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Full length article

Shredding for science: How smart TV design affects recyclability in practice

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ABSTRACT

Understanding how product design shapes recycling outcomes is becoming increasingly important as the demand for recyclable electronics grows. This study investigates how design choices influence recyclability through an analysis of four commercially available smart TVs from major brands. We conducted manual disassembly and controlled shredding tests to explore how materials and connections behave under realistic recycling conditions.

Our findings show that recyclability is mainly limited by plastics that are seldom recovered in practice, even when recyclable in principle. Most connections broke down effectively during shredding, with limited material losses. Some design features, however, still hindered recovery, such as ductile materials that trap others. Based on these findings, we propose design guidelines and compare them with existing literature. Our work contributes to the growing body of research linking product design with current recycling processes and can inform design practice and future regulations that support a more circular electronics industry.

1. Introduction

E-waste is one of the fastest-growing waste streams worldwide, driven by increasing consumption and short product lifespans. Global generation has surpassed 60 million tons annually and continues to rise (Shahabuddin et al., 2022; Andeobu et al., 2021; Liu et al., 2023; Baldé et al., 2024). This waste stream contains valuable, critical, and hazardous materials, yet only 22.3% is documented as having been properly collected and recycled (Baldé et al., 2024; Bakker et al., 2014; Bhoi et al., 2025).

The circular economy offers an alternative to the current linear model of production and disposal. Rather than relying on continuous resource extraction and waste generation, it aims to keep materials in use for as long as possible. This is achieved by narrowing, slowing, and closing resource loops through strategies that reduce material use, extend product life, and recover materials at the end of their lifecycle (Pan et al., 2022; Babbitt et al., 2021; Bakker et al., 2018).

There are various strategies to extend the life of electronic products, such as repair, reuse, and refurbishment (Pan et al., 2022; Potting et al., 2017). These have priority in a circular economy, but at some point products reach their End-of-Life, and recycling becomes the preferred option to recover their constituent materials (Babbitt et al., 2021). Recycling reduces the need for virgin mining and lowers the environmental impact of our products (Pan et al., 2022; Xavier et al., 2023), but current recovery rates remain low (Baldé et al., 2024).

Typical recycling processes include collection, depollution (the removal of hazardous components), shredding to liberate materials, sorting, and material regeneration (Liu et al., 2023; Xavier et al., 2023). Most efforts to improve recycling yields have focused on these downstream processes, through the development of better collection systems or more advanced recycling technologies. However, many of the problems encountered during recycling start with the product itself. The materials used, how components are joined, and how easily they can be taken apart are all factors determined in the design phase (Babbitt et al., 2021; Xavier et al., 2023; Wu et al., 2025).

The recyclability of a product is largely determined by the types of materials used and how easily they can be separated at end-of-life (van den Berg and Bakker, 2015). Inspired by (Knoche and Proske, 2024), we define **product recyclability** as the combined result of two subordinate properties:

– **Material recyclability:** the percentage of a product's mass composed of materials that are likely to be recycled through current E-waste recycling systems. This differs from *theoretical recyclability,* which refers to whether a material can, in principle, be recycled. Material recyclability reflects actual recovery potential within

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existing technological and economic constraints. For example, PET is recyclable in principle, but is rarely recovered from E-waste because the volumes present are too low to justify dedicated sorting; it therefore does not contribute to material recyclability in this context.
- **Technical recyclability:** The extent to which materials in a product with high material recyclability can be identified, separated, and processed in current recycling systems given the product's design. Even if a material is generally recovered from e-waste, poor product design, such as the use of inseparable connections between two different materials, can cause it to be lost in another fraction. Technical recyclability captures the influence of product design, joining methods, and component integration on the actual recovery of materials.

Material recyclability is therefore a precondition for technical recyclability: Improving the separability of materials that are not recovered in current e-waste streams will not increase actual material recovery. It therefore makes sense to first ensure high material recyclability before optimising joining methods and product architecture.

Design for Recycling (DfR) aims to improve product recyclability through design, but detailed data on which specific design features influence recyclability is still lacking (Wu et al., 2025). While a small number of case studies have examined design features impacting electronics recyclability (Parajuly et al., 2016; Balkenende et al., 2014), the vast majority of product categories remain unstudied. This study focuses on smart TVs as a practical and representative starting point. As complex products with a high material diversity and increasing market presence, smart TVs represent a significant and growing stream of e-waste (Statista Research Department, 2026; Urban Mine Platform, 2026). Multiple units across brands were available for testing, making them a practical starting point for this type of research.

This study is guided by the following research question: What is the material and technical recyclability of current smart TVs, and how does this depend on design decisions?

To answer this question, we first disassembled four smart TV models from 2021 to analyze their material composition and internal connections. To evaluate the practical impact of these design choices on recyclability, we then conducted controlled shredding tests on each model. Based on our findings, we propose actionable design guidelines aimed at improving the technical and material recyclability of future TVs.

This study is the first to systematically compare material and technical recyclability across multiple smart TV brands and to quantify how specific connection types affect material liberation and recovery in shredding tests. By directly linking connection methods to both material and technical recyclability outcomes, we provide novel, empirically grounded DfR guidance for smart TVs and contribute to more informed design strategies in consumer electronics.

This study focuses on design decisions at the product level related to recycling and does not consider detailed, component-level designs, such as PCB layouts. Also repairability and related disassembly processes are therefore not considered, as those processes require reversible disassembly and reassembly, while in recycling the processes are destructive. Collection rates and inefficiencies in end-processing are also outside the scope, as they are driven by system-level and operational factors rather than product design.

2. Background

2.1. E-waste recycling

E-waste recycling is a global challenge, shaped by differences in infrastructure, regulation, and economic context. In high-income regions such as Europe, North America, and parts of Asia, recycling tends to follow formal, regulated processes aimed at maximizing material recovery while minimizing harm to people and the environment. However, even in these regions collection rates remain low; in the EU, less than half of e-waste is formally collected and recycled (Baldé et al., 2024). In many other parts of the world recycling is often carried out by informal sectors, using methods that come with serious environmental and health risks (Liu et al., 2023; Ahirwar and Tripathi, 2021).

