Formulating (and evaluating) a Reuse, Recover, Recycle-index

FINAL report

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Glossary

ADP	Abiotic Depletion Potential
billion	1000 million
CCFL	Cold Cathode Fluorescent Lamps (typically used as display backlights)
CECED	Domestic appliances manufacturer's association
CFC, HCFC, HFC, HC	chemical group names of greenhouse gases (typically used in refrigerants)
CRM	Critical Raw Materials
CRT	Cathode Ray Tube (display)
EEE	Electric and Electronic Equipment
EN	European standard (norm) identifier
EoL	End-of-Life
ErP	Energy-related Products
Gt	Giga-tonnes (109 metric tonnes. 1012 kg)
GWP, GWP100	Global Warming Potential (time-horizon 100 years)
IEC/ISO/CEN, CENELEC	Global and European standardisation bodies
kt	kilo-tonnes (1000 metric tonnes, 106 kg)
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MEErP	Methodology for the Ecodesign of Energy-related Products
Mt	Mega tonnes (106 metric tonnes, 109 kg)
OEF	Organisational Environmental Footprinting
PEF	Product Environmental Footprinting
PPM	Process and Production Methods (distinguish PR=product related and NPR=non-product related)
ppm	parts per million
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (Directive, defines SVHC)
RoHS	Restriction of Hazardous Substances
RRR	Re-usability/Recyclability/Recoverability
SVHC	Substance of Very High Concern
VHK	Van Holsteijn en Kemna (author)
WEEE	(Directive on) Waste of EEE
WEEELABEX	European standards project WEEE
WFD	Waste Framework Directive
WTO	World Trade Organisation

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Executive summary

This study for the Belgian Federal Directorate-General for the Environment explores the formulation and evaluation of a 'recyclability' and 'recoverability' index, in the context of Circular Economy Package of the EU and a possible differentiated tariff for the extended producer responsibility introduced under the WEEE Directive.

The original assignment included 'reusability' as third resource efficiency aspect, but as 'reuse' is much more linked to repair and the reversibility of removal of parts from products, this aspect is covered in generic terms only, by referring to ongoing standardisation activities regarding 'reuse'.

The remainder of the study focuses on recyclability and recoverability of products and describes why recycling/recovery takes place, which processes are applied and their limitations are, and the assemblies/parts/materials of products that require a specific treatment for liberation and/or sorting so that the optimum final treatment for recycling (or recovery) can take place.

The study describes several methods that aim to describe the recyclability (or recoverability) of products and assesses these against criteria outlining an ideal method. The assessment shows that simple 'criteria' and 'scoring methods' lack the legal robustness required for reliability and reproducibility of methods. Methods that calculate a 'whole product recycling rate' are ill-equipped to deal with modern products and political priorities, and are based on inputs that do not vary if the design of the product, more specifically the joints that determine liberation and sorting effectiveness, vary. The complexity increases even more for methods that include an environmental assessment (Environmental benefit ratio, or Circular footprint formula). These methods also require the definition of an End-of-Life scenario, which introduces parameters that are outside the influence of the manufacturers of products. One method, the full metallurgical assessment has been found to be quite exact in predicting real-world recyclability (recoverability) of products but relies on complex software modelling and again requires a precisely defined end-of-life scenario.

It was therefore concluded that a new method should be developed to bridge the relative simplicity of criteria and scoring methods, and the exactness of whole product recycling and other more complex methods, but without trespassing beyond the boundaries of product design, taking into account liberation and sorting issues that are known from current and near future recycling practices.

The method that has been developed consists of two main elements: First is the selection of assemblies / parts / components that are relevant for the assessment of the specific product group. This selection should be made in awareness of real-world recycling challenges, relating to liberation and sorting difficulties. After having identified these parts, the method relies on a technical assessment of the joining methods for these parts (can be weak, standard or strong/complex) and the depth of assembly (how many layers need to be removed before the part is liberated and sorted for treatment in the optimum final treatment process). The number of joints are counted and assigned a weight, resulting in a multiplier that reduces the 'ideal score' of 10 (the ideal score is only reached if no recycling challenges exist). The recyclability score includes aspects related to depollution, and valorisation of metals, plastics and other miscellaneous materials. The recoverability score includes other forms of material recovery (backfilling, composting) and energy recovery.

The method has been tested on two different laptop designs (from 2009, including mercury CCFL lighting, and from 2012, unibody design). Although the method clearly shows differences, where the respective designs fare relatively good or bad, the evaluation also shows the influence of the selection of components for differential treatment and certain aspects related to assigning scores.

The study concludes that the newly developed method addresses most of the weaknesses found in other methods, but recommends that it is further developed, also by involving more experts and testing. Furthermore, it should be noted that similar activities are ongoing, in EU standardisation bodies following mandate 543, but also abroad, in the USA by iNEMI and it would be worthwhile to follow these other developments closely.

The use of the RR method in legal instruments first requires the method to be accepted and finalized. Implementing measures under the Ecodesign Directive 2009/125/EC are necessary to identify the materials / parts / assemblies that need to be taken into account in the assessment and can also specify the weighing factors used in the method. A mandatory RR score can then enable the consideration of the EoL performance of products during purchasing, the differentiating of EPR fees and the provision of EoL-relevant information (as required under the WEEE Directive).

Management samenvatting

Deze studie voor het Belgische federale Directoraat-Generaal Leefmilieu betreft het formuleren en evalueren van een index ('score') betreffende de recycleerbaarheid (recyclability) en mogelijk nuttige toepassing (recovery) van producten in de context van de Circular Economy Package van de EU en een mogelijk gedifferentieerd tarief voor uitgebreide producentverantwoordelijkheid als ingevoerd door de AEEA[1] (UK: WEEE) Richtlijn 2012/19/EU.

De gestelde taak had ook betrekking op herbruikbaarheid (reusability) als derde 'resource efficiency' aspect, maar omdat herbruikbaarheid vooral verbonden is aan de mogelijkheid tot repareren en het reversibel verwijderen van onderdelen van producten, is dit aspect slechts in algemene termen beschreven door verwijzing naar lopende standaardisatie activiteiten.

De studie richt zich vooral op de recyclability en recoverability van producten en beschrijft waarom recycling en hergebruik als nuttige toepassing plaatsvinden, welke processen daarbij worden toegepast en welke beperkingen deze kennen, en welke materialen / onderdelen / samenstellingen een specifieke verwerking vragen zodat de optimale eindverwerking kan plaatsvinden.

De studie beschrijft verscheidene methodes voor het beschrijven van de recyclability (of recoverability) van producten en zet deze uit tegen criteria voor het bepalen van de ideale methode. De afweging laat zien dat simpele methoden gebaseerd op 'criteria' of 'scores' niet de vereiste robuustheid hebben voor de toepassing in een wetgevend kader. Methoden welke een 'whole product recycling rate' berekenen zijn slecht toegerust om om te gaan met moderne producten en politieke prioriteiten, en zijn gebasserd op invoerwaarden die niet varieren als het product een verbetering heeft ondergaan, met name betreffende de verbindingen van materialen en onderdelene die de mate van het vrijmaken en sorteren van materialen beïnvloeden. Methoden die gebaseerd zijn op de milieuschade per schade-categorie (Environmental benefit ratio, of Circular footprint formula) zijn nog complexer en bevatten veelal elementen die niet beïnvloed worden door de producent, zoals een precieze definitie van het einde-levensduur scenario. De 'full metallurgical assessment', is waarschijnlijk de meest realistische bepaling van de recyclability van producten, maar vereist een complex software model en eveneens een precieze definitie van het einde-levensduur scenario.

Een nieuwe rekenmethode is ontwikkeld om de relatieve eenvoud van de 'criteria' en 'score' methode te combineren met de precisie van meer complexere methodes, waarbij rekening is gehouden met wat door productontwerp bereikt kan worden, en de problematiek van het vrijmaken en sorteren van diverse materialen / onderdelen door recyclers.

De ontwikkelde methode bestaat uit twee elementen: Het eerste is het identificeren en selecteren van die materialen / onderdelen / samenstellingen die relevant zijn voor de beoordeling van de recyclability van een specifieke productgroep. Deze selectie dient rekening te houden met de beperkingen van de technieken voor het vrijmaken en sorteren van materialen. Het tweede element betreft een technische beoordeling van de verbindingstechnieken die zijn toegepast in het product: Deze verbindingen worden ingeschaald als zwak ('weak'), standaard ('standard') of sterk/complex ('strong/complex'). Tevens wordt ook de gelaagdheid van de verbinding beoordeeld (hoeveel onderdelen dienen verwijderd te worden voordat het gevraagde materiaal / onderdeel vrijgemaakt is). Het aantal van een bepaald type verbinding dat verbroken moet worden wordt uitgedrukt in een factor welke de ideale score van '10' reduceert. De methode houdt rekeningen met het verwijderen van gevaarlijke stoffen, en het terugwinnen van metalen, plastics en diverse andere materialen. De score voor recoverability kijkt daarnaast naar mogelijke nuttige toepassingen als opvulmateriaal ('backfilling'), composteren en verbranding met energieterugwinning.

De methode is toegepast op twee laptops (waarvan één uit 2009 met achtergrondverlichting die kwik bevat, en de ander uit 2012 met een 'unibody' design). De evaluatie toont aan dat de methode de verschillen in productontwerp goed uitdrukt, maar liet tevens zien dat de score erg afhankelijk is van welke materialen / onderdelen / samenstellingen geselecteerd zijn voor beoordeling, plus nog wat andere zaken die de score bepalen.

De conclusie van de studie is dat de nieuw ontwikkelde methode niet de nadelen van de eerder beschreven methodes kent, maar dat de methode nog verdere ontwikkeling behoeft, bijvoorbeeld door meerdere producten te testen en andere experts hun oordeel te laten geven. Eveneens moet vermeld worden dat soortgelijke activiteiten uitgevoerd worden in het kader van mandaat 543 voor Europese standaardisatie organisaties en ook in de VS, door iNEMI.

Het toepassen van de RR methode in een wetgevend kader vraagt als eerste het afronden en algemeen accepteren van de methode. Vervolgens zijn implementerende maatregelen onder de Ecodesign Richtlijn 2009/125/EC nodig om de materialen / onderdelen / samenstellingen te identificeren die in de score moeten worden meegenomen. Bovendien kunnen deze maatregelen de wegingsfactoren vaststellen. De methode die vastgelegd is in de eventuele norm betreft dan slechts de berekeningsmethodiek, maar niet de politiek gevoelige kwesties. Een wettelijk verplichtte RR score maakt het dan mogelijk recyclability/recoverability mee te wegen bij aanschaf, een gedifferentieerd tarief in te voeren voor verwerkingskosten en te voorzien in informatie relevant voor verwerking (zoals ook gevraagd in de WEEE Richtlijn 2012/19/EU).

[1] AEEA = Afdanking elektrische en elektronische apparaten

Résumé

Cette étude pour la Direction Générale Environnementale de la Belgique explore la formulation et l'évaluation d'un indice de «recyclabilité» et de «récupérabilité» dans le cadre du paquet Économie Circulaire de l'UE et d'un tarif différencié éventuellement pour la responsabilité élargie du producteur selon les directives DEEE.

L'affectation originale incluait la «réutilisabilité» comme troisième aspect d'efficacité des ressources, mais comme la réutilisation est beaucoup plus liée à la réparation et à la réversibilité du retrait des pièces des produits, cet aspect est couvert en termes généraux seulement, en se référant aux activités de normalisation en cours.

Le reste de l'étude porte sur la recyclabilité et la récupérabilité des produits et décrit les processus de recyclage / valorisation, les procédés appliqués et leurs limites ainsi que les assemblages / pièces / matériaux des produits nécessitant un traitement spécifique de libération et / ou de tri. de sorte que le traitement final optimal pour le recyclage (ou la récupération) peut avoir lieu.

L'étude décrit plusieurs méthodes qui visent à décrire la recyclabilité (ou la récupérabilité) des produits et les évalue par rapport à des critères décrivant une méthode idéale. L'évaluation montre que les «critères» et les «méthodes de notation» simples n'ont pas la robustesse juridique requise pour la fiabilité et la reproductibilité des méthodes. Les méthodes qui calculent un «taux de recyclage du produit entier» sont mal équipées pour traiter les produits modernes et priorités politiques et sont basées sur des valeurs dímportation qui ne varient pas lorsque le produit a subi une amelioration, en particulier les joints qui déterminent le degré de libération et de tri des matériaux. La complexité augmente encore plus pour les méthodes qui comprennent une évaluation environnementale (rapport bénéfice-environnement ou formule de l'empreinte circulaire). Ces méthodes nécessitent également la définition d'un scénario de fin de vie, qui introduit des paramètres indépendants de l'influence des fabricants de produits. Une méthode, l'évaluation métallurgique complète, a été jugée assez exacte pour prédire la recyclabilité réelle (recouvrabilité) des produits, mais repose sur une modélisation logicielle complexe et nécessite à nouveau un scénario de fin de vie précisément défini.

Il a donc été conclu qu'une nouvelle méthode devrait être développée pour relier la simplicité relative des critères et des méthodes de notation, et l'exactitude du recyclage des produits entiers et d'autres méthodes plus complexes, sans toutefois dépasser les limites de la conception du produit, en tenir compte a problèmes de tri connus des pratiques de recyclage actuelles et futures.

La méthode qui a été développée comprend deux éléments principaux: Premièrement, la sélection des assemblages / pièces / composants qui sont pertinents pour l'évaluation du groupe de produits spécifique. Cette sélection doit être faite en tenant compte des défis du recyclage dans le monde réel, liés aux difficultés de libération et de tri. Après avoir identifié ces pièces, la méthode repose sur une évaluation technique des méthodes d'assemblage de ces pièces (faible, standard ou forte / complexe) et de la profondeur d'assemblage (combien de couches doivent être enlevées avant que la pièce soit libérée et trié pour le traitement dans le processus de traitement final optimal). Le nombre d'articulations est compté et affecté d'un poids, ce qui entraîne un multiplicateur qui réduit le «score idéal» de 10 (le score idéal n'est atteint que si aucun défi de recyclage n'existe). Le score de recyclabilité inclut les aspects liés à la dépollution et à la valorisation des métaux, plastiques et autres matériaux divers. Le score de récupération inclut d'autres formes de récupération de matériaux (remblayage, compostage) et de récupération d'énergie.

La méthode a été testée sur deux modèles d'ordinateurs portables différents (à partir de 2009, y compris l'éclairage au mercure CCFL, et à partir de 2012, la conception unibody). Bien que la méthode montre clairement des différences, lorsque les conceptions respectives sont relativement bonnes ou mauvaises, l'évaluation montre également l'influence de la sélection des composants pour le traitement différentiel et de certains aspects liés à l'attribution des scores.

L'étude conclut que la méthode nouvellement développée répond à la plupart des faiblesses constatées dans d'autres méthodes, mais recommande de la développer davantage, en impliquant également davantage d'experts et de tests. En outre, il convient de noter que des activités similaires sont en cours, dans les organismes de normalisation de l'UE après le mandat 543, mais aussi à l'étranger, aux États-Unis par iNEMI et il serait utile de suivre ces autres développements de près.

