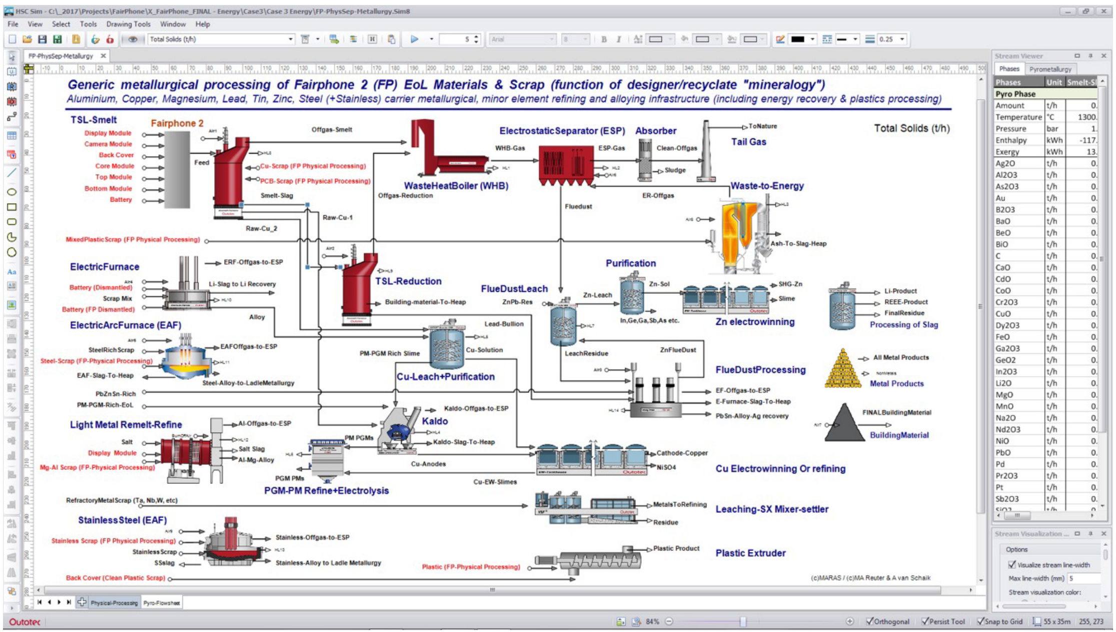

Figure 2: The metallurgical, energy and plastics processing flowsheet that can process the multitude of metals, alloys, functional materials and plastics in an end-of-life product. It covers steel, stainless steel, copper, lead, tin zinc, aluminum and magnesium as carrier metal metallurgical infrastructure as well as plastics recycling and energy recovery (note that all minor/critical/scarce metals are included).

For better recycling, one has to keep the complexity of intermediate materials to its lowest possible value. Creating complex mixtures of scrap and recyclate products (e.g. liquid metal during processing to refined products and alloys) negatively affects final recovery. Managing the complexity of all streams in Figures 1 and 2 will maximize the resource efficiency in general. But let's examine the different routes.

Route 1: Smelting the Fairphone 2

The first route involves a bath smelting process such as a TSL smelting unit. This means feeding the whole Fairphone 2 into a high temperature metallurgical reactor and recovering the materials mainly as metals, alloys and inorganic compounds. This is just the first step -- the rest of the processes after the reactor are displayed in Figure 2.

This route enables the recovery of all metals that have a high affinity for copper (e.g. gold, silver, palladium and copper itself) while less noble metals such as magnesium, aluminum, steel, lithium and tungsten and its alloy elements end in slag. All plastic reports to offgas as CO_2, H_2O, NO_x etc. It must be noted however that the advantage of this approach is that the energy from the burning of the plastics saves the use of primary fuels. The carbon in the plastics is also used as a reductant saving therefore the use of other reductants from primary resources. The disadvantage is that plastic is not recovered at all as material.

Figure 3 shows the recovery rates of only 20 elements using recycling route 1. While the study addressed all of the 46 elements in the Fairphone 2, these 20 have been selected by Fairphone based on their depletion rate and social and/or environmental impact in their mining or end-of-life phase, making the recycling of these metals more urgent.