Even within formal systems, there is no single approach. Companies and facilities often develop their own ways of extracting value from E-waste, based on available technologies, internal priorities, and how they interpret the value of incoming products (Laser, 2020). On top of that, E-waste recycling technologies are evolving. The sector is moving toward greener, more automated solutions, supported by ongoing research into efficiency, emissions reduction, and cost-effective recovery methods (Kaya, 2016; Rene, 2021; Goyal and Gupta, 2024). As a result, recycling not only varies between contexts but is also constantly evolving.

In the EU alone, over 500 companies are active in E-waste treatment (Liu et al., 2023), each with their own unique process. For specificity, this study uses the process of a major Western European E-waste recycling facility as its reference point (Appendix A: Fig. 6). The facility is a full-chain treatment operator, performing manual depollution, mechanical shredding, and physical sorting of mixed WEEE streams, and commonly processes screens. In e-waste recycling, the primary goal is to extract material fractions with the highest possible purity to maximize value, while minimizing processing steps and associated costs. In this E-waste recycling facility, the first step in the process is **manual depollution**. Here, trained workers remove hazardous components, such as batteries and large capacitors, by hand. This step is essential for safe recycling and compliance with European regulations (European Commission, 2012).

The remaining material is then **shredded**, reducing products to smaller fragments (Xavier et al., 2023). The aim of shredding is complete material liberation; breaking down products into homogeneous fragments each consisting of a single material. Incomplete liberation refers to breakdown into heterogeneous fragments containing multiple materials, which lead to contamination and material losses in subsequent sorting stages. Efficient liberation is essential for the successful recovery of materials (Kaya, 2016; Balkenende and Bakker, 2015).

A series of physical sorting steps follows:

- **Magnetic sorting** removes ferrous metals using magnets.
- **Eddy current separation** targets non-ferrous metals like aluminum and copper. Conductive materials are repelled by a rotating magnetic field, separating them from non-conductive plastics and ceramics.
- **Various sorters**: A set of sorting machines are used to separate remaining metals from non-metallic materials
- **Density separation** uses differences in density: heavier materials sink in a liquid, while lighter ones float.

Throughout the process, **sieving** is applied at various points to ensure fragment sizes match the requirements of each processing step. Fragments smaller than 1 cm^2 are difficult to sort effectively; these are sent directly to a smelting plant, where metals such as copper are recovered.

The final sorted fractions are further processed by a range of different companies, including both other pre-processors and end-processors. This downstream treatment may involve additional sorting steps. However, we set the scope of this study at the reference plant, so the variability introduced by different downstream routes is not accounted for. Metals are refined further through pyrometallurgical and hydrometallurgical techniques (Xavier et al., 2023; Kaya, 2016), outside the scope of the reference plant. Plastics, in this case ABS, PE, PP, and PS, are further sorted and regranulated downstream, also outside the scope of the reference plant.

This recycling process including depollution, size reduction, different physical sorting steps and the refining of materials is similar to other processes depicted in literature (Knoche and Proske, 2024; Menad, 2016; Kumar et al., 2017; Koninklijk Nederlands Normalisatie-instituut,