L'utilisation de la méthode RR dans les instruments juridiques nécessite d'abord que la méthode soit acceptée et finalisée. Les mesures d'exécution de la directive sur l'écoconception 2009/125 / CE sont nécessaires pour identifier les matériaux / pièces / ensembles à prendre en compte dans l'évaluation et peuvent également spécifier les facteurs de pondération utilisés dans la méthode. Un score RR obligatoire peut alors permettre la prise en compte de la performance de la fin de vie des produits lors de l'achat, la différenciation des frais de REP et la fourniture d'informations pertinentes pour la fin de vie (tel que requis par la directive DEEE).

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1 Introduction

1.1 Background

On 2nd of December 2015, the European Commission proposed –following up on its new *7th Environmental Action Plan (EAP7)*—a revised *Circular Economy Package*[2]. This Circular Economy Package consists of an *EU Action Plan for the Circular Economy* that establishes a programme of action, with measures covering the whole product life cycle, from production and consumption to waste management and the market for secondary raw materials. It includes specific proposals to amend the EU's waste legislation and turn waste into valuable resources, as well as specific elements addressing the Ecodesign Directive and its implementing measures.

The package, explicitly mentioning Ecodesign as a starting point, calls for new measures to close resource loops by addressing the "*5 R*" priorities in the waste policy: *Reduce, Re-use, Recycle, Recover, Remove*. This not only entails designing robust end-of-life measures on durability, reparability, spare parts availability, recyclability, etc. but also covers measures on light-weighting and use of recycled materials in production. For this purpose the Commission issued a mandate M/543 for the development of (test) standards regarding the above material efficiency aspects.

The Belgian federal government supports the circular economy initiative and, for the purpose of preparing possible legislative measures within the context of the Ecodesign Directive 2009/125/EC, seeks guidance on how to assess in particular the reusability, recyclability and recoverability of products.

1.1.1 Study brief

The tender document states that producers often have little or no knowledge on how their products are processed once they have become waste. On the other hand, waste treatment facilities generally are confronted with products that are not optimised for certain waste treatment operations, resulting in suboptimal recycling / recovery of materials.

Moreover, a product made from recyclable materials is not necessarily a recyclable product, as materials need to be separated from each other and sorted into as pure as possible material streams. The (cost) effectiveness of separation/sorting into recyclate also determines the recyclability of a product.

The information of the recyclability of products, if available, could lead to a better design of products, and possibly allows differentiation in rates applied to manufacturers within systems of extended producer responsibility.

A reuse/recycling/recovery (RRR) index could provide such information in an easy to disseminate form. This RRR index can be determined on the basis of product composition and a waste processing scenario.

1.1.2 Re-use, the first "R" in RRR

Although the study brief asked for an assessment of RRR methods, being "Reuse, Recycling and Recovery", the concept of "reuse" fits better in a context of product life extension (of whole product) and repair (using parts).

"Reuse of whole product" is a form of product life extension: The discarded product is not processed further as waste, but is (if necessary) cleaned, refurbished, remanufactured and/or repaired and starts a second life as a (refurbished/remanufactured) product. Standards regarding remanufacturing and product-life extension are being developed in the context of M/543.

"Part reuse" (also 'component reuse') is the removal of still usable parts for the purpose of repairing other products. The pivotal difference between part reuse and recycling / recovery of parts is the reversibility of the separation processes which is essential to reuse but not required/essential for recycling/recovery as long as polluting substances are not dispersed in an uncontrolled manner through irreversible treatment processes. For this reason the removal of parts for reuse is similar to repair of products, as repair requires removal of the faulty component in the first place without damaging the joints and connections to the 'mother' product.

Because of these differences in objective between re-use and recycling/recoverability it is not recommended to include reuse in the very same method for a recyclability/recoverability index. Reuse is better handled in standards or indexes aimed at product life extension and/or reparability.

The latest draft of a standard covering reuse of parts (prEN 45556) proposes an index based on either the mass, component count or value of reused parts versus the total mass/components/value of the product. The draft also states that

[2] "Closing the loop - An EU action plan for the Circular Economy". COM(2015) 614 final, Brussels, 2.12.2015

verification of use of reused parts is difficult if limited to physical properties of the product, as these are often identical to the original part. Therefore the only alternative verification is a 'paper trail' or supply of documents that provide proof of the secondary origin of the part.

1.2 Objectives

The objective of this study is the development and testing of a method for establishing recycling / recovery (RR) indices of products covered by the Ecodesign Directive (energy-related products).

In accordance with the study brief, the study incorporates the following elements (section indicated):

1. A literature review of existing methods; ..... Section 5.1
2. Evaluation of present RR methods and practical feasibility; ..... Chapter 2, 3 and 4 and Section 5.2
3. Case study:
    a. Choice of products for which an RRR will be prepared; ..... Section 6.8
    b. Development of a method for calculating the RRR index; ..... Section 6.1 – 6.7
    c. Establishing the RRR score of selected products; ..... Section 6.8
4. Evaluation of the scores and of product or treatment improvement options; ..... Section 6.9
5. Evaluation of the method and recommendations. ..... Section 7.1 and 7.2

The study is to reflect the state-of-the-art[3] of the recent years, indicatively 2015-2017 and is restricted to the EU 28.

Recycling is understood to be synonymous to material recovery (mechanical recycling, chemical or feedstock recycling, and biological or organic recycling). Other recovery includes energy recovery in the form of heat, steam, or electricity generation using plastics waste as substitutes for primary fossil fuel resources, and backfilling.

The thematic scope is understood to have a focus on 'post-consumer waste' and 'open loop' recycling as this reflects the reality of most end-of-life processes of ErP. Pre-consumer recyclability (as in "can process waste be fed back into a material loop") is foremost a material quality, difficult to assess on the actual product, and poses a less urgent problem than post-consumer recycling/recovery issues.

Reuse is covered by methods related to product life extension and repair.

1.3 Target audience

Legislators will not apply the RRR methods themselves, but must understand them sufficiently to decide on its application in legal requirements. For this they will probably rely on external expertise that help them identify appropriate methods, scope and verification procedures. So the first users of this RR index are, besides the policy officer, external experts consulted during preparation of possible measures and other persons/institutions involved in the legal procedures, including market surveillance.

If indeed measures based on RR methods are introduced, the second group of users will be manufacturers that will need to check compliance of their products with relevant measures and to produce the required information. This group includes importers of products, who must do (or commission) such an assessment or ask for related documents from the original manufacturer. In case of material declarations, the manufacturer (or importer) must also consult the 'upstream' supply chain for data.

If the RR index is to be used as mandatory information requirement (product sheet or label) consumers form a third group.

A fourth group of users may be a diffuse set of stakeholders such as consumer and/or environmental organisations, who may use such information in their reporting, opinion leaders, designers (of non-regulated products, in anticipation or for inspiration), educational facilities (design schools) and academics.

[3] "State-of-the-art" is to be understood according its meaning in European patent law, referring to existing and known technologies (synonym to 'prior art') and does not relate to the more commercial meaning of it ("the best possible technology")

1.4 Relation to Mandate M/543

The context of this study is partly formed by the mandate M/543 *on a standardisation request to the European standardisation organisations as regards ecodesign requirements on material efficiency aspects for energy-related products in support of the implementation of Directive 2009/125/EC of the European Parliament and of the Council*.

Mandate M/543 states the requested deliverables shall as far reasonably practicable deal with the following topics (where directly related to recycling and recovery[4]):

- Reusability/recyclability/recoverability (RRR) indexes or criteria, preferably taking into account the likely evolution of recycling methods and techniques over time;
- Ability to access or remove certain components or assemblies from products to facilitate their extraction at the end-of-life for ease of treatment and recycling;
- Method to assess the proportion of re-used components and/or recycled materials in products;
- Use and recyclability of Critical Raw Materials to the EU, listed by the European Commission[5];
- Documentation and/or marking regarding information relating to material efficiency of the product taking into account the intended audience (consumers, professionals or market surveillance authorities).

According to M/543 the assessment methods shall be reliable, accurate and reproducible not be prohibitively expensive and not imply lengthy tests.

[4] Other topics relate to durability, reparability, etc.

[5] Most recently in the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative, COM(2014) 297 final
http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0297&from=EN

2 Why we recycle / recover

Before describing the actual practice of recycling (and recovery), this chapter first describes 'why' we recycle. In doing so, it gives a context against which the role of the RR index to be developed, can be checked.

2.1 Recycling

Recycling, defined in the Waste Directive 2008/98/EC, Article 3.17 as: *"any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations"* is performed for two reasons:

1. Because one can make a profit with it.
2. Because there is a societal demand to handle waste carefully.

The first indent needs no further introduction as it is the basis for our current economic model. Making a profit in recycling however mainly applies to basic metals like steel (incl. stainless steel), copper, aluminium, zinc, tin, and some precious metals (platinum gold, silver, palladium) recovered from ErP scrap. Plastics are much harder to recover/recycle in an economically sound manner, especially if the diversity and the quality demands are high as in many ErP. Recycling of packaging plastics is more developed as the variety of plastics is less, the total volume handled is much higher.

Waste treatment of ErP thus requires a careful balancing of efforts (= costs) and gains (revenue): In Western-Europe treatment facilities the cost of personnel is some 1 euro/min. This means that a labourer has to recover 0.5 mg gold per second (at 30 000 EUR/kg), 100 g steel per second (at 0.15 EUR/kg), and approximately 25 g plastics per second (at 0.5 to 1 EUR/kg), assuming no other costs involved. This is challenging and it is no surprise that many waste treatment facilities work with subsidized labour. For machines the costs are usually lower and the throughput is higher. The quality however may be lower, but more on that in the next chapter.

The second ident, to handle waste carefully, has led to regulations dealing with waste and ErP waste in particular. These regulations are aimed at the waste phase (WEEE) and the design phase (Ecodesign, RoHS, REACH) as described in the next sections.

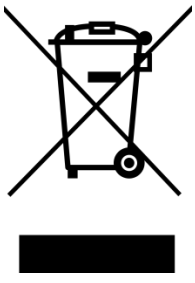
2.1.1 Waste phase

The objective of the WEEE Directive 2012/19/EU was to reduce environmental problems related to the handling of waste of electric and electronic products, by making the manufacturers (including importers) responsible for the collection and proper treatment of waste electric and electronic equipment (WEEE). This principle has been introduced in the first WEEE Directive 2002/96/EC and is maintained in the recast Directive 2012/19/EU.

By making producers responsible for the waste phase, the design and production of electric and electronic equipment (EEE) which take into full account and facilitate its repair, possible upgrading, re-use, disassembly and recycling is encouraged. The producer is allowed to choose to fulfil this obligation either individually or by joining a collective scheme.

Most producers, if not all, have set up collective schemes for the financing of the collection, treatment, recovery and environmentally sound disposal of 'historic' WEEE from private households placed on the market before 13 August 2005. The financing of treatment of WEEE placed on the market after 13 Aug 2005 (recognisable by the crossed out wheelie bin and a black bar underneath) may be related to the waste from his own products placed on the market. It is the phrase 'own' waste that can be interpreted as individual producer responsibility.

Figure 1. Marking for EEE placed on the market later than 13 Aug 2005 – based on EN 50419: 2206



Proper treatment is described in ANNEX VII *"Selective treatment for materials and components of waste electrical and electronic equipment referred to in Article 8(2)"* as the removal [6] (and monitoring towards environmentally safe treatment) of several components/substances from separately collected WEEE.

These components or substances are:

- capacitors containing polychlorinated biphenyls or other hazardous substances;
- mercury containing components (switches, gas discharge lamps);
- batteries;
- printed circuit boards;
- toner cartridges, inks, and pastes;
- plastics containing brominated flame retardants;
- asbestos;
- cathode ray tube (incl. removal of fluorescent powders);
- CFC, HCFC, HFC, and HC (gases have to be treated appropriately);
- liquid crystal displays (of minimum size or backlighted with gas discharge lamps);
- external electric cables;
- refractory ceramic fibres;
- radioactive substances.

Although the requirements are aimed at waste operators, it is obvious that the legislator also targeted the manufacturer (designer) of the products, in an attempt to make recycling easier for waste treatment operators.

2.1.2 Design phase

RoHS & REACH

The RoHS Directive 2011/65/EU and the REACH Regulation No 1907/2006/EU apply to (substances in) products that are placed on the EU market and thus should be considered already at the design phase of a product.

Both RoHS and REACH impose substance bans, whereby the bans under ROHS are limited to WEEE, and the bans under REACH are more often a generic ban.

- The RoHS Directive prohibits placing on the market (by weight of homogeneous substance): Lead (0,1 %), Mercury (0,1 %), Cadmium (0,01 %), Hexavalent chromium (0,1 %), Polybrominated biphenyls (PBB) (0,1 %), Polybrominated diphenyl ethers (PBDE) (0,1 %), Bis(2-ethylhexyl) phthalate (DEHP) (0,1 %), Butyl benzyl phthalate (BBP) (0,1 %), Dibutyl phthalate (DBP) (0,1 %), Diisobutyl phthalate (DIBP) (0,1 %);
- REACH regulation 1907/2006 prohibits many substances, including DEHP, BBP, DBP and DIBP for their use in toys (but not for other products which is why the RoHS has them covered). DecaBDE (Decabromodiphenyl ether), a PBDE, has also been banned under REACH (max. 0.1% by weight).

Other flame retardants and plasticizers may be considered hazardous as well, but are not (yet) restricted. Examples are: Tetrabromobisphenol A (TBBPA or TBBP-A) used as flame retardant in printed circuit boards and ABS. As this FR is chemically bound to the resin, exposure risk is reduced and it can be incinerated in pyro metallurgic processes, given appropriate flue cleaning. Synergists for flame retardants may be based on antimony, which in certain forms (antimony trioxide dust) may be toxic.

Ecodesign

The Ecodesign Directive 2009/125/EC allows establishing ecodesign measures that address resource efficiency (RE) aspects of products over the complete life cycle of products, including the waste phase.

The current EU Ecodesign measures have shown that when RE parameters relate to the consumption of non-energy consumables during the use-phase (e.g. n-up printing, duplexing) and/or where they relate to a minimum requirement on technical product life (e.g. hose bend tests or running hours of motor of vacuum cleaner), these measures can be successful and enforceable.

[6] "Removed" means manual, mechanical, chemical or metallurgic handling with the result that hazardous substances, mixtures and components are contained in an identifiable stream or are an identifiable part of a stream within the treatment process. A substance, mixture or component is identifiable if it can be monitored to verify environmentally safe treatment. It does not mean that all components need to be physically removed from the product, as long as the components can be verified to have undergone environmentally safe treatment. Therefore the smelting of integral smart phones can be considered removal (if the smelter is equipped with technology reducing or controlling polluting emissions).

Other RE requirements such as substance bans, recycled content, disassembly time and/or origin of resources rely on an extensive 'paper trail'.

Ecodesign measures relating to specifically the waste phase are rare but are slowly being introduced in proposals for ecodesign requirements for electronic displays and a voluntary agreement on imaging equipment.

2.1.2.1 Proposal for ecodesign requirements – Electronic displays

The proposal for ecodesign requirements for electronic displays of summer 2016 introduces several waste phase related resource efficiency requirements.