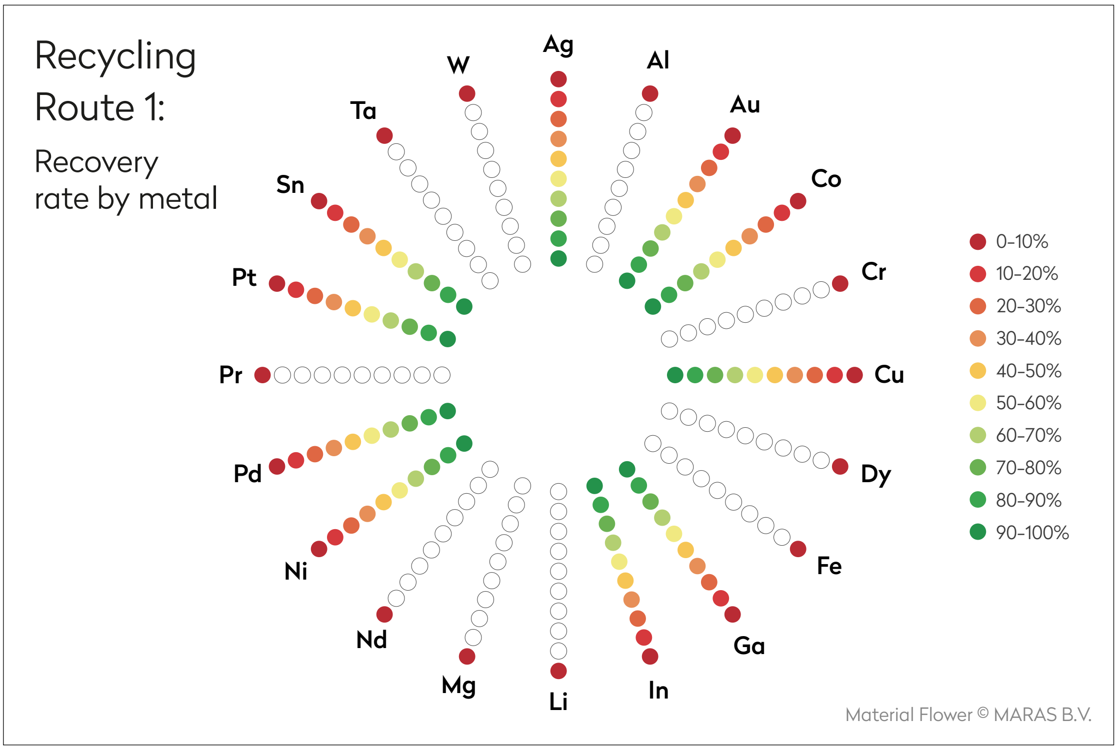

Figure 3:
Materials Flower for Recycling Route 1 (Total Smelting & Metal refining); developed by Van Schaik and Reuter.

Route 2: Dismantling and selective smelting

The second route looked at selective smelting, which includes separating the Fairphone 2 modules and putting them through the most suitable metallurgical and plastic recovery processes as shown in Figure 2. For example:

- Camera, core, top and bottom modules go to top submerged lance (TSL) furnace
- Display module goes to light metal remelt/refine, for optimal recovery of materials such as magnesium
- Battery goes to an electric furnace, for optimal recovery of materials like lithium and cobalt
- Back cover goes to the plastic extruder, for optimal recycling of the polycarbonate (plastic)

This route tests the effect of modularity. Thus, this example fits the material of each module to the process that best recovers it but also best uses the energy content of each material to its optimal economic benefit.

We have included only the modules that are easily separated, and no further disassembly has been done. We are aware that making dismantling economically feasible will depend on a variety of factors (such as time) that go beyond the scope of this study. These and other limitations are addressed in the conclusion of this document.

The various processes involved in route 2 are also displayed in Figure 2.

Route 2 delivers the widest range of recovered materials, and in contrast to route 1, also successfully recovers plastics in a usable form because the the plastic case is sent directly to the plastics extruder. It also results in successful recovery of magnesium (90%), which is completely lost in the first route. (To learn more about material loss in the different processes, please refer to Appendix 1.)

Figure 4 shows the recovery rates of 20 of the most significant materials using recycling route 2.