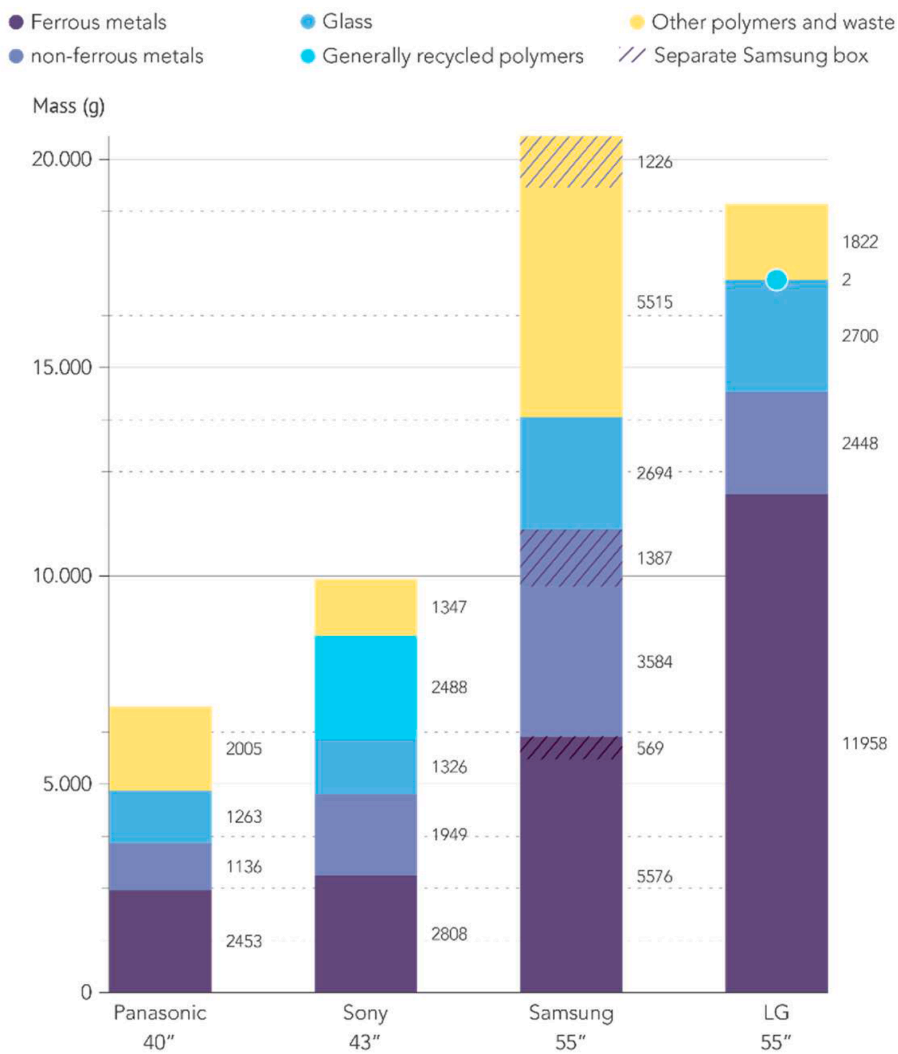


Fig. 1. The material composition (in grams) of four smart TV models (Panasonic, Sony, Samsung, LG). The bars represent the total mass per material category: ferrous metals, non-ferrous metals, glass, generally recycled polymers, and other polymers and waste. Only ABS, PP, PE, and PS are considered as generally recycled polymers from EEE waste streams.

2019; Wagner et al., 2019; Wagner et al., 2019).

2.2. The TV as a case study

Globally, only 25% of discarded screens were properly collected and recycled in 2022 (Baldé et al., 2024). In Western Europe, collection and recycling rates are considerably higher, though they vary by country. As an example, in the Netherlands in 2024, 53% of the discarded screens, including products such as televisions, computer monitors, and other display devices, were documented as properly collected and recycled (Nationaal WEEE Register, 2025). TV sets form a major share of this stream and come in two main types: Cathode Ray Tube (CRT) and Flat Panel Display (FPD), such as LCDs. Earlier generations of FPDs used cold cathode fluorescent lamp (CFL) backlights containing mercury, but the shift to LED backlighting in newer models has largely eliminated mercury from TV designs (Althaf et al., 2020; Wang et al., 2018). Since the EU WEEE Directive mandates selective treatment for mercury-containing products, this shift has simplified recycling (European Commission, 2012).

A typical smart TV has a screen made of glass and shatter-resistant polymers, such as polycarbonate (PC). Behind the screen, several thin polymer films diffuse and filter the light to produce the image. The electronics are mounted on a metal chassis, usually steel, which provides structural support and rigidity. Finally, the entire assembly is enclosed by a back cover, which is usually made of plastic. Appendix A: Fig. 7 shows the typical TV architecture, based on the four studied smart TV models.

3. Method

To gain insight into how different materials, connection types, and architectural features affect the recyclability of smart TVs, we analyzed four commercially available FPD models (Appendix B: Table 3). The selected TVs represent various screen technologies (LCD, OLED, QLED), sizes, and price points, aiming to reflect the diversity found in the 2024 consumer electronics market. We first disassembled one unit of each model to analyze its material composition and internal connections. Next, we conducted shredding tests at a recycling facility to observe how these features behave under real recycling conditions, and to identify design choices that support or hinder material recovery.

3.1. Disassembly

Each television was manually disassembled down to component level using basic handheld tools, following the disassembly map method (De Fazio et al., 2021). For every component, we recorded its mass, quantity,

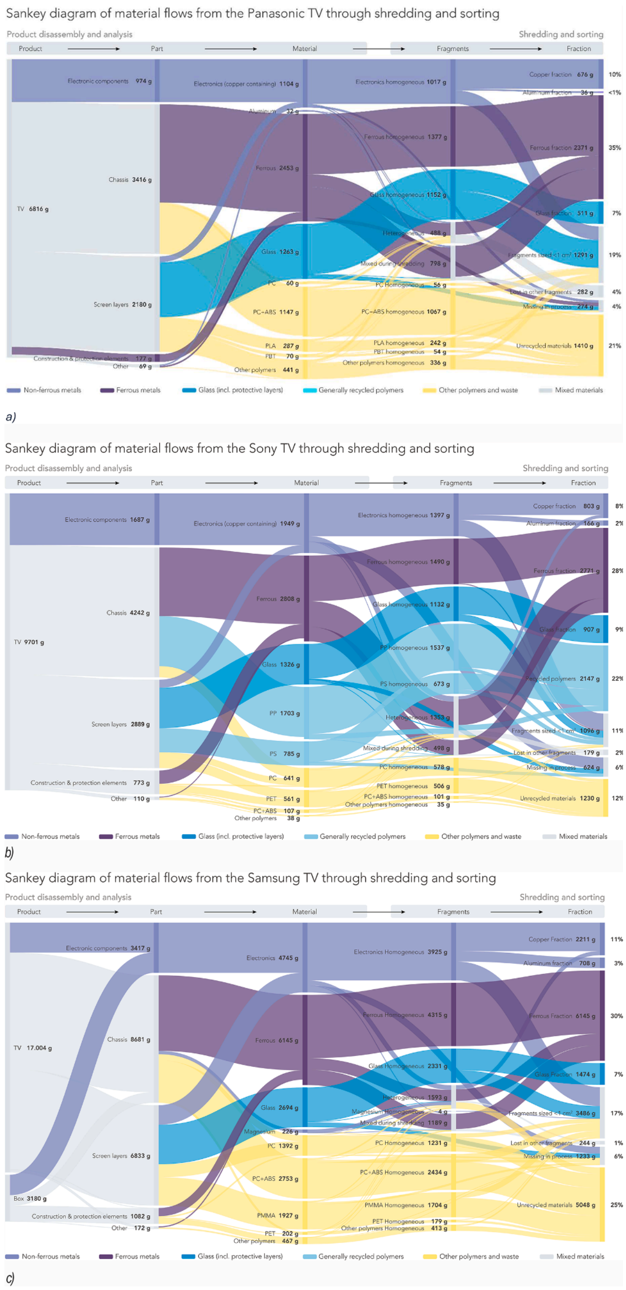


Fig. 2. Sankey diagrams of material flows in the smart TVs across five levels of observation: product, part, material, fragments, and fraction. The first three levels (product, part, material) are derived from disassembly, while fragments and fraction originate from shredding and sorting. The flows illustrate where materials are found in the product, into what type of fragments they are shredded, and into which fraction they are likely to be sorted. The different colors represent overarching material types to support visual differentiation across stages. Flows where different materials are mixed are displayed in grey. Process losses are indicated in the final fraction step as "missing in process". a) Panasonic. b) Sony. c) Samsung.