One of the requirements states that manufacturers shall ensure that welding or gluing other than through the use of double-sided adhesive tape are not used as joining or sealing techniques for the following components, when present:

- batteries;
- PCB assemblies larger than 0.1 dm2;
- display panels larger than 1 dm2;
- mercury containing components;
- capacitors; and in addition;
- PMMA boards;
- internal power supplies.

The marking of plastic parts heavier than 50g is required (exemptions apply to very small parts or parts that are difficult to mark).

The products shall be equipped with a Mercury logo and Cadmium logo, indicating presence or absence of the substance.

For each product family, suppliers shall provide information relevant for dismantling, re-use, recycling and recovery at end-of-life. This includes the provision of a table indicating which parts contain which flame retardants and their quantities.

A full overview of the proposed requirements is included in Annex B.

2.1.2.2 Voluntary Agreement imaging Equipment

The Voluntary Agreement by the European imaging equipment seems to have drawn inspiration for the EPEAT criteria (see also section 5.1.1). The Voluntary Agreement version 5.2 of April 2015 presented the following criteria related to recyclability.

For all product models first placed on the EU market after 1 January 2012:

- Plastic parts >100 g shall be manually separable into recyclable plastic streams with commonly available tools.
- Product shall utilize commonly used fasteners for joining components, subassemblies, chassis and enclosures.
- Non-separable connections (e.g. glued, welded) between different materials shall be avoided unless they are technically or legally required.
- Product plastics shall be marked by material type (ISO 11469 referring ISO 1043, resin identification code, SPI, DIN, or country specific). Marking requirement does not apply to plastic parts weighing less than 25 g or with surface area less than 50 cm^2; tape; plastic protective and stretch wraps and labels; or plastic pieces when due to shape marking is not possible. Exempted are plastic parts contained in reused complex modules.

In order to limit the variety of materials used, plastic casing parts with a mass greater than 100 grams have to consist of one single polymer or a polymer blend. All plastic casing parts may only consist of up to four separable plastics or polymer blends.

The use of coatings for special parts is to be reduced to a minimum, unless it can be demonstrated that it does not alter recyclability. Galvanic coatings on plastic parts are not permissible.

For all new product models first placed on the EU market after 1 January 2015 the minimum percentage of postconsumer recycled plastic content, calculated as a percentage of total plastic (by weight) in each product shall be presented.

A full overview of the proposed requirements is included in Annex B.

2.2 The potential role of an RRR index

Considering that recycling is driven by legal demands and economics, what is the potential role of an RR index? An RR index could:

1. inform manufacturers on the performance of their products and allows comparison with other products (if introduced horizontally, for all manufacturers of products in a specific group). This could introduce recyclability as a discerning parameter against competition:
2. enables the introduction of a differentiated treatment fee, providing an incentive to design better recyclable products.

That is, if indeed the RR index is able to transfer a better real-life recycling performance into a single index or value.

The WEEE Directive introduced the concept of extended producer responsibility, in which the producer (or the person responsible for placing the product on the EU market) is also made responsible for proper treatment of the product in the waste phase. In other words, this means manufacturers have to pay for the costs of treatment (of WEEE).

As it is too costly for most manufacturers to set up a manufacturer-specific recycling/recovery infrastructure, and most WEEE are collected via municipal waste facilities, manufacturers have delegated their obligations for proper treatment to market parties that collect disposal fees or levies (where applicable) from manufacturers and buy treatment capacity from waste treatment operators (bidding process).

A RR index could be instrumental in this process as currently the fees are indiscriminate of the recyclability of products placed on the market. If however a system could be set up that differentiates the fees in relation to the product recyclability, with lower fees applying to better recyclable products, this could introduce a strong financial incentive to design products with better recyclability.

3 How to recycle / recover: Possibilities and limitations

Now that we know 'why' products are recycled this chapter explores 'how' the recycling actually occurs. It dives into the different technologies available, indicating capabilities and limitations, but without giving value judgement on which technology should be preferred over another – this is the responsibility of the waste treatment facility operators.

3.1 Trends in product design that complicate RR

Over the last couple of decades recycling of ErP products has become increasingly challenging, because of certain product design trends putting pressure on the economics of recycling. These trends are:

- less use of metals, and less precious metals (copper replaced by aluminium as electric conductor, less gold content in printed circuit boards, etc.) and more use of metals for which no economical post-consumer recycling infrastructure exists (rare earth elements[7]);
- more use of plastics, and more complex plastic combinations in a single product / part (co-extrusion), and plastics with adverse additives or surface treatment (flame retardants, fillers, fibres, etc.);
- more use of complex material combinations (composites, coatings, nanomaterials, multi-layered films, etc.);
- more diversity of products, combined with miniaturisation in particular in the home electronics sector[8], make it harder to optimise the treatment of a mixed waste flow.

To illustrate the increase in material complexity of products: the total number of different materials applied in products has increased dramatically: Of the 83 stable (nonradioactive) elements, at least 70 of them can be found in smartphones. That's 84% of all of the stable elements in a single product[9]. A similar trend is observed in other products:

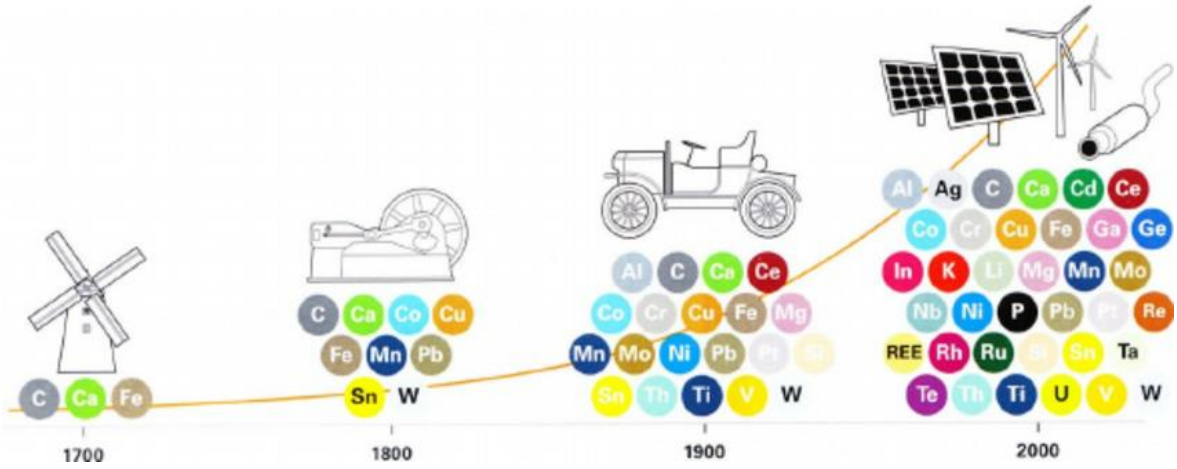
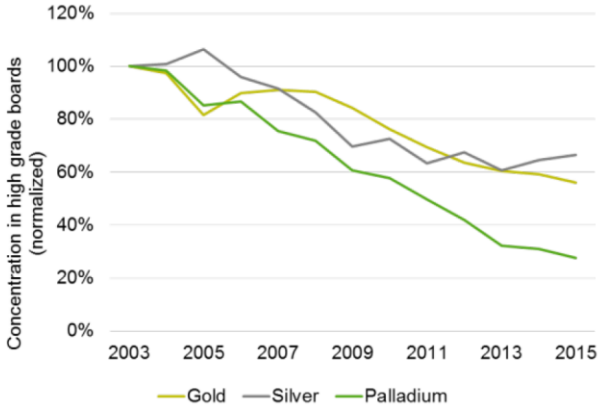


Figure 2. Development of energy technologies during the last 300 years and elements used [Achzet and Reller, 2011] [10]

At the same time, especially in the last two decades, the content of precious metals has decreased, mainly to reduce purchase prices.

Figure 3. Precious metals in high grade PCB[11]

[7] As prices of virgin REE may peak or plummet, often as a result of global resource politics, recycling industries are reluctant to invest in technologies for recuperation of CRM if no long-term recovery value can be ensured (as happened with Indium);
[8] Judged by sharp increase of market acceptance, not technical feasibility (digital cameras and home office equipment became more mainstream some 20 years ago, the smartphone is some 10 years old, the tablet became more popular some 7 years ago and home assistants such as Amazon's Echo were introduced only last year).
[9] https://www.acs.org/content/acs/en/education/resources/highschool/chemmatters/past-issues/archive-2014-2015/smart phones.html
[10] https://www.researchgate.net/figure/284903528_fig2_Figure-8-Development-of-energy-technologies-during-the-last-300-years-41-with



Of course, the above design trends also bring benefits: They make the product prettier, allow light weighting, combine multiple functions in a single product, make the product more robust, increase product life, etc. but these advantages are only visible when taking an holistic view, that takes into account the (avoided) impacts across the whole life cycle of the product – which is the realm of full life cycle analysis.

3.2 Recycling technologies

As a response to these design trends and pushed by increasing legal requirements regarding the performance of recycling facilities (WEEE recycling targets), waste treatment operators and suppliers of waste treatment equipment have developed numerous methods to address these challenges.

As products are collected and processed in a continuous flow or a batch of fairly similar products (small household products are treated together, etc.) the recovery technologies are optimised for the best yield of the flow/batch. This also means they are generally not optimised for the processing of very specific product groups. Some exclusions apply, such as processing routes for CRT or flat panel TVs, computers, smartphones, imaging equipment. This is usually done to meet certain legal requirements (WEEE).

The recycling/recovery of materials entails the (repeated) liberating and sorting of materials for more specific treatment. The goal of each treatment is depollution, recovery of value (valorisation) or both. However:

1) Depollution is hampered as:
   a) the pollutants are not easily identifiable in the waste product (it may not be visible from the outside or from liberated parts or particles, whether the product contains polluting or harmful substances);
   b) the pollutants are often difficult to separate from non-harmful materials (they may be dispersed in the product, like brominated flame retardants in plastic casing, or 'hidden' in printed circuit boards, or present in parts that are not easily dismantled, etc.);
   c) all the above leads to increased efforts and higher costs for depollution.
2) Valorisation is often difficult as:
   a) material types and grades are not easily identifiable, and/or separated from other materials;
   b) which requires application of extensive liberation and sorting techniques, especially for plastics and valuable or critical metals;
   c) makes secondary materials (especially plastics) relatively expensive.

Many Plastics are combined with additives to achieve certain characteristics or material properties. Examples are flame retardants, plasticizers (especially in PVC) or fibres. These additives can influence the attractiveness for recycling (the value when made available on the secondary materials market).

Recycling is mainly the act of liberating materials from a product (freeing the material from its surrounding materials) and sorting of materials (putting materials in the correct waste flow[12]), which itself is a combination of identification of a material and the physical handling. Certain techniques are necessary to prepare waste flows for subsequent treatment.

[11] Trends in electronic products – the canary in the urban mine? (PDF Download Available). Available from: https://www.researchgate.net/publication/308330588_Trends_in_electronic_products_-_the_canary_in_the_urban_mine [accessed Jul 17, 2017]

[12] Even the drying of materials after a float/sink bath can be considered a form of sorting where water is sorted from the waste stream.

Given that most spectroscopic sorting relies on recognition and handling the material using jets of pressurized air, so that they are placed in the correct bin, the waste flow needs to be as consistent in size and weight as possible. This is where cutting techniques (shredders) and sieves come in.

The current array of recycling processes can be categorised in either manual or automated processes, processes for liberating and sorting (can also be combined into one process, as in many smelt/refine processes) and processes for sorting materials by group (metals, plastics, etc.).

Table 1. Overview of liberation and sorting processes

Process	Main principle	Technology
Liberation	Manual	Yield varies with skill, experience and time/money available for a certain task
	Shredding	Shearing Grinding / crushing
	Disassembly	Robotic (LIAM by Apple)
Sorting	Manual	
	Static electromagnetic fields	Magnetic sorting Eddy-current Induction
	Density / wet	Sink/float Hydro Cyclone separation Flotation Magnetic density
	Density / dry	Shaking table / vibration table / ballistic separation / gravity separation table Dry cyclone Air classification Triboelectric and electrostatic sorting
	Spectroscopic sorting	Colour / polarized sorting XRT NIR MIR
	Hybrid	combination of the above, e.g. NIR + colour sorting
	Other / emerging	RAMAN XRF RAMAN LIBS TERA Hz TRA
Final treatment	for metals	Hydrometallurgy Pyro metallurgy
	for plastics	Regrinding Depolymerisation
Supporting processes	drying, sieving, grinding	
Recovery processes	material recovery (recycling, backfilling, composting) energy recovery	

Most sorting technologies are binary, either the material is selected or rejected. Some technologies (magnetic) allow sorting in three streams in a single step.

3.3 Manual liberation and sorting

The yield from manual treatment depends on the skills, experience and tools of the operator and in many cases offer very high quality output. However the capacity is dependent on the number of experienced personnel (and size of facilities available). The costs are relatively high and depend on possible external factors such as subsidized work.

Manual treatment is even today often applied in the first depollution step of a mixed waste flow, for removing batteries, capacitors, and valuable displays and electronics. In large enough waste flows, for specific products, depollution can be performed in automated processes (such as an automated line for treatment of flat panel displays, whereby mercury and phosphors are collected separately, next to various plastics and metals)

3.4 Automated liberation

3.4.1 Shredding

The purpose of shredders is 1) to liberate materials (to separate them from each other) and 2) to create a uniform output that can more easily be treated by subsequent processes, mostly by diminution.

3.4.1.1 Shearing

Shearing is the cutting of a product into smaller particles, using rotating knives. It allows creation of a fairly even distribution of particle sizes.

In most facilities whole ErP, after depollution, enter a 'coarse' shredder, which mainly separates large metals, plastics and assemblies (printed circuit boards, motors, etc.). After removal of metals through magnetic and non-ferrous metal sorters the residual waste stream of mainly plastics is fed into a second, more 'fine' shredder combined with a sieve, which outputs a rather uniform flow of waste particles. This flow can then be sorted using various 'wet' or 'dry' sorting techniques for plastics and other materials.

3.4.1.2 Grinding / crushing (rotating chain mill)

An alternative to shredders that shear are hammer mills which separate parts of products by repeated blows. More suitable for ErP are so-called 'rotating chain mills', where a large heavy chain is rotating in a chamber filled with ErP. On the side is an opening through which the shredded materials can leave the drum. The degree of liberation can be adjusted by the process parameters such as the speed of rotation of the chain, the size of the opening, and the retention time the products/materials spend in the milling chamber [13] [14].

Depending on the type of feed and the settings one can create a stream whereby main components such as printed circuit boards, motors, batteries, capacitors remain relatively intact resulting in variable particle sizes (as opposed to shredders, where these parts are cut in rather uniform sizes, before sorting starts) and allow easier depollution by sorting (often manual because of the variable particle size, or automated whereby robotic sorting allows dealing with the variable particle size as well, or automated sorting after 'fine' shredding, or in any combination of the above [15]).

3.4.2 Robotic disassembly (& sorting)

Robotic sorting has been applied since 2013. Robotic disassembly is more recent, and the most well-known example is LIAM by Apple, designed to take apart Apple products (smartphones)[16]:

LIAM is actually not a single robot, but a disassembly line comprising 29 different robots organized in an conveyor line with 21 stations, or “cells.” Every 11 seconds, an iPhone 6 can be taken apart into eight different pieces.