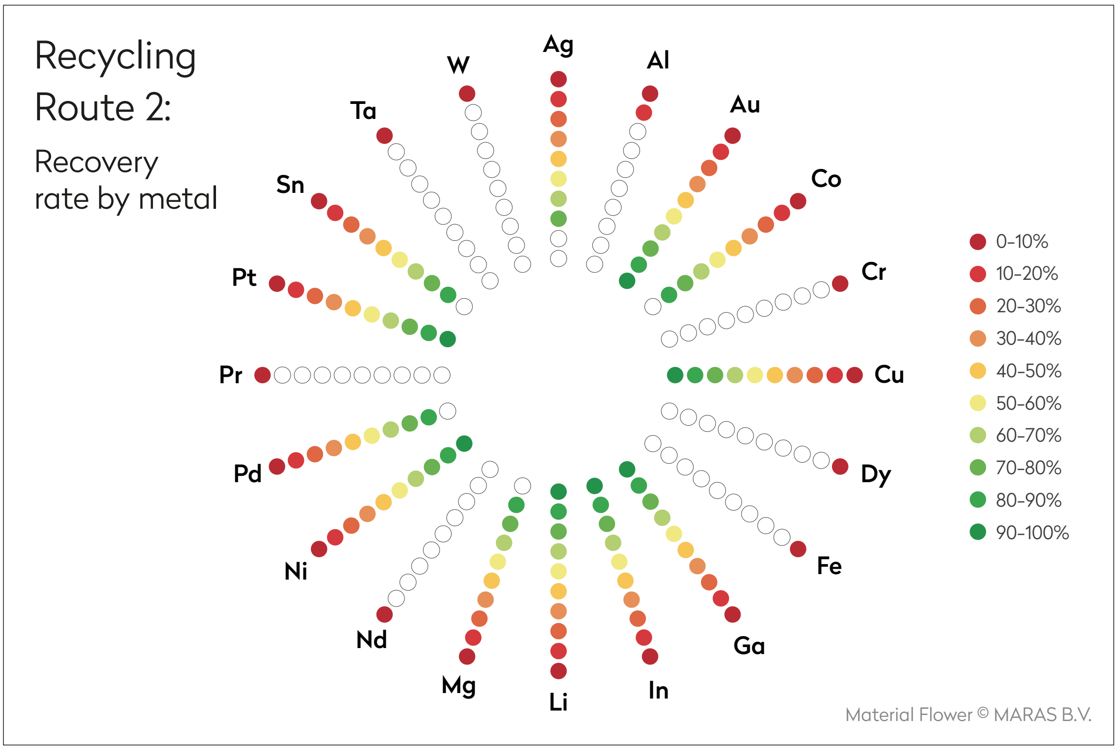

Figure 4: Materials Flower for Recycling Route 2 (Dismantling & selective smelting); developed by Van Schaik and Reuter.

Route 3: Shredding, physical pre-processing and metallurgy

The final route involves removing the battery and feeding the remainder through a cutting mill, followed by separating the small pieces (scrap) into different valuable scrap fractions. The separation is achieved by using the physical properties of the elements, for example using the different degrees of conductivity and magnetism to separate iron and other ferrous metals from the non-ferrous non-magnetic materials (e.g. copper, aluminum and magnesium). Optical sorting is also used to separate plastic pieces from metal-rich PCBA pieces.

You can see more detail in Figure 1 which shows the physical separation.

The outputs of figure 1 become the inputs of the appropriate processes in Figure 2.

These fractions are processed using the appropriate technology either metallurgically, for energy recovery (mostly from burning polymers), or into plastic products as detailed in Figure 2.

This example also simulates the effect of a product that cannot be dismantled. (Only the battery was removed for safety reasons).

Route 3 is the best for recovering the most bulk (non-precious) metals (e.g. steel, aluminum, magnesium, etc.) and results in the highest overall recovery rates by weight. However, it is less efficient in recovering valuable metals like palladium or tin as these go lost for example in complex plastic and bulk metal scrap mixtures especially when compared to route 2. It also produces impure mixed plastic recyclate which cannot be easily reused for consumer applications – it's used best as a secondary fuel resource instead as physical recycling will perhaps isolate one or two valuable plastic fractions but also create another heap of junk plastic.

Figure 5 shows the recovery rates of 20 of the most significant materials using recycling route 3.