and material type in a Bill of Materials. Materials were sorted into categories that reflect output fractions in the reference WEEE recycling process. This classification was based on magnetic properties, density, visual identification, and, where polymers were concerned, FTIR spectroscopy. The categories were:

- Non-ferrous metals
  - Electronics (copper-containing)
  - aluminum
- Ferrous metals
- Glass
- Generally recycled polymers (i.e. polymers with high material recyclability): PP, PE, PS, ABS
- Other materials: Generally not recycled (thus with low material recyclability)

In addition, we counted and categorized the connections according to their bonding mechanism: form closure, force closure, and material closure (Pahl et al., 2007) (Appendix B: Table 4). Form closures are mechanical connections where parts are held together because of their geometry. Form closures found in smart TVs include friction fits, turn locks, and hooks. Force closures are connections that hold components together by applying pressure or friction between surfaces. Force closures found in smart TVs include screws, inserts, and snap-fits. Material closures are the result of joining components, either directly or by using additional material, using molecular and adhesive forces over the working surface area. Material closure types found in smart TVs are adhesives, tape, and coatings. The analysis did not include electrical connections, as they were only used to connect two components that both end up in the precious metals fraction. Their plastic elements are lost during recycling, but these material losses are very small and therefore considered acceptable.

3.2. Shredding and sorting

As the tested FPDs did not contain hazardous materials such as mercury backlights or embedded batteries, depollution was not required before shredding. To minimize process losses and cross-contamination, a smaller-scale four-shaft shredder was used. To ensure a fair comparison with the recycler's full-scale industrial shredder, which uses a larger sieve to control particle size, no sieve was installed in the small-scale shredder. According to the recycler, the blades in the small-scale setup already produce fragments of comparable size.

Each TV was cut into pieces no larger than 45 × 45 cm with a jigsaw before the test to fit the shredder's input size (Appendix A: Fig. 8). Four products were shredded for each TV model, with each model processed and collected separately to enable comparison across the different TV designs (Appendix A: Fig. 9).

We simulated the automatic sorting process of the shredded fragments through manual sorting (Appendix A: Fig. 10). This had two purposes: (1) to assess the breakdown of connections during shredding, and (2) to track the flow of materials to the various material destinations. The first step in the manual sorting process was to identify and count the intact connections. Next, the fragments were sorted into homogeneous fragments, grouped by material fraction, and heterogeneous fragments containing multiple materials.

Among the heterogeneous fragments, we identified a separate category labeled "mixed during shredding". These fragments were not connected in the original product but became attached during shredding, for example, pieces of sheet steel folded around other materials (Appendix A: Fig. 11).

Heterogeneous fragments were further sorted based on their expected destination in the recycling process, following consultation with an expert from the reference E-waste recycling company. During a semi-structured interview, we showed the expert different types of heterogeneous fragments and asked them to estimate their likely sorting outcome based on their processes. This approach was used because actual industrial sorting could not be applied for the test due to the small sample size.

The interview resulted in the following sorting principles used to determine the likely destination of heterogeneous fragments:

- If **electronics** constitute a significant portion of a heterogeneous fragment, the fragment will typically end up in the precious metals