Liam removes the following components/materials from the iPhone 6: cover glass assembly (REE, precious metals and indium), battery (Li, Co), main logic board (precious metals), receiver (REE as neodymium), speaker (REE as neodymium), alert module (Tungsten), rear facing camera (REE), and housing (metals, plastics).

Some components, like the battery, are tricky to remove: Because of the risk of exploding batteries, the iPhone is put into a steel compartment called the “sandbox” while it’s being disconnected and unscrewed. The battery is then heated up to loosen the glue, while a suction cup pulls the battery out. The battery is allowed to cool down before it’s removed from its metal box. If the battery does not cool down sufficiently, sand is poured into the box in which it stays until it is cool enough.

Apple estimates that each Liam can take apart 1.2 million iPhone 6 units in a year (Apples sells over 200 million phones annually), and it currently has two lines running – in California, and the Netherlands.

[13] http://www.thm-recyclingmaschinen.de/nc/en/recycling-machines/tqz-turbo-crusher/thank-you-tqz.html
[14] https://www.andritz.com/products-en/group/recycling/cross-flow-shredder-qz
[15] https://zenrobotics.com/references/baetsen/
[16] https://www.apple.com/environment/pdf/Liam_white_paper_Sept2016.pdf

3.5 Wet sorting

3.5.1 Gravity separation table / wet

Non-ferro metals such as copper and aluminium can be further separated by using their difference in density using the "shaker table". A vibrating inclined table, with ridges alongside the surface, is fed with uniformly sized particles suspended in water. The vibration allows lighter materials (aluminium) to jump over the ridges, follow the inclination, for collection at the bottom end, whereas the more dense materials (copper) remain behind the ridges and are fed to the side of the table. In the most lower point a mix of materials may still occur, which may be minimised by the table settings, particle size of the feed, etc.

3.5.2 Sink-Float

Parts are shredded t(or ground) to similarly sized pieces and placed in a tank containing a liquid. Plastics with a density less than the liquid will rise to the surface and can be skimmed. Plastics with higher densities will sink to the bottom and can be removed using an auger.

Plain water will suffice sorting polyolefins (PE, PP) from the rest (possibly containing other floating materials such as woods, foams, etc. if not sorted before), but for most other plastics a saline solution, with a tightly controlled density, allows sorting plastics with densities higher than water. Usually multiple baths are applied, allowing sorting in three or more categories of waste. Reagents are applied to make plastics less hydrophobic, resulting in better sorting.

The particle size should be very even to allow a good sorting. The difference in density for proper sorting is around 0.2 g/cm^3.

Nonetheless, float-sink sorting is complicated as the density of even a single plastic type can vary according supplier. Another complication is the presence of bubbles (foams) that may include denser particles, incomplete separation of plastics, and presence of various additives (flame retardants, fillers, etc.) that affect the density of a polymer significantly: Talc-filled PP (15%) has a density similar to that of ABS and similar applications, but should not end up in the same end treatment. This method is appropriate of the difference in densities is smaller and needs finer control. Also soft PVC has densities similar to plastics with which it should not be mingled.

In many cases the light fraction has a large share of carbon black pigmented plastics which are difficult to sort in downstream NIR sorting. On the other side, the heavy fraction often contains brominated plastics for which little interest exists. Both result in challenging economics for this process[17]. Another drawback is that the particles have to be dried before other processing steps commence.

3.5.3 Flotation

In flotation a mixed stream of fairly similarly sized particles are mixed with a reagent in a water bath which, depending on the properties of the materials, make them more hydrophobic (forcing them to float to the surface when air bubbles are introduced) or hydrophilic (remain suspended). The floating particles can be skimmed off.

A major application of this technique is the sorting of PET from PVC (difficult if based on density alone), or for separating styrene-based Plastics (ABS, HIPS) and PP from other plastics. The particles have to be sufficiently small in order to rise with the air bubbles.

3.5.3.1 Sink-float combined with flotation

The combination of both sink-float and flotation can improve the yield [18].

3.5.4 Magnetic density separation – MDS (emerging)

A fairly recent addition to sink/float technology is the magnetic density separator: It is a liquid (water) bath containing iron (nano) particles, in which a mixed stream of particles is fed from one side, and an electric current is applied: This results in a bath with stratified density which allows up to six groups of plastics to be sorted in one process.

[17] REMIX – Interim reports 1 and 2, Call for tenders N° 154/PP/ENT/PPA/12/6476, p.35
[18] http://www.protec-srl.com/how-it-works/?lang=en

3.5.5 Hydro cyclone & centrifugal sorting

The hydro cyclone uses centrifugal forces (spinning vortex) to sort materials on the basis of their specific density: Heavier particles are forced outward whereas lighter particles remain in the middle of the vortex. It is considered a simpler yet more effective form of sink-float sorting.

As the vortex applies a force 100-2000 times the gravity acceleration, the process is characterised by high settling rates, fast sorting and high load. There are variations in drum shape and inclination, fluid characteristics and feed characteristics.

3.6 Dry sorting

Sorting is mainly done on the basis of material properties and hence there are technologies particularly suited to detecting metals, plastics or other materials.

3.6.1 Magnetic sorting

Magnetic sorting is the removal of ferromagnetic metals (that are drawn to a magnetic field, like iron, steel, nickel and cobalt and various man-made magnets) and magnetic materials from a mixed waste stream by permanent magnets or electromagnets.

Most ErP contain significant shares of ferrous metals (iron, steel and alloys): Washing machines contain 35-45%[19] and laptops may still contain some 10 % ferrous materials.

The particles are ideally properly liberated so that no ferro/non-ferro combinations remain, which contaminate either the sorted or remaining stream. The presence of ferrous particles in the remaining fraction (if sent to non-ferro recycling this is unfortunate, but has limited environmental consequences).

The opposite however, of non-ferrous fractions ending up in the ferrous stream is more damaging as these fractions could contain valuable precious metals, copper, aluminium or other light metals which are considered lost when they end up in a ferro-smelter (not available for economic recovery).

Problems in liberation and subsequent sorting can be ferro/non-ferro combinations that are difficult to separate such as copper windings packaged in soft steel laminates (in an electric motor), bronze bushings (primarily Cu with 10-30% Sn) and brass parts in sanitary water equipment (typically 55-70% Cu and 45-30% Zn) connected to steel parts.

3.6.2 Eddy-current sorting

Eddy-current sorting is the removal of non-ferrous metals like aluminium, copper, magnesium, etc. that are repelled by an externally applied magnetic field (diamagnetic) or exhibit a weak attraction to a magnetic field (paramagnetic) from a mixed material waste stream.

The electric field is applied underneath a conveyor belt moving the particles to be sorted and the responsible magnetic force either pushes the material away from the belt or allows it the weakly remain attracted. Either way, carefully positioned bins catch the repelled parts for subsequent processing. Polymer parts or other inert materials that are not affected by the currents have their trajectory unchanged.

Downstream sorting within the non-ferro fraction is also important as many metals are incompatible: Aluminium in a copper smelter reports to the slag phase and is not used again as aluminium (although use of the slag in Cementous products is possible). Copper dissolves in aluminium smelting and is lost.

Eddy-current can be used to sort within non-ferrous materials e.g. sort Al and Cu: As these materials have different densities and conductivities the resulting trajectories are different. Other technologies for sorting non-ferro are based on differences in density (moving jig, gravity separation table), electro conductivity, or x-ray imaging.

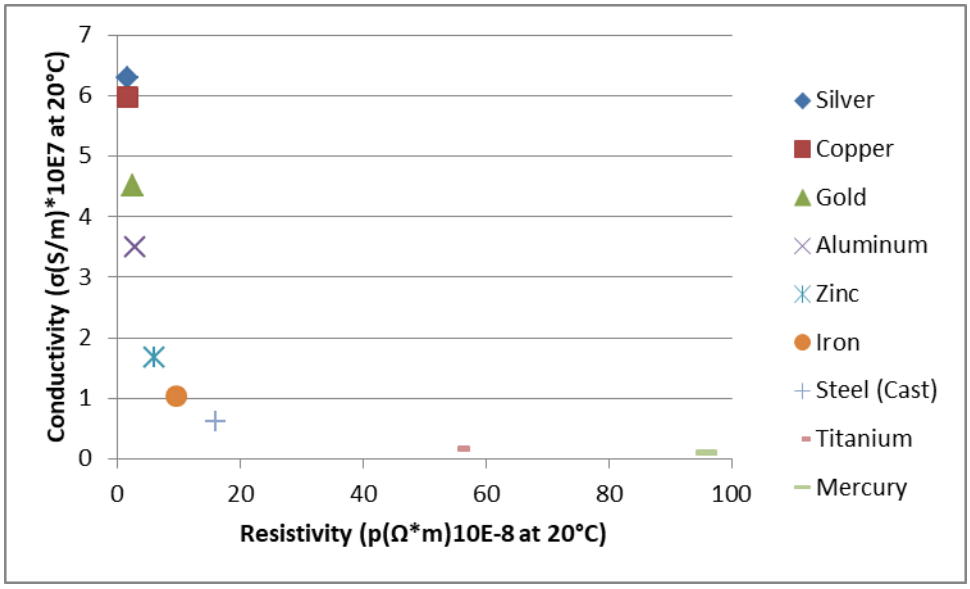
Similar to magnetic sorting proper liberation is key to avoid cross contamination of sorted fractions. An example where liberation of for instance copper and aluminium is challenging are heat exchangers where aluminium fins are attached to a copper tube. In shredding (hammering) processes these two ductile materials are often hammered into a single piece of metal, and not properly liberated. Further , finer, shredding is then required to allow sorting of the materials.

[19] Table 11, JRC reference value study 2016

3.6.3 Induction sorting

Induction sorting allows sorting of metals that cannot be separated sufficiently in magnetic or eddy-current separators. The main measuring criterion is the electrical conductivity of the material. Antennas positioned under a belt or chute emit electromagnetic waves. Particles that traverse through this field change the EM waves and a sensor connected to a computer detects the signal difference for each individual particle, which makes it possible to accurately sort particles with conductor thicknesses as small as 1mm. The separation is performed by either jets of pressurised air, or small mechanical 'kickers'.

Figure 4. Conductivity & resistivity of selected metals



The technique allows identification of a metal particles in a stream of non-metal particles, or allows sorting on the basis of the field characteristics of the particles (to separate stainless steel from copper etc.).

3.6.4 Screening

Screening is the sorting of commingled waste on the basis of particle size and density. A sieve and a trommel screen are examples of simple sorting by size of the particle: larger particles fall through larger openings in the screen. Trommel screens allow internal transport of the waste flow and can screen multiple fractions (= sizes) by installing different screen openings in succession in a trommel.

Ballistic separators also apply a screening bed, but add an inclined position and vibration. The smallest particles fall through the openings in the bed, the heaviest particles collect at the bottom end of the bed, whereas the lighter particles collect at the top end of the bed, and thus allows separating three fractions in a single station.

3.6.5 Gravity separation table

The gravity separation table is applied in the sorting of a feed that has similar geometric characteristics and only a small difference in density. The table is inclined and vibrating, and a continuous flow of pressurised air is blown through the bed, fluidising the particles. The light material stratifies on the top layer and moves with the fluidised flow, and the heavier materials remain closer to the bed surface and follow the ridges. As the table is inclined and vibrating and equipped with ridges, the lighter particles remain relatively fluidised and stream downwards, whereas the denser particles are collected by the ridges and stream sideways.

Instead of dry sorting, the gravity separation table can also be fluidised using water if air is insufficient as fluidizer.

3.6.6 Air cyclone

Flakes with a fairly similar size can be sorted using a vortex of air which pushes heavier particles to the sides whereas lighter particles remain in the middle.

This technique is mainly applied to sort various non-metallic materials (plastics versus non plastics) or similar materials with different densities (plastics of various densities).

3.6.7 Air classification

In this technology a blast of air is blown through a steady stream of falling mixed plastic particles: The more dense particles continue falling, whereas the lighter particles (like foams) are blown into a separate collector. This method is more appropriate if there are large differences in densities.

3.6.8 Triboelectric and electrostatic sorting

Electrostatic sorters have been used in the plastics industries for decades. The plastics are charged by ion bombardment and a slight positive or negative static charge is imparted tot the particles or flakes. The particle with the higher dielectric constant is charged positive against the particle with the lower constant. An electrostatic field is applied across a falling stream of particles, which is then separated into positive and negatively charged flakes. Differences in (tribo)electric/electrostatic technologies are related to the means used to convey the charge (particles rubbing against each other, spinning drums, fluidized-bed, vibrating chute, corona discharge, etc.)

Electrostatic sorting can sort plastics of similar density: It has been used to separate PET film from PET flake and HDPE from LDPE with purity greater than 90%.

3.6.9 Spectroscopic sorting

Spectroscopic sorting relies on the interaction of matter and electromagnetic radiation (this excludes static electric and magnetic fields).

3.6.9.1 Visible light / colour sorting

Originally developed for the glass recycling sector, this technology allows sorting particles on the basis of reflection (colours) or transparency (to distinguish transparent from pigmented particles) exposed to the visible light spectrum.

An electronic camera determines the colour of particles / flakes in a mixed waste flow. Software calculates the position and location of the particle and at the end of the conveyor belt it is either dropped or blasted, using an air jet, into a different container. A rather uniform particle size and density is required so that trajectories are predictable. Sorting in 2 or 3 streams is possible. The technology can also be applied to identify and sort 'green' circuit board fragments from a stream of mixed particles.

Dirty or coated/covered particles may not be properly identified and could lead to contaminations or lower yields.

3.6.9.2 Polarized light

Polarization can be used as sorting process when white light enters a material that polarizes the light. Personnel or a machine equipped with polarized lenses can detect the polarized plastic and remove it. It is in particular useful to sort PET from PVC as these plastics can have the same densities, but polarized light is simpler to apply than X-ray attenuation or sink-float.

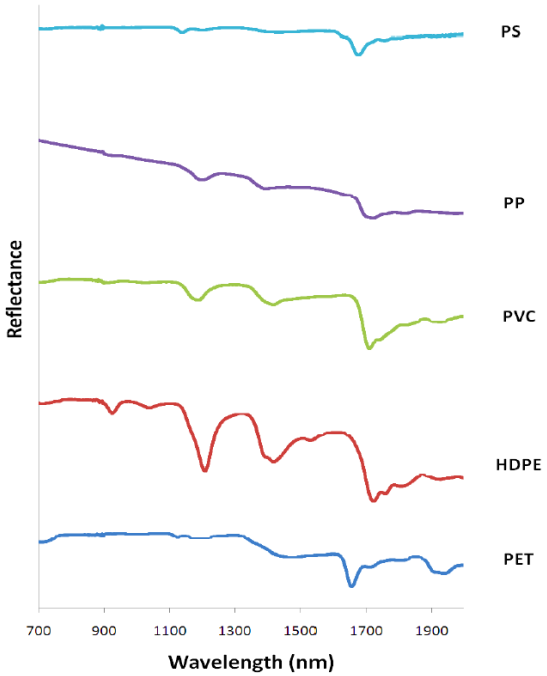
3.6.9.3 X-ray transmission imaging – XRT

Particles are exposed to X-rays that penetrate the product and are picked up by a sensor. As denser areas (at atomic level) will absorb some of the X-ray energy, a pattern emerges at the sensor. X-ray is especially suited to detect 'heavier' atoms like halogens and was first applied to sort PVC from mixed plastic packaging waste. The technology also allows identification of halogenated (brominated) substances like flame retardants. The exact type of flame retardants is however not registered, nor the exact amount of retardants. XRT detection is not able to remove plastics with less than 4% of additives.