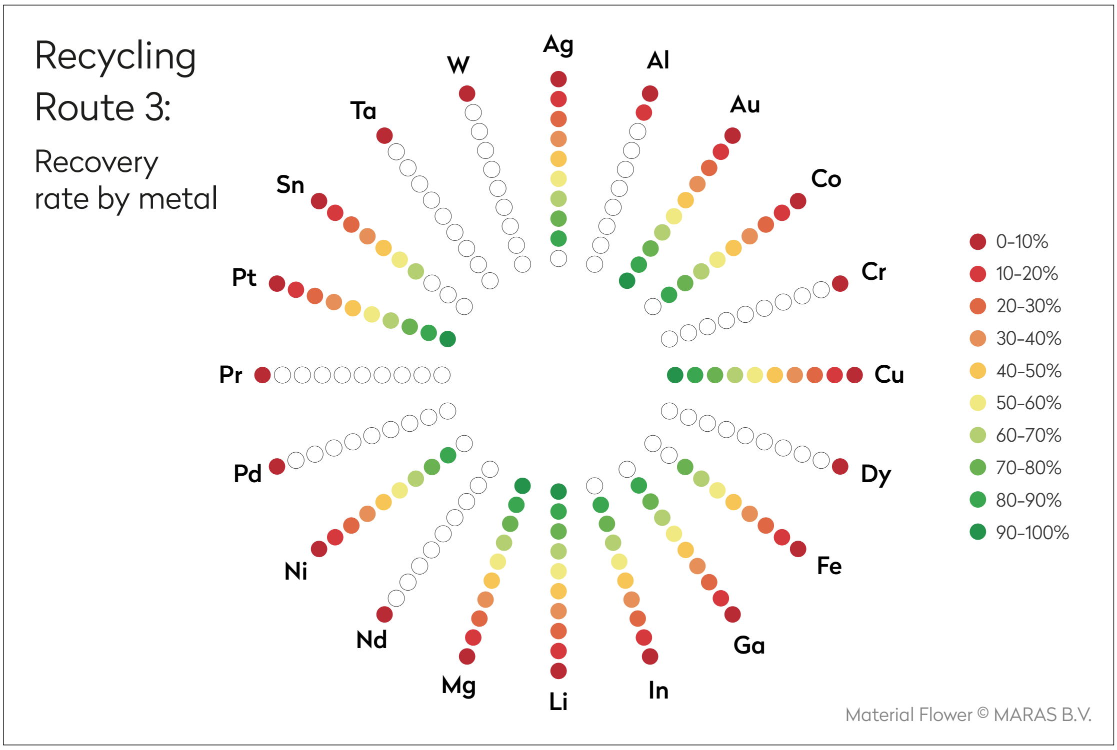

Figure 5: Materials Flower for Recycling Route 3 (Shredding, physical pre-processing and metallurgy); developed by Van Schaik and Reuter.

This example shows the effect of especially the large volume of mixed plastic fraction that is created by cutting up the product. This mix of plastics with its range of fillers potentially contains all the element, materials, alloys etc. of the Fairphone 2, so the effect of impurities on the final plastic quality that can be created from this junk mix is challenging.

Conclusions

To reiterate, the primary goal of the recyclability study was to determine which of the currently available recycling processes (including physical separation, metallurgical, energy recovery, plastics processing) could offer the best material recovery rates for recycling the Fairphone 2. We also wanted to understand how modularity could contribute to improving recyclability.

The findings of the study revealed the advantages and disadvantages of each of the proposed routes. We looked at three metrics, namely (1) metal recycling rate, (2) total material recycling rate (which includes the previous) and (3) Total recycling and recovery rate (materials and energy).

Route 1 (smelting) offered the lowest percentage of recovered materials by weight (14% metal recycling, 25% total material recycling and 36% recovery (= recycling + energy recovery) for all materials), as well as a poor range of materials recovered.

Route 2 (dismantling/selective smelting) offered greater recovery of materials by weight (19% metal recycling, 28% total material recycling and 31% recycling/recovery as well as the widest variety of materials recovered.

Route 3 (shredding) offered the highest percentage of materials by weight (22% metal recycling, 30% total material recycling and 31% recycling and recovery), but the variety of materials recovered was more limited than route 2 due to the nexus of creating complex mixtures, dust etc. by shredding/cutting.

This begs a simple question for recycling: What are the optimum steps for processing of a product?
The more separation steps, the more residues. When recycling a mono-material product, the steps are simple; for a mobile phone you need many more steps to recover as many of the 46 elements as possible.

Recycling of complex products is a trade-off between bulk and minor element recycling, where often one material will be (in more or lesser extent) be 'sacrificed' for the recovery of the other. This is what the results of the different routes show (as presented in the 'material flowers'). The overall recycling rates do not always reflect this, due to the lower weight of precious (scarce, critical) elements present.