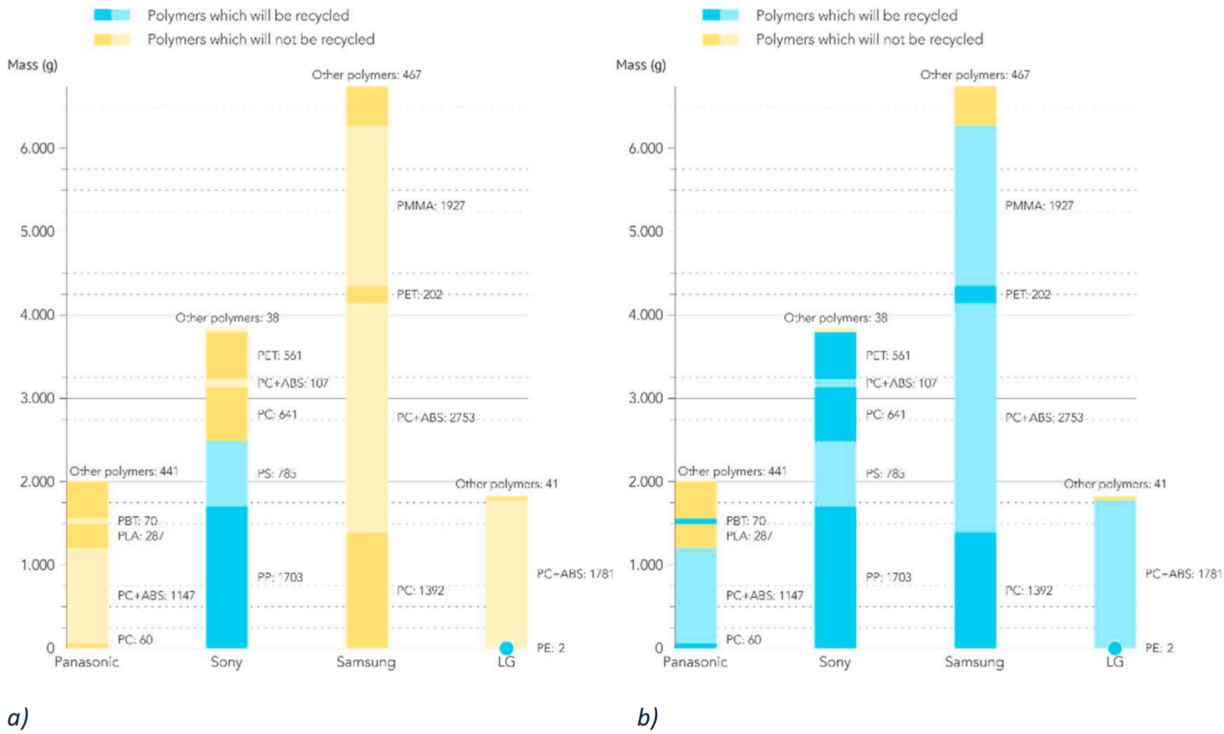


Fig. 3. The plastic content of the Panasonic, Sony, Samsung, and LG smart TVs. Polymers that are likely to be recycled are shown in blue, while polymers not likely to be recycled are shown in yellow. a) The current recycling scenario. b) A scenario where all in principle recyclable polymers are recycled (based on (ANSYS inc., 2024)).

fraction. This allows for the recovery of metals, including copper, but results in the loss of other materials.

– If **steel** constitutes a significant portion of a heterogeneous fragment, the fragment will typically end up in the ferrous fraction, allowing steel recovery but resulting in the loss of other materials. While the ferrous fraction can be further refined by downstream processors, this study set the system boundaries to the reference recycling plant, and such subsequent steps were considered out of scope.
– If a **polymer** constitutes a significant portion of the heterogeneous fragment, but the other material is likely to increase its density, the entire fragment is categorized as lost.

We sorted the fragments until only those smaller than 1 cm^2 remained, as these fragments are sent to downstream processors without further separation by the reference recycling plant. Although PCBs, including their mounted components, were classified as copper containing materials during disassembly (destined for the precious metals fraction), some aluminum heat sinks mounted on the boards liberated during shredding. These were added to the mass balance as separate aluminum outputs. The entire process of fragment sorting was completed in 225 hours.

We used Sankey diagrams to visualize the flow of materials across five levels of observation: product, parts, materials, fragments, and fractions. The first three levels are derived from disassembly, while fragments and fractions originate from shredding and sorting, respectively. The difference between the original product mass and the recovered fragments was classified as process loss, assumed to result from material retention in the shredder. This also occasionally lead to a material surplus when retained material was released during the next shredding run.

4. Results

The disassembly of the TVs allowed us to construct both a Bill of Materials for each model (Appendix B: Table 5-8), and corresponding disassembly maps documenting the process (Appendix A: Fig. 13). While most models followed a standard TV layout (Appendix A: Fig. 7), the Samsung TV stood out. Rather than integrating all electronics into the main body, it used a separate external box to house a large portion of the electronics. The material composition of each smart TV model is shown in Fig. 1. The external box is indicated separately.

The total mass of the TVs varies significantly, mainly due to differences in screen size. All four models contain ferrous metals for structural parts, non-ferrous metals for the electronics, various plastics, and glass in the screen layers. Of these four models, only the Sony TV uses commonly recycled plastics: polypropylene (PP) and polystyrene (PS). The LG TV contains a relatively high percentage of ferrous metals because its screen assembly includes a large steel frame and a steel bar mounted to the back for additional support.

The Sankey diagrams in Fig. 2 show the material and technical recyclability of the Panasonic, Sony and Samsung TVs. During shredding with the small scale shredder, the steel bar at the back of the LG TV caused a blockage (Appendix A: Fig. 12). The blades of the shredder could not cut through the bar, causing the machine to jam. As a result, we were unable to process the LG TV further, and we excluded it from further analysis.

The Sankey diagrams show that most material loss is due to the use of plastics that are generally not recycled, which accounts for 12–25% of the total mass of the TVs. Some material is classified as lost because fragments were too small to be sorted in the reference recycling plant (<1 cm^2), but copper-containing fragments in this size range are still recovered, as the fine fraction is sent to the smelting plant. This is why this loss mainly affects plastics and glass. Although a significant portion of material ends up in heterogeneous fragments, the actual loss from this category remains limited (1–4%). This is because these fragments often contain a substantial amount of steel, which is likely to be sorted into the ferrous metal fraction. The Sony TV stands out because it contains some plastics that are more commonly recycled (PP and PS). This means a relatively small percentage of its materials remains unrecycled.

The speakers in each TV contain ferrite magnets, a magnetic ferrous

Fig. 4. The different connection types found in the Panasonic, Sony, Samsung, and LG smart TVs. The material closure types (glue/tape/coating) are shown in terms of fused area (dm^2). a) The number of each type of connection found in each TV during disassembly. b) The liberation grades of the connection types. The total sample of connections is noted at the base of each bar (4x each TV model), and the liberation grade of the types of connections as a weighted average from all the TVs is visualized using a dotted outline.

material. These magnets often stick to other ferrous fragments during shredding, which helps them end up in the correct recycling fraction. However, according to the recycler, they also stick to the machines themselves, making them difficult to remove during processing.

Currently, only a small portion of the plastics that are recyclable in principle are recycled in the reference E-waste recycling plant (PP, PE, ABS, PS). Many other plastics are recyclable in theory, but dedicated infrastructure is needed to process them. For example, PET is recycled at large scale from plastic bottles, but occurs only in small amounts in E-waste, making recovery for many plants economically unviable.

Fig. 3 shows that up to almost 100% of the plastic used in smart TVs is recyclable in principle. However, based on input from WEEE recyclers, there is a clear disconnect between what can be recycled in theory, and what is likely recycled in practice. This figure assumes that the identified plastics contain minimal additives causing problems in recycling. In reality, this is unlikely; we found that some plastics contained additives,

a) b) c)

Fig. 5. Examples of intact connections found in the shredded fragments of different smart TVs. a) A piece of aluminum is still attached to part of the plastic housing because of an adhesive. b) A piece of plastic, steel, and PCB are still connected because of an unliberated screw. c) The metal insert is still attached to the plastic housing.

such as PC with glass fiber or other fillers in the Panasonic TV (Appendix B: Table 4), but their exact content and concentration were outside the scope of this study. Polymers that could not be identified were assumed to be non-recyclable.