3.6.9.4 Near-infrared spectroscopy - NIR

When illuminated by near-infrared radiation NIR (800 to 2500 nm), different materials exhibit different reflections over the wavelength spectrum. These reflections are picked up by an electronic line-scan camera and analysed thereby also calculating the position of the flake on a moving conveyor belt. As with other sorting technologies a blast of pressurised air diverts the flake into a designated bin.

Figure 5. Reflectance spectra of five resins[20]



Usually NIR is applied in several stages to deal with a mixed stream, whereby each stage removes a single type of plastic. Plastics using carbon black as pigment do not reflect sufficiently to allow proper identification and are often removed in the first stage. As NIR is reflection based it cannot 'see' through materials covering other materials, as with labels, coatings, dirt, paint, etc.

Most near infrared sorting system can selectively sort HD polyethylene from LD polyethylene (LDPE, HDPE) or polypropylene (PP), and PET (polyethylene terephthalate) from polyamide (PA), polycarbonate (PC). Moreover, the system can also distinguish between polystyrene (PS) and ABS. NIR can also detect several PVC types.

Modern NIR equipment can now also distinguish (besides the standard 7 packaging plastics) several engineering plastics (PC, PBT, PUR, POM), blends, and BPPA flame retardants.

[20] Hamed Masoumi, Seyed Mohsen Safavi, and Zahra Khani , Identification and Classification of Plastic Resins using Near Infrared Reflectance Spectroscopy, World Academy of Science, Engineering and Technology International Journal of Mechanical and Mechatronics Engineering, Vol. 6, No 5, 2012.

Figure 6. Technical data for LLA Instruments NIR equipment, adapted for sorting WEEE[21]

Technical data

NIR technology	KUSTA1.9MPL-24V	KUSTA1.7MSI	KUSTA1.9MSI
Input material	Shredded plastic chassis of electro- and electronics devices (PC, monitor, small appliances)		
Sorting module	idEwaste	idEwaste (Flakes)	idEwaste (Flakes)
Sorting width	400 - 2800 mm	800 - 2000 mm	800 - 2000 mm
Sorting speed	Max. 3 m/s (Depending on fraction size)	Max. 1 - 2,5 m/s (depending on fraction size)	Max. 3 m/s (depending on fraction size)
Fraction size	> 30 mm	3 - 30 mm (depending on sorting width)	
Spatial resolution	= Sorting width / 64	= Sorting width / 318	= Sorting width / 192
Plastics	ABS, PS, PA, PBT, PC, PE, PP, PET, PVC, PMMA, PUR, POM		ABS, PS, PA, PC, PE, PP, PET, PVC, PMMA, PUR, POM
Mixed plastics (Blends)	PC+ABS, PPE+SB, PVC+ABS	PC+ABS	PC+ABS
Flame retardants	ABS+TBBPA, ABS+TBBPAep, PS+TBBPA, PS+TBBPEep	ABS+TBBPA, ABS+TBBPAep	ABS+TBBPA, ABS+TBBPAep, PS+TBBPA
Impurities		Paper/Cardboard/Wood	

Another module is adapted for recognition/sorting of circuit boards.

Figure 7. Technical data for LLA Instruments NIR equipment, adapted for sorting PCBs[22]

Technical data

NIR technology	KUSTA1.9MPL-24V	KUSTA1.9MSI
Input material	Shredded plastic chassis and printed circuit boards from electronic devices	
Sorting width	400 - 2800 mm	800 - 2000 mm
Sorting speed	Max. 3 m/s	Max. 3 m/s
Fractions size	> 30 mm	2 - 30 mm

Identification of the following fractions

Printed circuit boards	Phenol- and epoxide resin saturated printed circuit boards
Plastics	ABS, PS, PA, PBT, PC, PE, PP, PET, PVC, PMMA, PUR, POM
Mixed plastics (Blends)	PPE+SB
Impurities	Silicone foils (e.g. from mobile phones, PC keyboards), melamine-formaldehyde resines (MF) of e.g. special junction boxes, liquid crystal displays (LCD)

Such NIR sorters have been developed for mixed waste streams downstream a shredder. The picture below shows shredded (THM crusher, rotating chain mill) material from power supplies / battery chargers. The flakes of (low grade) printed circuit boards are easily visible, as well as clots of copper winding wire (from voltage transformers).

[21] https://www.lla-instruments.com/process-analysis/waste-sorting-recycling.html
[22] https://www.lla-instruments.com/process-analysis/waste-sorting-recycling.html

Figure 8. Mixed flow of shredded power supplies / battery chargers

The identification of black polymers which contain about 0.5 to 3 mass percent soot or black master batch is still an essential problem in recycling sorting processes based on near infrared spectroscopy (NIR), because small amounts of carbon black or soot absorb all light in the NIR spectral region. And black coloured plastics are widely used throughout ErP.

3.6.9.5 Mid-infrared spectroscopy - MIR

Spectroscopy in the mid infrared spectral region (MIR) offers a possibility to identify black polymers. Mid-infrared MIR spectroscopy is an efficient method for spectrally characterizing black plastic parts and assigning them to the corresponding polymer types. Using the LITRAN system (photon up-conversion) should allow economical sorting of black plastics, since measuring rates of several thousand measurements per second can be achieved. The sorting of normal non-black household plastics can also be carried out with the LITRAN system[23, 24]

The spectral range of the LITRAN system can also be adapted to detect flame retardants in engineering plastics.

3.6.9.6 Mid-infrared thermography MIR-T

Mid-infrared thermography is a technique based on analysis of the reflection (heat dissipation pattern) of particles exposed to medium infrared radiation (700 – 4000 nm). It is particularly useful for detecting paper/cardboard types in a mixed waste stream. The sensor detects heat dissipation depending on the material and thickness of the material, to distinguish the paper of cardboard, the basis weight of the paper, as well as different qualities of paper / cardboard together.

3.7 Hybrid sorting

Today, there is not one single technology "that does it all": Most plastic waste sorters combine multiple technologies, depending on the waste fractions being treated and the requirements for the end-product.

Most often NIR is used for sorting dry flakes, but the drawback is NIR cannot sort most black plastics. X-ray based sorters can detect brominated substances. Visible light sources can easily and quickly sort various plastics, but not if contaminated with coatings, labels, dirt etc.

[23] W.Becker, K.Sachsenheimer, M.Klemenz; Detection of Black Plastics in the Middle Infrared Spectrum (MIR) Using Photon Up-Conversion Technique for Polymer Recycling Purposes, 8 September 2017 [www.mdpi.com/2073-4360/9/9/435/pdf]
[24] O.Rozenstein, P.Eldon, J.Adamowski, Development of a new approach based on midwave infrared spectroscopy for post-consumer black plastic waste sorting in the recycling industry, Waste Management Volume 68, October 2017, Pages 38-44

Manufacturers have begun to offer 'hybrid' sorting stations that combine multiple (dry) techniques, not only spectroscopic, but also magnetic/eddy-current sorters etc.

One should also not neglect the importance of pre-treatment of the waste stream: A steady flow of dry, uniformly distributed particles, of similar size and weight, is important to achieve the highest sorting yields: Diverging weights, shapes etc. affect the trajectories and result in wrong sorting.

A special case of hybrid sorting is the robotic sorting station by Zen Robotics.

3.7.1 Robotic sorting

Robotic sorting as commercialized today employs an array of abovementioned sorting techniques with robotic manipulation of objects. Current systems have multiple sensors connected to a processor that decides on the appropriate action[25]:

- NIR – near infrared spectrum sensors;
- 3D sensor system;
- Hi-res RGB camera;
- Imaging metal detector;
- VIS – visual light spectrum sensor;

These technologies allow the robot to correctly position the gripper of an arm as it 'knows' how to best approach the object and puts it in one of the maximum eight fraction bins per station (4 bins per arm, and max. 3 arms per station).

Robotic sorting is currently most often applied to sort mixed construction and demolition waste, but it can be tuned to process other wastes as well.

3.8 Emerging sorting technologies

3.8.1 XRF - X-ray fluorescence (emerging)

Energy dispersive X-ray fluorescence (EDXRF) analysers expose particles to a high energy radiation such as X-ray, but also gamma rays are possible) and detect the spectrum of X-rays emitted. Each element has a different pattern.

This technique also allows quick detection of presence of heavy metals in the 10-100 ppm range such as cadmium, lead, chromium, antimony, tin, mercury, bromine (and chlorine) and other toxic metals. Sorting is again based on pressurized jets that alter the trajectory at the end of the conveyor belt.

XRF seems able to quantify the Br element contains in polymer samples, and the applications of this technology in continuous sorting are new and needs improvement in term of speed of acquisition.

3.8.2 RAMAN laser spectroscopy (emerging)

Raman spectroscopy relies in scattering of monochromatic light from a laser in the visible, NIR or Near UV range. It does not rely on the measurement of absorbed or reflected radiation, but instead uses the Raman scattering effect.

Although initially suffering from the same drawback as NIR in that it could not be used to analyse black plastics, recent advancements have improved the technology. Besides black plastics the technique can also detect Plastics that contain brominated flame retardants. It can be combined with laser fluorescence.

The technology is however 2-3 times as expensive as NIR.

3.8.3 LIBS - Laser induced plasma spectroscopy (emerging)

Laser induced plasma spectroscopy LIPS (or laser-induced breakdown spectroscopy, LIBS) uses a laser beam to evaporate a tiny amount of the sample and excite it to a plasma. The light emitted from the plasma (spectral lines) is analysed and reveals the elemental composition of the material.

It can detect the presence of certain atoms, like chlorine or bromine, or plastics with mineral fillers, but cannot detect the different polymer types. LIBS can recognize light atoms (which is not possible with XRT), brominates elements (not possible with NIR), and the different types of brominates flame retardant (which is not possible with XRT).

[25] www.zen-robotics.com

LIBS allows the detection of Br, is also able to give information on the type of brominates flame

retardant. But, the main limitation for continuous sorting is the time for acquisition. At the moment there is no industrial application.

3.8.4 TERA Hz - Terahertz spectroscopy (emerging)

Terahertz is located between microwave and infrared radiation in the electromagnetic spectrum and can penetrate materials that are opaque to visible and IR radiation. As the radiation (wave) passes through plastics, the material absorbs certain portions of the terahertz wave, creating an absorption signature. The technique can be applied to black plastics as well. Different plastics, regardless of colour, have specific absorption signatures.

3.8.5 TRA- Polymer tracing (emerging)

Polymer tracing is the identification of a material by an added tracer with a specific 'signature'. A small concentration of the tracer, that exhibits specific luminescence properties after irradiation (can be X-rays), is added to the polymer batch.

The candidate plastics for tracing are those which are difficult to sort using conventional techniques such as black coloured plastics, or those with densities close to plastics with which they should not be mixed.

The tracers currently investigated are often rare-earth oxides such as Y_2O_3, CeO_2, Nd_2O_3, GdO_3, Dy_2O_3 and Yb_2O_3, in concentration levels of 100 ppm.

Deployment of such a tracer system also requires significant organisational and normative hurdles to be overcome.

3.9 Final treatment / processing

With final treatment is meant the last process (or series of processes that can be viewed together as they are intricately linked) that returns a secondary material to a state in which it can be reused again for its original purpose.

3.9.1 Plastics

3.9.1.1 Depolymerisation/ chemical recycling

Depolymerisation is the breaking of the chemical bonds between the polymer-chains, reducing them to the monomer state. This allows easier separation of different plastics and reuse as feedstock for new polymerisation processes.

Two processes are highlighted below:

Creasolv (emerging)

In the Creasolv process, patented by Fraunhofer Institute, proprietary solvents are used to selectively dissolve the target polymer. After the cleaning from impurities the desired polymer precipitates by adding the CreaSolv® precipitation formulation. The ingredients of the formulations are commercially available.

The Creasolv process allows removal of most BFR types from styrene WEEE plastics (ABS, HIPS). The reduction in the impact strength of the Creasolv recyclate is an issue[26].

Centrevap (emerging)

The 'Centrevap' process has been developed to remove insoluble additives down to around 0.5 micron provided that the density of the additive particles is significantly greater than 0.95 g/cm3.

For example, the process can remove antimony trioxide additive very efficiently. However the solvent combination used for the Centrevap process trials did not allow the removal of brominated flame retardants to the standard set for this project because the BFRs were partially soluble in the chosen solvent[27].

Ioniqa (emerging)

[26] Keith Freegard, Gayle Tan & Roger Morton – Axion Recycling Ltd, Develop a process to separate brominated flame retardants from WEEE polymers, Final Report, Project code: PLA- 037, for WRAP, May 2006

[27] Keith Freegard, Gayle Tan & Roger Morton – Axion Recycling Ltd, Develop a process to separate brominated flame retardants from WEEE polymers, Final Report, Project code: PLA- 037, for WRAP, May 2006

Like CreaSolv is Ioniqa a process in which a polymer, in this case PET, is dissolved, whereby the chemical bonds are removed by a catalyst and the original monomer is the beginning of a new, like virgin, recyclate.

The depolymerisation process takes place at a relative low temperature and using a magnetic field the catalyst is recycled and reused. The catalyst used results in higher concentration of monomers compared to traditional recycling processes through higher selectivity and higher plastics conversion.

The process can in principle be modified to treat other types of plastics and is still under development.

3.9.1.2 Compatibilization

Compatibilization is the process of enhancing the product qualities or properties of a mixed blend of plastics, by adding an additive called compatibilizer, or compatibilizing agent.

It is currently being looked at as a process to improve the quality of polymer batches that are not 100% pure, i.e. is contaminated with other plastics that have detrimental effects on the final product qualities.

Compatibilization cannot solve all problems and make totally incompatible plastics compatible again. Instead it should be regarded as a process performed by compounders who create generic or bespoke batches of plastics, by (in case of recyclates) adding compatibilizers, modifiers (that enhance strength or stiffness), dispersion agents (to better distribute impurities), and conventional additives such as colorants, flame retardants, fibres, etc.

Compatibilization is mostly applied to PP-PE plastics.

BOSS

BOSS[28] is the abbreviation of "baffled oscillation separation system", a process developed and marketed by the UK-based *impact-solutions*. It is designed to be suitable for all sizes of recyclers, by separating mixed rigids of PE from PP, using only water, to give two 100% pure Polyolefin outputs, split into two fractions of 90/10 PE & PP.

PE & PP purities as high as 95% are obtainable, with a third stream comprising 100% of the heavier substances. BOSS is equally able to process material such as PP contaminated with nylons, or even artificial grass.