To conclude, when selecting the preferred recycling route, it is insufficient to look at total weight alone, in part because the higher weight (in route 3, for example) is contributed primarily to bulk (non-precious) materials. We also need to consider the variety of materials recovered because of the scarcity and/or potential sourcing issues of high-value (precious) metals that are present in the phone in much smaller weights.

Therefore, based on both total weight and variety of materials recovered, recycling route 2 appears to be the best option for recycling the Fairphone 2.

The Material Flowers can serve as a tool for this discussion and help the industry to make the choice for a certain recycling route. The Recyclability Index shows the total rates, but can vary according to how plastics and organics in passive components are recovered or lost. Our next study, the environmental impact study will explore this further.

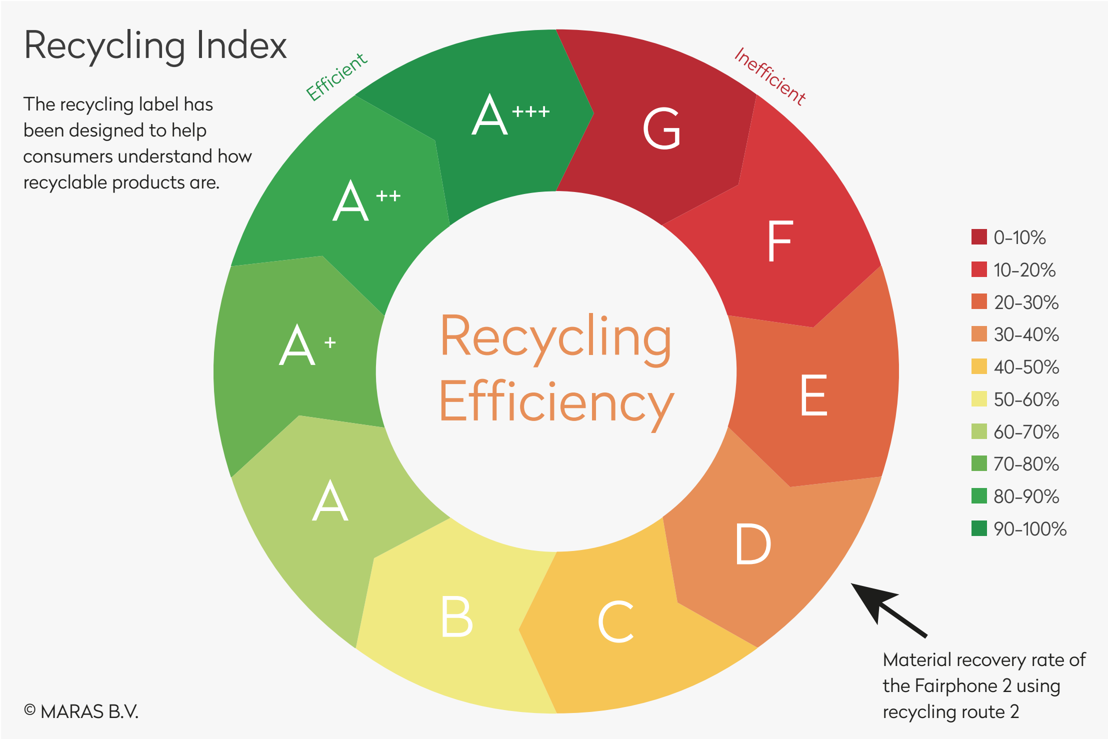

Figure 6:
Recyclability Index of the Fairphone 2, representing total recovery of route 2; developed by Van Schaik and Reuter.

Because recycling route 2 relies on partially dismantling the Fairphone 2 and its modular components, it offers a strong argument in favor of a modular design approach. In addition, the modular construction improves the recovery of minor high-value elements such as gold, especially if these are well concentrated on specific modules.

The above conclusions are based on the findings that include all of the materials in the Fairphone 2. But the advantages of modularity are also obvious when you look at the study's insights on individual materials. Here are just a few examples:

- Materials such as gold, copper, silver, cobalt, nickel, palladium, platinum, gallium, indium and zinc can all be recovered in high percentages (80 to 98%), and modularity promotes their recovery.
- Different recycling routes can result in very different recovery rates for specific materials. For example, in route 1, magnesium completely oxidizes in the furnace, meaning a 0% recovery rate. However, using the method in route 3 (where magnesium is liberated and sorted from the other materials into a high quality recyclate), you can recover 92% or 90% with route 2 but with less CO_2 emissions.
- Tungsten and tantalum are very difficult to recover unless the parts containing them are removed and processed separately (which supports the argument for greater modularity).
- Plastic recovery depends heavily on how much of the plastic can be separated before the recycling or physical sorting process begins (another advantage of modular design).