Fig. 4 presents the connection types identified in each smart TV (a), and their corresponding breakdown behavior observed during shredding (b).

Fig. 4 shows that some connection types behave quite consistently in a shredding process, resulting in similar liberation grades across TVs, but others are more unpredictable. Hooks and snap fits consistently achieve high liberation grades across all TVs (>90%). Turn locks also perform well, reaching a similar liberation grade, though they were only found in the Sony model and in small numbers. Screws show lower but consistent breakdown grades, averaging around 60%. Friction fits, inserts, and tape display little consistency. Glue shows variable liberation behavior between TVs but generally performs poorly. Coating does not liberate at all and was only observed in the Panasonic TV, as the results of the LG TV could not be processed. Fig. 5 shows examples of connections that are still intact after shredding and thus resulted in heterogeneous fragments.

5. Discussion

The findings show that the main opportunity for improving Smart TV recyclability lies in material choice, not in the breakdown of connections during shredding. Heterogeneous fragments accounted for only 1–4% of total mass loss, while unrecycled plastics accounted for 12–25%. This study is the first to systematically compare material and technical recyclability across multiple smart TV brands and to quantify how specific connection types affect material liberation and recovery in shredding tests. The findings directly inform the design guidelines derived in this section, and strengthen the evidence base for Design for Recycling of electronics. The following sections discuss material recyclability, technical recyclability and connection behavior, and the derived design guidelines.

5.1. Material recyclability

In terms of material recyclability, all of the TVs contained ferrous and non-ferrous metals, polymers, and glass. However, only the Sony model used commonly recycled plastics: polypropylene (PP) and polystyrene (PS). Most models relied on a mix of polymers that are rarely recovered in practice, such as PC, PC+ABS, PMMA, and PBT, resulting in material losses of 12–25%. This issue is not unique to TVs. Other products, such as robotic vacuum cleaners, show similar losses, with only 45% of plastics likely to be recycled at End-of-Life (Parajuly et al., 2016).

This material selection is partly explained by functional requirements. For example, PC provides impact resistance and stability in structural housings, and PMMA offers the optical clarity needed for light-diffusing sheets (ANSYS inc., 2024). Substitution with more recyclable alternatives is not always straightforward and may require significant redesign.

Additives are another concern. Although the additive content of the plastics in the TVs was outside the scope of this study, engineering polymers used in electronics commonly contain additives which can reduce the quality of recycled output (Wagner et al., 2019; Bracquene, 2021). Like the choice of polymer itself, these additives are often there for good reason: Glass fiber improves structural stiffness, and flame retardants are required for fire safety, which makes simply removing them difficult. Plastics recovery is also limited by economics; many engineering polymers simply do not occur in large enough quantities in WEEE to make dedicated recycling viable (Wagner et al., 2019). As recycling technologies develop, a broader range of plastics may be recoverable in the future, but under current conditions material choice remains the primary barrier to the recyclability of smart TVs.

5.2. Technical recyclability

As little material was lost through heterogeneous fragments, the technical recyclability of the TVs was very similar to their material recyclability. Although such fragments were common, actual losses remained limited at 1–4% of the total mass. This is because heterogeneous fragments were typically caused by unliberated connections or sheet steel folding around other materials during shredding. Steel often constituted the majority of the fragments' mass, meaning most of the material is likely recovered through magnetic separation. The other materials trapped within them were often lighter, so losses in terms of mass remained small.

Our findings show that while many fasteners break down during shredding, a few specific types consistently lead to material loss. Snap fits, hooks, and turn locks consistently performed well, while screws were less effective. Glue, tape, inserts, and friction fits showed inconsistent results and often left materials joined, and coatings did not separate at all. This inconsistent behavior can be explained by several factors. For material connection types such as glue and tape, variations in behavior are likely linked to the type of adhesive used. For form- and force-closure connections, tolerances around the joint, material type and thickness, and nearby design features all appear to play a role. This means that even connections of the same type can behave differently depending on their local design context, making precise design guidelines difficult to formulate.

Certain material properties can also cause material loss during shredding and sorting. Brittle materials, such as glass, tend to break into small fragments or dust. These fragments are usually homogeneous but are not separated further and are sent directly to the smelting plant processing the precious metals fraction. This is the intended outcome for electronic components, but when other materials are part of this fraction, they are lost. Very ductile materials such as sheet steel tend to fold around other materials during shredding, which was also concluded by (Balkenende et al., 2014). These heterogeneous fragments are often picked up by magnetic sorting and end up in the ferrous fraction, causing

Table 1
List of guidelines derived from findings and compared to guidelines in literature.