3.9.2 Metals

3.9.2.1 Hydrometallurgy

Hydrometallurgy, or leaching, puts metals into a low-temperature aqueous solution, reaching +90 °C under atmospheric conditions, and +200 °C when under pressure for separating different elements and compounds. Various processes exist, based on either acid (low pH) or basic (high pH) aqueous solutions. Hydrometallurgy generally first increases the entropy of metals, before recovering the ions in solution with a significant input of energy for lowering the entropy again.[29]

Hydrometallurgy in this context means the whole infrastructure revolving around the dissolving of metals in solutions in order to extract primary metals and other metals.

Several companies and institutes are working on small-scale hydrometallurgical solutions to treat e-waste and recover REE and precious metals from electronics.

3.9.2.2 Pyro metallurgy

Pyro metallurgy, also known as smelting, uses high temperatures (sometimes above 2000 °C) to drive chemical reactions as well as melting (just remelting metals) or smelting (chemical conversion from compound to metal) processes. The processes vary depending on the metal and materials being smelted. The advantage of smelting is that it concentrates metals into metal alloys or similar, therefore decreasing their entropy.[30]

Pyro metallurgy in this context means the whole infrastructure revolving around the smelting of metals in ovens and furnaces in order to recover primary metals and other metals.

If the product contains multiple recoverable metals, such as a printed circuit board that may contain copper, gold, palladium, silver, etc., the products undergoes a series of smelting operations, sometimes combined with hydrometallurgical processes, to recover its value.

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[28] http://www.impact-solutions.co.uk/impact-recycling/boss/

[29] UNEP (2013) Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the Inter-national Resource Panel. Reuter, M. A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C.

[30] UNEP (2013) Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the Inter-national Resource Panel. Reuter, M. A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C.

3.9.2.3 Basic metal infrastructure

The processing of recyclate streams currently mostly occurs on the back of large-scale production of base metals with compatible thermodynamic properties, i.e. carrier metals:

1. Fe: in BOF and EAF;
2. Al: remelt/refine
3. Ti: remelt
4. Mg: hydrometallurgic, remelt
5. Li: hydro- & pyrometallurgy
6. RE: hydrometallurgy
7. RE: Special battery recycling
8. Sn: smelt/refine
9. Cu/Ni: smelt/refine
10. Pb: smelt/refine
11. Zn: RLE/fume
12. Ni/Cr: stainless steel processing
13. Mn: TRIP steel austenitic

Materials that enter these processes may exit either in the carrier metal (dissolved, as alloy), as intermediate compounds in dust/slime/speiss/slag for further recovery if valuable and economic, or as compounds that cannot be further recovered. The elements are thus either recovered as element (as/in carrier metal or from compound), tolerated in carrier element or compound (element in alloy, not detrimental to carrier metal or end product, like slag for cement production) or simply lost (no economic recovery possible and/or not functional in the end product). These two latter functions are not recycling for the same purpose and result in loss of the material (it does not help to avoid consumption of virgin materials).

When recycling a product containing metals it is therefore important that the metals end up in the correct carrier metal infrastructure, as otherwise they can be considered 'lost'. These are the most important 'lessons' that can be learnt from the metal wheel pictured below:

In steel recovery: Copper is detrimental to steel properties, cannot easily be removed from the carrier metal and remains either present in the carrier metal or is lost as compound. Aluminium and several other light metals/metalloids such as magnesium and silicon ends up as oxides in the slag, and may be used in cement production. They will however not return to their metallic form for reuse and are therefore considered lost. REE report to compounds but are not economically recoverable. REOs report to the slag.

Benign to the carrier metal (up to certain content) are nickel, cobalt, silicon, molybdenum, titanium, chromium, vanadium, wolfram, tantalum, niobium. There is no immediate need to remove these metals from the fraction sent to the smelter.

In aluminium recovery: Precious metals like gold, silver platinum and palladium report to the carrier metal aluminium but are not useful alloying elements and thus considered 'lost'.

Steel and copper can be alloying elements and acceptable to a certain degree. Both are however not returned to their metallic form and their function depends on the exact alloy. REOs report to the slag.

In copper/nickel recovery: Copper/nickel smelting allows the recovery of many precious or noble metals such as Au, Pt, Pd, Ag, etc. Also cobalt

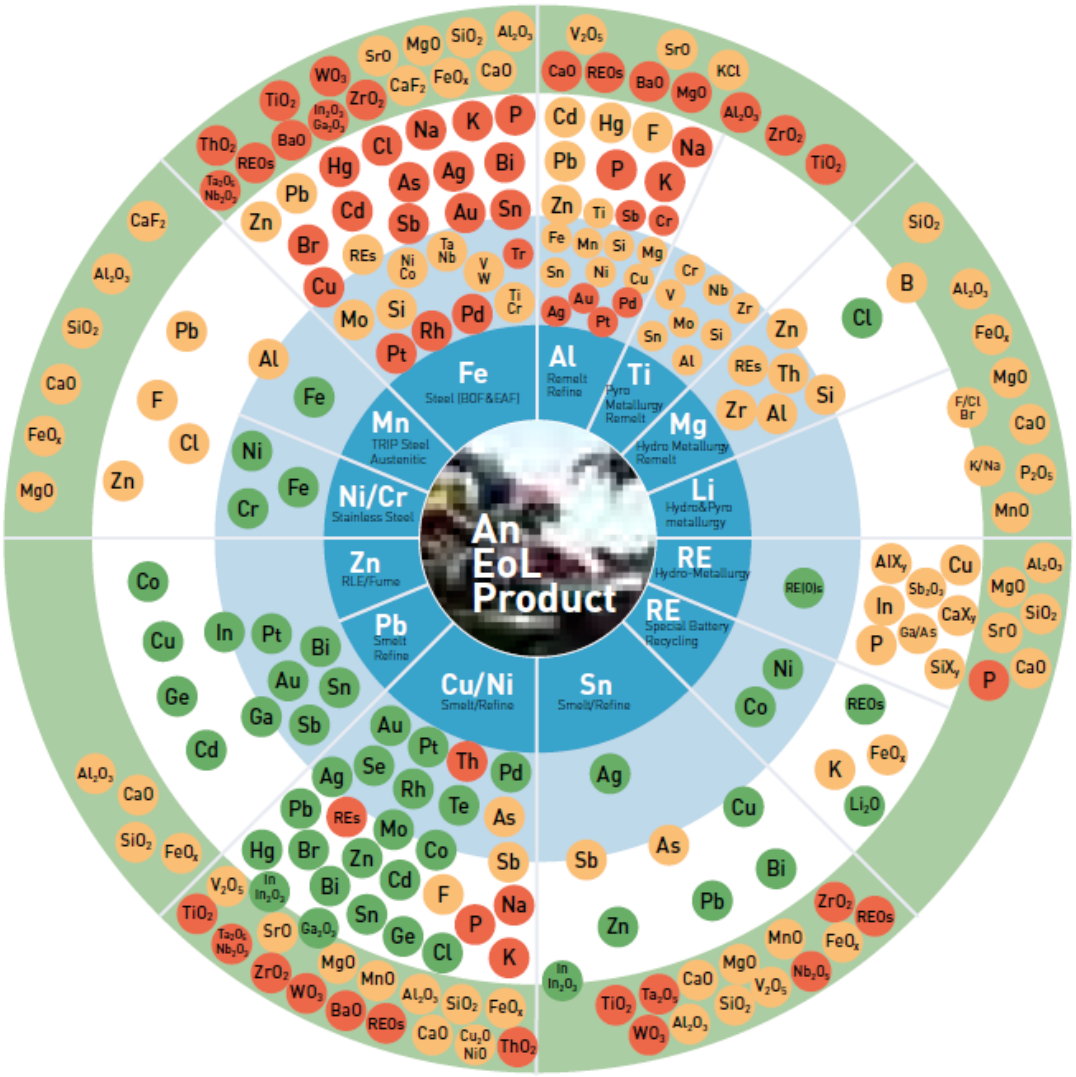
Both steel and aluminium report to the slag as oxides, and may be used in cement production. They will however not return to their metallic form for reuse and are therefore considered lost. REEs however report to compound or slag, as REO, and cannot yet be economically recycled.

Special battery recycling: Special battery recycling (usually involving some hydrometallurgy at some point) can recover Cobalt and Nickel (both are also recoverable in Cu/Ni processing), certain rare earth oxides (REO) and lithium oxide. (e.g. Recupyl SAS). Lithium cannot be recovered in Fe/Al/Cu processing routes.

Hard metals / refractory metals: Recovery of tantalum and wolfram from spent tools is possible, but the recovery from small electronic scrap (tantalum capacitors, wolfram filaments in heaters) is not compatible with the Cu/Ni infrastructure, nor the Fe-infrastructure and both tantalum and wolfram end up as unrecoverable oxides in the slag.

Still, vibration motors in smartphones (but also in darts) contain significant amounts of tungsten and can be made separable, so that dedicated processing can take place.

Figure 9. The "metal wheel" reflects the destination of different elements, as a function of interlinked metallurgical process technology[31]



Society's Essential Carrier Metals: Primary Product Extractive Metallurgy's Backbone (primary and recycling metallurgy). The metallurgy infrastructure makes a "closed" loop society and recycling possible.

Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy) Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).

Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy) Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).

Mainly to Benign Low Value Products Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

El **Mainly Recovered Element** Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.

El **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost** With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag/slag also intermediate product for cement etc.).

El **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.

[31] Fig. 4, p.30 in UNEP (2013) Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M. A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C.

3.10 Recovery processes

3.10.1 Material recovery

3.10.1.1 Recycling

Recycling is the most prominent form of material recovery (apart from reuse) and has been described in the previous sections.

3.10.1.2 Composting

Composting is, according to the definitions in the 2008 Waste Directive actually a form of recycling, but for ErP, the use of fully compostable products is rare. And it is not to be expected, at least not in the near future, that compostable parts of products are easily recognised and separated from other, non-compostable fractions in the generic waste treatment facilities.

In addition, the Council of the European Union recently proposed to define the organic output from mechanical biological treatment (MBT) as recycling and let it count towards the recycling targets, but the composting sector rejected this proposal because the product of MBT facilities does not meet composting standards. After pre-sorting unsorted municipal waste, drying and mechanical separation, an organic fraction remains, which then undergoes a biological treatment. But the quality of the organic output from MBT facilities is often not good enough for agricultural use. The impurity levels do not meet the European standard as proposed in the European end-of-waste report for biodegradable waste. [32]

So, if even the output of organic municipal waste should not count as compost, it is hard to expect that the output of a WEEE treatment facility does meet the quality requirements. In this study composting is considered a recovery process, diverting materials from incineration, backfilling or landfill, but not recycling which assumes materials can be reused for their original purpose.

3.10.1.3 Backfilling

Backfilling means "a recovery operation where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials" [33].

Backfilling is thus considered a form of recovery if it replaces other materials prepared to fulfil a particular function. Associated with the term backfilling is the notion of a permanent placement of the material on/in particular sites; The material is not intended to be returned to the economic material cycle. There is no specification of the type of waste other than it has to be suitable, meaning appropriate for the purpose and without causing environmental harm.

Backfilling is a recovery process in which a waste material is:

- used instead of other virgin materials,
- suitable for the application (complying with the necessary properties for the particular performance), and
- applied in a process of landscaping engineering.

3.10.2 Energy recovery

3.10.2.1 Gasification / syngas

Gasification or syngas production is a recovery process whereby the polymer is broken down to chemicals that can be used as fuel for other processes. The benefit of gasification, as opposed to plastic waste incineration (with heat recovery), is that much more applications are possible for the syngas created and the recovery of energy is much cleaner.

Certain gasification processes can also be used to remove/recover bromine from plastics with brominated flame retardants, and therefore have a recycling element.

3.10.2.2 Incineration with energy recovery

As defined in Waste Directive 2008/98/EC, Annex II, Recovery operations.

[32] http://www.orgaworld.com/mbt-not-organic-recycling
[33] Commission Decision 2011/753/EU.

3.11 Outlook on recycling/recovery technology

Although the preceding sections show a vast and diverse array of technologies for preparing waste products and their materials for reuse in possibly its original purpose, it is incorrect to think that the problems in recycling of ErP are solved. No matter how many technologies are available, there will always be trade-offs and losses.

A simple example: A smartphone contains gold in the various electronic bits scattered around in the tiny housing. Full recovery of gold is indeed possible, however at the expense of the possible recovery of the plastics, steel, aluminium magnesium, rare earth elements and many other elements for which economic recovery is not possible after being processed in a copper/nickel smelt-refine facility. Simply put, one can recover most of the elements at modest recovery rates, or recover few elements at the highest rates, but not all of the elements at the highest rates.

Losses are also unavoidable in each step in liberation and sorting, as parts are seldom fully liberated, as sorting systems cannot handle correctly all possible variations in particles and because of a certain degree of randomness in such operations.

To reduce the losses, increase the yields and avoid the need for trade-offs, treatment technologies are continuously developing, to better deal with modern products and to improve the economics of the sector.

The section on 'emerging technologies' shows that many developments are aimed at solving the plastic sorting problem, using a form of spectroscopic technology to better (quicker, cheaper, with higher quality) identify and sort plastics. Nonetheless it is expected for the foreseeable future that still a sequence of technologies is needed to arrive at usable plastic waste fractions, each with unavoidable losses.

Not so visible but just as important are the developments in the metallurgical field (see 'Final treatment'), where various processes are developed to better (cheaper, with higher quality) liberate and sort metals and compounds, especially rare earth elements, precious metals and other specialty metals (hard metals like tungsten and tantalum). As the basic metallurgical processes are relatively well understood, the developments are mainly optimisations of known reactions and processes.

Developments in mechanised liberation should be mentioned as well: shearing is a well-established process and no innovations are expected. Rotating hammer mills (with rotating chains) are more recent and mimic manual liberation with a handheld hammer. Most advanced is robotic disassembly whereby robot arms and tools completely replace manual labour, even mimicking the fine motor skills required to loosen screws etc.

Robotic sorting will undoubtedly become more significant, as pattern recognition software and *machine learning* advances and allows machines (robots) to better recognise parts to be sorted from a mixed stream (based on the combination of colour, shape, material, etc.).

Quite possibly robots will replace manual labour more and more, but manual labour also fulfils secondary objectives such a providing a meaningful job / activity for people, providing income, social interaction and structure, that will then be lost. Furthermore, most technologies have been around for quite a few years and still almost 40% of EU plastic waste is landfilled and a similar large percentage is incinerated for energy recovery, indicating the slow pace in dealing with (plastic) waste [34].

And this brings us to the biggest problem, not to be solved by treatment technology, which is the collection rate. The CWIT study[35] indicates that 35% (3.3 mt) of all the WEEE discarded in the EU (9.5 mt) ends up in official collection and recycling systems. Some 33% is recycled under non-compliant ('informal') conditions and the remaining 1/3 was either exported (16%), scavenged for valuable parts (8%) or simple thrown in general waste bins (8%). Diverting the other 2/3 of WEEE arising to the official channels could probably double the output of the recycling industries (assuming the 'informal' route ultimately results in recycling of the main materials, in mt) in a single stroke.