For more information about the recovery and loss of specific materials, please refer to Appendix 1.

Next Steps

Combined with the results of mapping our materials and the materials scoping study, this recyclability study gives us unprecedented insight into the materials used in the Fairphone 2 at every stage of their life cycle.

While this study dramatically improves our insight into the options for recycling smartphones, it is also important to recognize its limitations. To start, this study is the first of its kind, and we are therefore unable to compare the results to different types of smartphone designs.

In addition, more research is required to fully understand the benefits of modularity. For example, we know that the Fairphone 2's modularity makes our smartphone easier to dismantle, but we don't yet have the metrics to be able to quantify the cost savings versus phones that are not modular.

Despite these limitations, the recyclability study will be extremely valuable as we shape how we manage the end of life of our products. For instance, it will determine the types of recycling partnerships and processing methods we pursue in the future. But as we've seen above, the success of different recycling processes is closely tied to the design of the original product, the materials it is made from and the ease of disassembly. Therefore, we'll also use the results of the study to inform our design decisions for our future products.

Beyond informing our own product lifecycle decisions, we hope that the rest of the industry will benefit from the results of this study and be inspired to gather similar data on a wider range of electronics products. We also hope other players will be encouraged to take a closer look at how product design can impact materials use and recovery, moving us all one step closer to a circular economy.

This study received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 680640.

Appendix: Material Loss and Recovery Findings

Element of interest to Fairphone	Element symbol	Explanation
Tungsten	W	- Lost to slag - stable oxide.
Iron	Fe	- Lost to slag in non-ferrous smelting - stable oxide when sent to Cu/Ni processing route (i.e. when present on Printed Circuits Board/Passive Components etc). - Recovered when sent to Electric (Arc) Furnace and (Stainless) steel processing. In these routes, no recovery of nobler elements than Fe is possible (i.e. Au/Ag/Cu etc will dissolve in the steel alloy - no refining possible) and have to be diluted.
Tantalum	Ta	- Lost to slag - stable oxide.
Tin, Nickel, Copper	Sn, Ni, Cu	- Recovered to high rates in Cu/Ni processing route (TSL). In the case of copper it also dissolves in steel/aluminum/magnesium alloy if ending up in one of these processes as a consequence of design. Only dilution with virgin material/pure scrap can result in desired alloy qualities to mitigate the effects of Cu, Sn, Sb etc. in steel. Ni is desired in stainless steel alloys.
Cobalt	Co	- Recovered to high rates in Cu/Ni processing route (TSL) , but also in a reduction furnace where Co reports to an alloy phase from which it can be refined. This step shown as alloy reporting to Cu+Leach+Purification section.
Indium/Silver	In	- Recovered to high rates in Cu/Ni/Zn/Pb processing route (TSL).
Rare earth metals	Dy, Nd, Pr	- Lost to slag as these form stable oxides - unless to RE processing route.
Magnesium	Mg	- Lost to slag when ending up in Cu/Ni (TSL route) - stable oxide/very reactive. - Recovered when sent to Light Metal processing, however very reactive and sensitive to contaminants (i.e. reacts with C from adhesives, plastic layers, etc). Lost if present as MgO (stable oxide).
Aluminium	Al	- Lost to slag - stable oxide/very reactive. Lost to slag when ending up in Cu/Ni (TSL route) - stable oxide/very reactive. This happens as a consequence of design (i.e. high rates of Al_2O_3 present in (passive) electronics). - Recovered when sent to Light Metal processing, however never to 100% (forms Al_2O_3 during refining, which is lost to dross). It is reactive and sensitive to contaminants. Lost if present as Al_2O_3 (stable oxide) but also as carbide, sulphide, phosphide etc. Thus each recycling step of aluminum creates a loss due to its reactivity. A similar discussion holds true for Si and SiO_2.
Palladium, Platinum, Gold (and other PGMs to special refining infra-structure) Silver, Gallium (+Indium / Germanium)	Pd, Pt, Au, Ag, Ga, In, Ge	- Recovered to high rates in Cu/Ni/Pb/Zn processing route (TSL). - Dissolves in steel/aluminium/magnesium alloy if ending up in one of these processes as a consequence of design. Cannot be recovered. Only dilution with virgin material/pure scrap can result in desired alloy qualities.