Nr.	Guideline	Argumentation	Relation to literature
MATERIAL RECYCLABILITY			
1.	Use materials which are generally recycled in standard E-waste recycling processes.	Other materials will most likely not be recycled; using them reduces the material recyclability of your product.	(Balkenende and Bakker, 2015; Beitz, 1993; Dowie and Simon, 1994; Kriwet et al., 1995; Xing et al., 2003; Hultgren, 2012; Fakhredin, 2018; Balkenende, 2014; Go et al., 2015; Bovea and Perez-Belis, 2018; Dimitrova et al., 2018; Leal et al., 2020; Shahbazi and Jönbrink, 2020; Berwald et al., 2021; Feenstra et al., 2021)
2.	Aim for PP, PS, PE, and ABS when using plastics in the design.	These four plastic types are likely to be recycled from WEEE.	(Hultgren, 2012; Dimitrova et al., 2018; Berwald et al., 2021; Feenstra et al., 2021)*
3.	Minimize additives in plastics	A plastic stream with too high concentrations of certain substances cannot be used as recycled plastics (e.g. BFRs and high concentrations of glass fibre).	(Hultgren, 2012; Berwald et al., 2021; Feenstra et al., 2021)
TECHNICAL RECYCLABILITY			
4.	Minimize the number of fasteners.	Reducing the number of fasteners reduces the amount of heterogeneous fragments.	(Dowie and Simon, 1994; Kriwet et al., 1995; Xing et al., 2003; Go et al., 2015; Leal et al., 2020; van Schaik and Reuter, 2012)
5.	If two connecting parts cannot be made from the same or two compatible materials, use connection types that support liberation.	Intact connections don't pose a problem when the two materials are supposed to be sorted into the same fraction, otherwise they cause losses and sometimes contaminations in the recycled materials.	(Parajuly et al., 2016; Dowie and Simon, 1994; Kriwet et al., 1995; Go et al., 2015; Dimitrova et al., 2018; Leal et al., 2020)
6.	Avoid the use of permanent magnets, especially attached to non-ferrous materials such as PCBs.	Permanent magnets stick to the machines used in recycling plants and can pull a variety of materials into the ferrous fraction.	(Hultgren, 2012; Berwald et al., 2021; Feenstra et al., 2021)
7.	Choose fasteners of a material compatible with the parts connected.	Fasteners are often recycled together with the host component, so their materials should be compatible to combat pollution and losses.	(Dowie and Simon, 1994; Xing et al., 2003; Hultgren, 2012; Balkenende, 2014; Go et al., 2015; Dimitrova et al., 2018; Leal et al., 2020)
8.	Make sure materials (excluding electronic components) break down into fragments of a relatively large size (> 1 cm)	Fragments smaller than 1 cm^2 will be sent to the smelting plant processing the precious metals fraction, which means other materials are lost. This guideline is challenging for designers to operationalize, and requires further research.	(Balkenende and Bakker, 2015; Fakhredin, 2018)
9.	Avoid parts of ductile materials that are likely to plastically deform during shredding, such as sheet steel.	This material is likely to fold around other materials in the shredding process, leading to heterogeneous fragments and losses.	(Balkenende et al., 2014; Fakhredin, 2018)

* (Berwald et al., 2021; Feenstra et al., 2021) Also name PA, PC, PC+ABS and HIPS as generally recycled plastics, so there is a partial agreement in literature.

the enclosed non-ferrous materials to be lost. Even when polymers are successfully liberated from other materials, sorting them into pure fractions remains difficult, as many plastic types share similar physical and chemical properties (Bracquene, 2021). Beyond the behavior of materials during shredding, the sensitivity of output fractions to contamination also varies. The plastics fraction is particularly sensitive, as some contaminants are difficult to separate using density-based sorting (Fenwick et al., 2023), while the ferrous fraction is relatively tolerant of contaminants.

These issues show that designers need to consider not just whether a material is recyclable, but also how it behaves in the recycling process. At the same time, not all connections need to be broken down for effective recycling. Sometimes, connected materials can be recycled together during the end-processing stage, so separating them is unnecessary. Steel screws, for instance, can remain in steel fragments without issue. Similarly, coatings (depending on the type) on metals are usually removed during smelting without causing contamination. A complete breakdown is not always necessary; what matters is whether materials that stay connected do not disrupt the recycling process.

5.3. Design guidelines

Our findings on the material and technical recyclability of smart TVs directly inform the design guidelines presented in Table 1. We compared these guidelines to the literature to show how they align with earlier work.

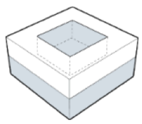
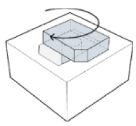
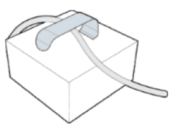
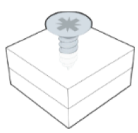
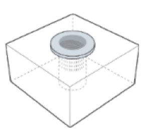
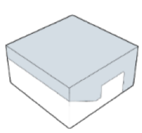
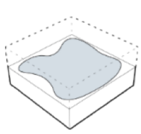
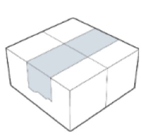
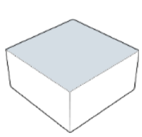
In addition to the practical guidelines, we also formulated a set of recommendations for suitable connection types to improve the technical recyclability of future products (see Table 2). Comparing these to literature was less straightforward. Research on the behavior of different connection types is limited, with each study focusing on a different subset of connections and using different terms to describe them. This complicates drawing direct comparisons and points to the need for more consistent research in this area.

While some DfR methods aim to calculate or score product recyclability (Leal et al., 2020; Peters et al., 2012), our results show the limits of this strategy. Material choice is only part of the picture; features such as sheet steel layers and rigid structural elements can significantly shape recycling outcomes. Factoring in connection types widens the scope, but the results are inconsistent, and a final score can lead to a false sense of accuracy. Recycling performance is also highly dependent on product type and processing scenario.

Applying DfR guidelines is not always straightforward in practice either. The Sony TV shows that using commonly recycled plastics in a smart TV is possible, but whether this was a conscious DfR decision or simply the result of other choices is unknown. For many components, switching to more recyclable materials would mean real compromises: some polymers are there for good reasons, like optical clarity or strength, and finding recyclable alternatives may require substantial redesign or added cost. The same applies to connection types: adhesives or coatings may be the only viable option for achieving a secure bond or protecting components from wear, even if they perform poorly in shredding. Recyclability is one of many requirements a designer has to balance.

This is especially true in the broader context of the circular economy,

Table 2
Recommendations on connection types to improve technical recyclability of future electronics, and their relation to literature. ✓ = Good compatibility with recycling processes. ~ = Compatibility with recycling processes depends on design. ✗ = Bad compatibility with recycling processes.