[34] https://www.slideshare.net/Ouniyeh/plastics-facts-in-europe

[35] Huisman, J., Botezatu, I., Herreras, L., Liddane, M., Hintsa, J., Luda di Cortemiglia, V., Leroy, P., Vermeersch, E., Mohanty, S., van den Brink, S., Ghenciu, B., Dimitrova, D., Nash, E., Shryane, T., Wieting, M., Kehoe, J., Baldé, C.P., Magalini, F., Zanasi, A., Ruini, F., Männistö, T., and Bonzio, A., Countering WEEE Illegal Trade (CWIT) Summary Report, Market Assessment, Legal Analysis, Crime Analysis and Recommendations Roadmap, August 30, 2015, Lyon, France

4 What to recycle / recover: Challenges

Following the 'why' and 'how' of recycling (and recovery) this chapter describes 'what' is recycled. Of course, these are the ErP as stated in the study brief, but each ErP contains parts, components, assemblies, materials and substances that each poses a series of challenges for the 'how' of recycling. This chapter describes these challenges and provides recommendations on product design that can improve current practice.

4.1 Introduction

Chapter 2 presented an overview of recycling technologies and briefly introduced their capabilities but also their limitations. This chapter will link these capabilities and limitations to recommendations regarding product design, in order to better prepare products for treatment using present day and near future recycling technologies.

Recycling technologies aim at reclaiming the most value from waste products against the lowest costs. This means that especially ferrous metals, non-ferrous carrier metals, and precious metals, are recycled at high rates, as incentivized by the (mass-based) recycling rates required by WEEE.

The recycling of trace materials, especially those with relatively little value, is however more challenging, either technically and/or economically (often these are linked). The same goes for plastics, which are difficult to recycle to a level that can compete on quality and price with virgin materials.

This chapter describes the present day difficulties in the recycling (and recovery) of the materials and components in ErP, these being mainly energy using products.

Regardless of what technology is applied, recycling an ErP requires liberation of parts/components ending at material / substance level. In-between are various sorting steps to place liberated parts/materials in the correct waste stream ultimately leading to the optimum final treatment.

The first step in ErP (or WEEE) treatment involves an initial sorting on typology (refrigerators, CRT equipment, large appliances, IT, etc.).

The second step is the extraction of high-risk components or components that require a careful treatment as generic treatment may induce occupational health hazards (mercury escaping from broken CFL bulbs, batteries exploding in shearing machinery) and/or create problems in later sorting (shearing of high grade PCB results in losses of PGM), etc. Special attention is paid to refrigeration equipment containing ozone-depleting elements and CRT equipment filled with toxic elements. The WEEE Directive requires that hazardous substances are removed in a proper, controlled manner.

Next, the depolluted WEEE goes through a process of automatic or manual dismantling at the end of which homogeneous compounds are identified, which are the bases for future secondary raw materials or which require energy recovery operations or controlled disposal.

How depollution is actually achieved depends on the product and the economics of recycling: Toxic metals present in electronics are not removed in waste treatment facilities, but usually during final treatment of the component in smelters or baths. Plastics with brominated flame retardants are often removed from a mixed waste stream by automated processes further downstream.

This requires proper liberation and sorting of materials so that each can be reused as close as possible to its original use. As materials may be polluted with intentionally or unintentionally added substances that may not be desired or even allowed anymore in the reused material, or may cause possible harm to the waste treatment personnel, depollution is a crucial step in the recycling of products.

The vast array of materials that comprise ErP [36] can be grouped into five basic categories: metals, plastics including composites, ceramics, bio-based materials and a rest group comprising other materials not found in the first four groups.

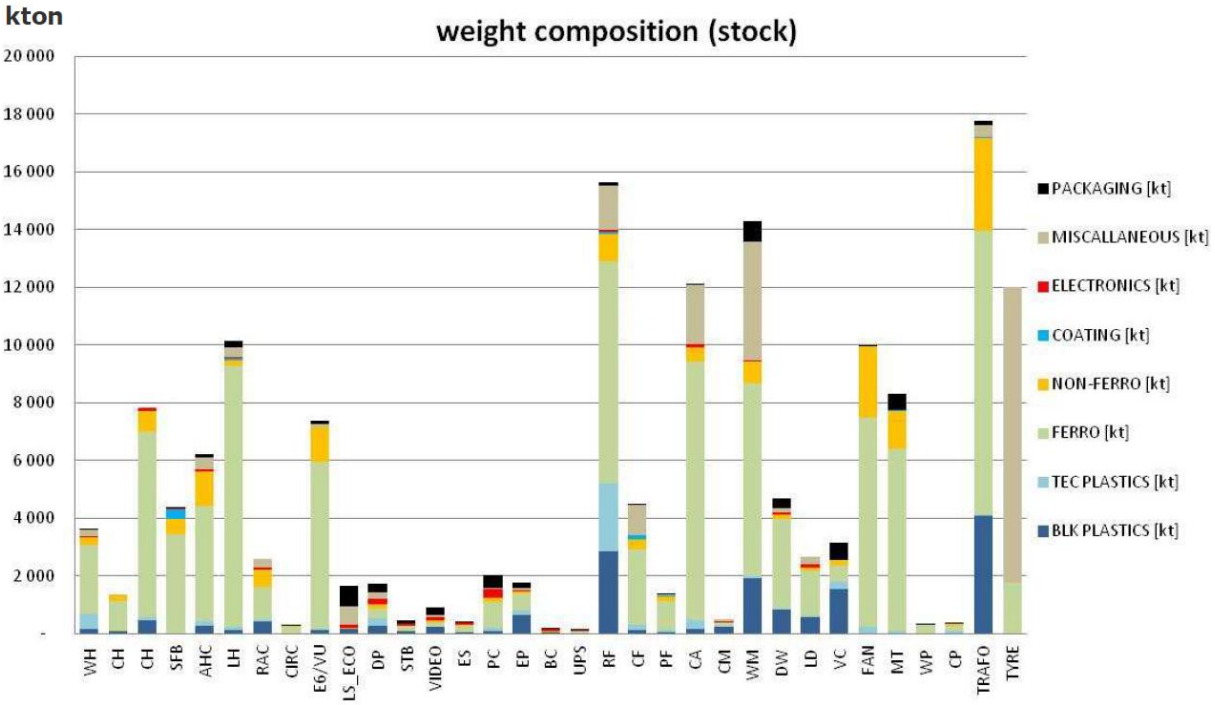
1) Metals (incl. metalloids, etc.)
   a) carrier metals (ferro, non-ferro)
   b) precious metals (PGM) and copper, mercury, rhenium
   c) rare earth elements
2) Plastics (& composites)
   a) thermoplasts

[36] The http://www.matweb.com database has over 115 000 different materials registrations, of which 74% concerns plastics.

b) thermosets
3) Ceramics (glass, ceramics, concrete, et.)
4) Bio-based products
5) Others (non-metals, gases, fluids)

The figure below shows the total of materials, contained in ErP, that entered the EU28 in 2010, by product group and material category.

Figure 10. Total of materials in ErP in stock in 2010, by product group[37]

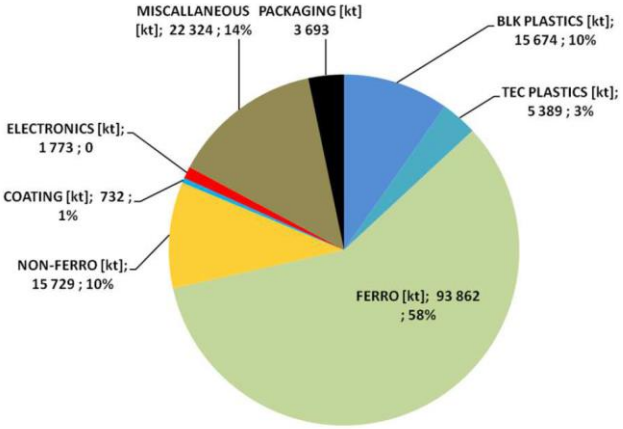


WH	WH dedicated Water Heater	**UPS**	UPS Uninterruptable Power Supply
CHC	CHC Central Heating Combi	**RF**	RF Household Refrigeration
CH	CH Central Heating Boiler	**CF**	CF Commercial Refrigeration
SFB	SFB Solid Fuel Boilers	**PF**	PF Professional Refrigeration
AHC	AHC total Heating & Cooling	**CA**	CA Cooking Appliances
LH	LH Local Heaters	**CM**	CM household Coffee Makers
RAC	RAC Room Air Conditioner	**WM**	WM household Washing Machine
CIRC	CIRC Circulator pumps <2.5 kW	**DW**	DW Household Dishwashers
E6/VU	E6/10 VU Ventilation Units (res & nonres)	**LD**	LD household Laundry Drier
LS_ECO	LS Light Sources, mln units ECO	**VC**	VC Vacuum Cleaners
DP	DP electronic DisPlays	**FAN**	FAN Industrial Fans >125W
STB	STB Set Top Boxes	**MT**	MT Motors 0.75-375 kW
VIDEO	VIDEO	**WP**	WP Water pumps
ES	ES Enterprise Servers	**CP**	CP Standard Air Compressors
PC	PC Personal Computers	**TRAFO**	TRAFO Utility Transformers
EP	EP & IJ imaging equipment	**TYRE**	TYRE
BC	BC Battery Charged devices		

When combined into a single chart, the single most present material is steel sheet and other ferrous metals (58%). The group 'miscellaneous' (14%) comprises mostly natural and synthetic rubber for tyres (note: natural rubber is listed as Critical Raw Material).

Figure 11. Total of materials in ErP in stock in 2010, by material

[37]Special report – Material Inputs for Production, pertaining to the study on ecodesign impact accounting (interim report), VHK, 30 March 2016

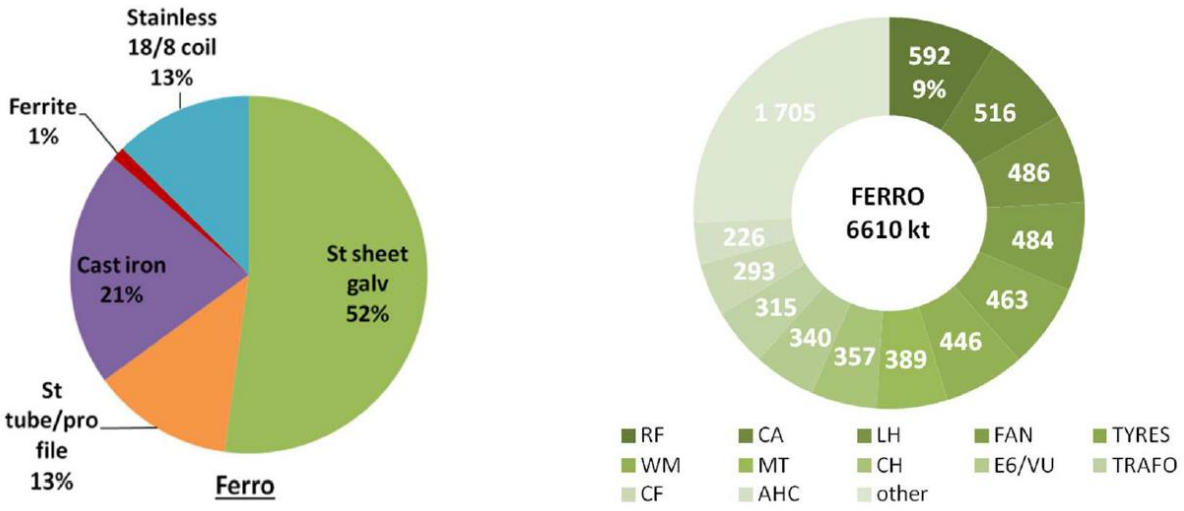


4.2 Metals

Ferrous metals

Metallic parts in a product can be located in housing and structural components. Galvanized steel sheet is the single most used form of metal, followed by profiled steel (tubes, rods), cast iron and stainless steel. Ferrous metals enter the EU market mainly in the form of refrigerators, cooking appliances, local heaters, fans, tyres (steel reinforcement), washing machines, electric motors, central heating, etc.

Figure 12. Ferrous metals used in ErP

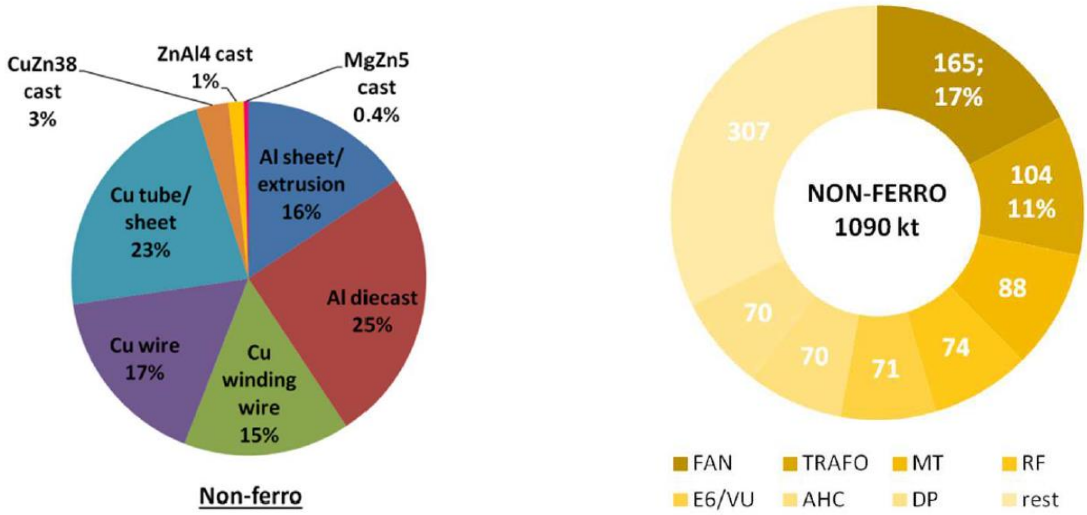


Where these are made of ferrous metals the recovery is relatively unproblematic, using shredding and magnetic separation. Spill over of ferrous metals into copper or aluminium waste streams is a waste of the metal, but not detrimental to the end product and the economic and environmental loss is limited.

Non-ferrous metals

The use of non-ferrous metals is mostly copper (over 50%, divided over Cu tube/sheet, wires and winding wires (in motors)), and aluminium (extrusion 16% and die-cast 25%). The remainder are brass (CuZn), Zamak (ZnAl) and MgZn alloys (for lightweight housings, etc.)

Figure 13. Non-ferrous metals used in ErP



For non-ferrous carrier metals (copper, nickel, zinc, tin, and aluminium, titanium, magnesium, lithium, etc.) more care needs to be given to correct liberation and sorting as certain metals are incompatible with the processing of other metals: precious metals dissolve in the aluminium smelt and negatively affect the quality (and is a great loss of economic and environmental value).

Critical raw materials, including rare earth elements (REE)

Critical raw materials are various materials for which there is a supply risk and the relevance for society is relatively high.