CONNECTION TYPE	COMPATI-BILITY WITH RECYCLING	ARGUMENTATION	RELATION TO LITERATURE
Friction fit 	~	Inconsistent breakdown during shredding	-
Turn-lock 	✓	Is likely to break down during shredding. However, we only had a small sample of this type of connection in the TVs.	Assuming a "press-turn fastener" is the same thing as a turn-lock, Beitz (1993) agrees.
Hook 	✓	Is likely to break down during shredding.	-
Screw 	~	Does not always break down during shredding.	Berwald et al. (2021), Fakhredin (2018), Hultgren (2012), and Parajuly et al. (2016) agree.
Insert 	~	Inconsistent breakdown during shredding.	Berwald et al. (2021) agree.
Snap fit 	✓	Is likely to break down during shredding.	Beitz (1993) agrees.
Adhesive 	~	Does not always break down during shredding. However, this depends on the type of glue used.	Beitz (1993) only discusses plastic/metal adhesive bonding, and says it scores average on recyclability. Van schaik and Reuter (2012, 2014) agree with this. Fakhredin (2018) mentions adhesives are not suited for recycling.
Tape 	~	Inconsistent breakdown during shredding.	Not specifically mentioned in literature, but closely related to adhesives.
Coating 	✗	Is unlikely to break down during shredding.	Van schaik and Reuter (2012) agree that coatings rarely liberate.

where recycling is just one of many strategies. Although recycling must always be considered, it is one of the lowest strategies on the R ladder and should not be pursued at the cost of lifetime extension or repair (Potting et al., 2017). Every product requires an evaluation of its likely End-of-Life scenarios. Some components are failure-prone and benefit most from design for repair; others are unlikely to need replacement and are better optimized for recycling. Such decisions often involve trade-offs. For example, the use of screws may lead to material losses in recycling, but are crucial for repair. Circular design is about balancing these strategies rather than maximizing one at the expense of others.

5.4. Limitations and future work

Although this study aimed to approximate real-world recycling, several limitations remain. Using a small-scale shredder minimized process losses, but it may have affected fragment sizes. In addition, while hand sorting was guided by recycler input, it may have overlooked factors affecting technical recyclability, such as the recognizability of materials by automated sorting systems. Furthermore, material losses were calculated by weight, but other perspectives, such as material value or environmental impact, could highlight different aspects of the materials lost. In addition, some material was inevitably lost during shredding, which leads to inaccuracies that should be considered when interpreting the results.

It is also important to note that almost all fractions from the reference recycling plant are further refined downstream. The exact routes vary and evolve over time, depending on factors such as fraction composition, material values, and processing costs. To provide a clear and consistent analysis, we set the system boundaries at the reference plant. The findings should therefore be seen as a snapshot of current practice, offering an approximation of recycling outcomes rather than a complete account of the chain. While downstream processing may reduce some of the losses observed, recyclers generally seek to minimize such extra steps, as each additional process adds cost. The more effectively materials are sorted early in the chain, the more economically viable their recovery becomes.

The limited impact of heterogeneous fragments on material losses may be related to the TVs' size and their relatively low concentration of internal connections. Smaller products with more compact and complex product architectures, could produce different results. More broadly, recycling outcomes vary across products and recycling practices. Rather than assuming general validity from one case, we need comparative studies across products and contexts to generate a set of adaptable principles that can inform design practice.

One architectural feature that appeared to affect the recyclability of the LG TV in our tests was a steel bar that blocked the small-scale shredder used in this study. Since most recycling facilities operate with larger shredders, this issue is unlikely to pose problems in practice. Yet it does raise an interesting question: could such design choices, made to strengthen and stabilize a product, also complicate its end-of-life processing in certain contexts? This is an angle that deserves closer attention in future research.

It is worth noting that the way in which TVs are recycled today is shaped by current technologies, economics, and policy, all of which are subject to change. Developments in material recognition and sorting (Bhoi et al., 2025), plastics recycling (Wagner et al., 2019; Anderson et al., 2021), policy instruments such as the EU Digital Product Passport (Koppelaar et al., 2023; European Parliament and Council, 2024), and geopolitical shifts affecting the supply and demand of materials (Groves et al., 2025) will all influence what can be recovered, and at what cost. DfR is not a fixed target; it needs to move with the practice.

Future research could examine how differences in recycling practices at the local, regional, European, and global levels affect product recyclability. This could help identify which DfR strategies are broadly effective and which depend on specific contexts. Additionally, it is important to investigate the tensions between Design for Recycling and other recovery strategies, such as repair and lifetime extension, to better understand trade-offs within a circular economy. Furthermore, investigating the recyclability of other product categories could provide broader insights into product recyclability. There is a broad range of electronic product types, each characterized by specific materials, features, and likely distinct recycling challenges (Babbitt et al., 2020). Finally, since connection types behave differently across the studied TV models, other factors besides their type must influence their breakdown. These underlying factors require further investigation.

6. Conclusion

This study examined the material and technical recyclability of four commercially available smart TVs, based on controlled shredding tests and manual sorting. The results show that a large part of the material loss is caused by plastics that are not recycled in practice, despite being recyclable in theory. Regarding technical recyclability, most materials were successfully recovered. Heterogeneous fragments were common, but actual losses from these fragments remained limited. Some connection types showed very consistent behavior in terms of liberation, providing actionable advice for product designers. However, others behaved inconsistently across the TV models and require further investigation. Based on our findings, we proposed guidelines to support the design of more recyclable electronics, and facilitate the transition to a more circular electronics industry.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT and DeepL to edit and improve the language of the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Dorien C. van Dolderen: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Doris L. Versloot:** Methodology, Formal analysis, Data curation, Conceptualization. **Soroush Aghaeian:** Writing – original draft, Formal analysis. **Conny A. Bakker:** Writing – review & editing, Supervision. **A. Ruud Balkenende:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2026.109114.

Data availability

No data was used for the research described in the article.

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