Table 2. EU List of critical raw materials (2017) [38], [39]

Critical Raw Materials 2017	Materials and applications [40]	Critical Raw Materials 2017	Materials and applications
Antimony	alloys, flame retardant, solder, semiconductors	**LREEs (light REE)**	Neodymium
Barite (source of Barium)		**Magnesium**	Casings, body of portable electronic gear
Beryllium	Be-Cu-alloys, BeO ceramics, metallic beryllium in electronic contacts	**Natural graphite**	Batteries (NiMH & Li-ion)
Bismuth	Wetting agent in thick-film printed wiring boards	**Natural rubber**	In tyres for transport
Borate (contain Boron)		**Niobium**	Niobium-steel alloys, welding alloy, magnets, capacitors
Cobalt	Lithium-ion and NiMH batteries	**PGMs (Platinum Group Metals): gold, palladium, platinum, rhodium**	(multilayer-) capacitors, connectors, contacts, transistors, diodes, Ag-Cu-Pd-soldering
Coking coal		**Phosphate rock**	
Fluorspar (source of		**Phosphorus**	

[38] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_nl
[39] http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2017:0490:FIN
[40] Unep, Metal Recycling – opportunities, limits & infrastructure, table 8, p. 68

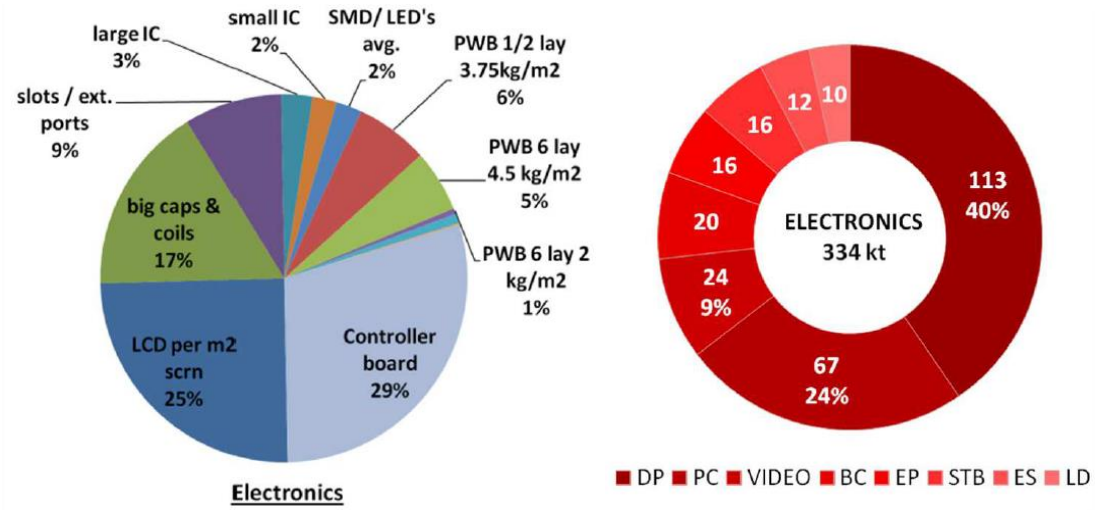
Critical Raw Materials 2017	Materials and applications [40]	Critical Raw Materials 2017	Materials and applications
Fluor)			
Gallium	Semiconductors, laser diodes, LEDs, photodetectors, photovoltaic cells	**Scandium**	see LREE
Germanium	Photovoltaics, glass fibre, optical glasses, semiconductors	**Silicon metal**	Semiconductors, photovoltaics
Hafnium		**Tantalum**	Capacitors
Helium		**Tungsten**	Vibration device, electrodes, filaments
HREEs (heavy REE) & LREE (light REE)	Dysprosium, Scandium, Lanthanum, Yttrium & Neodymium in magnets, phosphors, fuel cells, NiMH batteries	**Vanadium**	Ferro-alloys, red phosphor emitter
Indium	Indium-Tin-Oxide (ITO) layer in flat panels, thin-film photovoltaic, semiconductors, LEDs		

The critical raw materials include both heavy rare earth elements HREE and light rare earth elements LREE, which are found in various parts and components, often in very minute quantities, with the possible exception of neodymium in permanent magnets. Rare earth elements have very specific optical and magnetic properties, which explains their application in various specific electronic components.

Electronics

The special report on material consumption shows that some 334 kt enters the EU annually in the form of 'electronics'. This comprises printed circuit boards, displays and other parts/assemblies.

Figure 14. Electronics used in ErP



Some 2/3 of the electronics are contained in display products (televisions etc., 40%) and computers (24%). The rest is video equipment, battery operated devices, imaging equipment (EP), set top boxes, enterprise servers, etc.

For large copper and aluminium parts the current recycling infrastructure is considered adequate, but problems arise with specific material combinations that, for optimum recovery, need more care during waste treatment, avoiding possible losses. The following sections highlight:

- batteries;
- printed circuit boards;
- LCD displays;
- lamps and motors/drives (incl. HDD);
- non-PM motors;
- heat exchangers.

4.2.1 Batteries (Li, Co and Ni, and REE)

Liberation of the battery from products is preferably not done by shredding as puncturing lithium battery cells may result in fires. Other types of batteries could spread toxic or valuable elements over the mixed waste stream from which they are more difficult to recycle.

Liberation of batteries in compartments closed by snap-fit lids is easy. If the compartment is closed by a screw then external force (manual blow by hammer) often suffices to liberate the battery. If an automated process is used, like in a rotating hammer mill, then downstream sorting is necessary which can be manual or (theoretically) by optical scanning software that recognizes battery shapes/patterns combined with a pressurized air jet sorter or a robotic arm.

Batteries contain various valuable elements, some hazardous, others critical raw materials[41].

Table 3. Battery chemistries

Elements in batteries (% weight)	**Primary (non-rechargeable)**	**Secondary (rechargeable)**					
	Zinc-alkaline	**Ni-Cd**	**NiMH** button	cylindrical	prismatic	**Li-ion**	**Li-polymer**
Fe	5-30	40-45	31-47	22-25	6-9	24.5	1
Ni		18-22	29-39	36-42	38-40		2
Zn	15-30						
Mn	10-25						
Cd		16-18					
Co			2-3	3-4	2-3	27.5	35
Li						($LiCoO_2$)	($LiCoO_2$)
REE (La, Ce, Pr, Nd)			6-8	8-10	7-8		
Cu						14.5	16
Al							15
K							
carbon (graphite)			2-3	<1	<1	16	15
plastics			1-2	3-4	16-19	14	3
H_2O			8-10	15-17	16-18		

Legend:

highly toxic
toxic
critical raw material (REE = Rare Earth Element)
toxic and critical raw material

[41] Source: Metal Recycling – opportunities, limits, infrastructure, Table 44 (p. 228)

Both NiMH and Li-Co based batteries contain critical raw materials, but the percentages of Li and Co in "Lithium batteries" are significantly higher than in NiMH.

Cobalt can be recovered through Fe or Cu/Ni process routes: in steel processing it is a benign element, in Cu/Ni processing it can be recovered as element. In Al processing Cobalt reports to the metal phase and is not recovered.

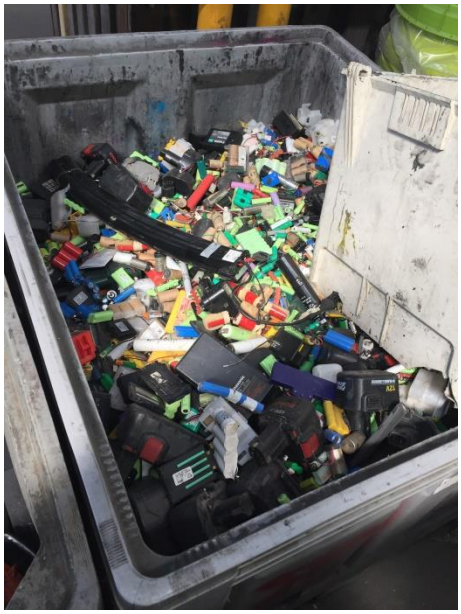
If batteries are treated in Cu/Ni smelters, not only the lithium is lost, but iron, aluminium, nickel and manganese as well. If Lithium batteries are treated in Fe-smelters, aluminium, lithium and copper are lost. It is therefore essential that Lithium containing components are separated from components that require other processing routes. In practice, this means the battery has to be liberated and sorted away from the rest of the products, to enable Lithium recovery.

Lithium can be recovered through Lithium-hydrometallurgy processing (primary route) but for post-consumer applications special battery recycling processing (as by Accurec[42] and Recupyl[43]) is the only option, as the primary route is not suited for spent batteries. In other processing routes, including generic battery recycling Fe, Cu and Al can be recovered but the Lithium is lost. Currently only 5% of the lithium batteries that enter the EU is collected[44].

Sorting by battery type (chemistry) is still often problematic as the actual chemistry of the battery is often difficult to recognise from prints (or the print has faded). The Battery Directive 2006/66/EU requires the labelling of the battery with the crossed-out bin logo, accompanied with chemical symbols "Hg", "Cd", and/or "Pb" where applicable. The Directive also states that batteries or accumulators should be readily removable by end-users, or by "qualified professionals" (e.g. electronic repair shops or services) "independent of the manufacturer".

Button cells and Li-ion pouches are fairly easy to sort as the size and shape are typical for their chemistry, but mignon type batteries (AA, AAA, etc.) and battery cartridges require reading the fine print: Primary and secondary cells have the same size.

Figure 15. Batteries removed from products



[42] http://www.accurec.de/
[43] http://www.recupyl.com/105-lithium-ion-battery-recycling.html
[44] Lithium fact sheet, GLOBAL 2000 Verlagsges.m.b.H., Neustiftgasse 36, 1070 Vienna

4.2.2 Printed circuit boards (PGM)

Printed circuit boards may contain valuable and/or hazardous elements, and critical raw materials[45].

Weight-share	**Fe**	**Al**	**Cu**	**plastics**	**Ag (ppm)**	**Au (ppm)**	**Pd (ppm)**
Monitor-board	30 %	15 %	10 %	28 %	280	20	10
PC-board	7 %	5 %	18 %	23 %	900	200	80
Mobile phone	7 %	3 %	13 %	43 %	3000 (=0.3%)	320 (0.03%)	120
Portable audio	23 %	1 %	21 %	47 %	150	10	4
DVD-player	62 %	2 %	5 %	24 %	115	15	4
Calculator	4 %	5 %	3 %	61 %	260	50	5
Value-share	Fe	Al	Cu	SUM precious metals	Ag (ppm)	Au (ppm)	Pd (ppm)
Monitor-board	4%	14%	35%	47%	7%	33%	7%
PC-board	0%	1%	13%	86%	5%	69%	12%
Mobile phone	0%	0%	6%	93%	11%	71%	11%
Portable audio	3%	1%	73%	21%	4%	16%	3%
DVD-player	15%	3%	30%	52%	5%	42%	5%
Calculator	1%	4%	10%	85%	6%	76%	3%

(1 ppm = 0.01% weight)

The content of valuable metals in printed circuit boards enables recovery (recycling) of these metals: The table above shows that even if the gold in a mobile phone is only 0.03% of the weight, it represents 71% of its (recoverable) value. Gold is considered a good precursor or indicator of presence of other valuable metals like silver, palladium, platinum, etc. The total number of elements present in printed circuit boards can surpass 40 different elements.

Depending on the population of the board with devices, the gold content may range from 0 (zero) to over 100 ppm. Umicore and other precious metal converters refer to grades:

[45] Source: Metal Recycling – opportunities, limits, infrastructure, Table 10 (p. 71)

- very high grade: gold content of minimum 400 ppm
- high grade: gold content of minimum 200 ppm
- medium grade : gold content of minimum 100 ppm
- low grade: gold content of minimum 50 ppm
- very low grade: gold content lower than 50 ppm

Umicore does not mind the removal of large Al/Fe-parts but asks to be careful, especially in case of shredding and sorting, not to lose valuable (precious) metals in side streams. For high and medium grade boards pre-treatment may be avoided and boards can be shipped as they are.

The value of recovered and unrecovered metals (by Umicore) in PWBs picked from shredding of mixed WEEE amounts to approximately ~7500 USD/t[46]. This includes:

- Metals recovered and paid = Ag, Au, Pd, Cu.
- Metals recovered but unpaid = Sn, Pb, Ni, Sb.
- Metals unrecovered = Fe, Si, Al, Zn, Mn, Ta, Ti.
- Additional metals analysed but not detected: Pt, Bi, Co, As, Te, Cd, W, Ga, Mo, Zr, V, REE (La, Ce, Pr, Nd, Tb, Dy).

Precious metals like gold, silver, platinum, palladium etc. are best recovered in the Cu/Ni process route, where all these 'noble' metals report to the Cu-fraction can be removed in subsequent processing. In steel-smelting these precious metals report to the carrier element (as alloying element, however with little benefit) or as compounds (sulphates, oxides, etc.) which (in the case of these precious metals) cannot be economically recovered from e.g. slags etc. In Al-processing, these elements report to the aluminium-fraction with little benefits.

Therefore, in order to enable the recovery of valuable elements contained in printed circuit boards, these components have to end up in the integrated Cu/Ni-processing route.

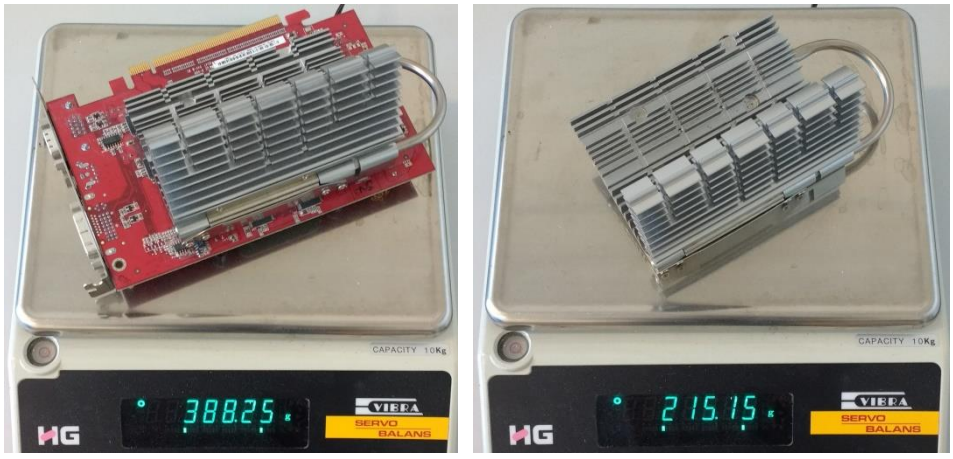
Preferably, large parts of Fe/Al can be removed to allow recovery of Fe and Al (if not removed, the Fe/Al is lost in Cu/Ni processing). Also, if not properly liberated or sorted, the presence of Fe/Al may divert printed circuit boards to Fe or Al processing routes where recovery of precious metals is not possible.

Shredding is not advisable for medium- to high-/very high-grade boards, as this introduces losses of valuable metals.

The preferred treatment for medium- to very high-grade printed circuit boards is therefore liberation from large Fe/Al parts and avoiding shredding. This is currently best achieved through manual liberation/sorting.

The picture below shows that for certain electronic components (here: a graphics card) the mass fraction of the heat sink can be significant: 55% of the total. If this card is sent to the Cu/Ni smelter, the aluminium is lost as slag. Removal and separate processing of card and aluminium results in higher recovery of materials.

Figure 16. Mass of graphics card with heat sink and mass of heat sink



Recycling does not mean that (if hazardous substances are present) depollution must take place as a separate activity, requiring the removal of the polluting substances from the product in one or more operations. Some waste treatment operators do not take apart products like mobile phones, but sent them as a whole to an integral copper/nickel smelter. This meets the definition of *recycling* as certain valuable elements (copper, gold, palladium) are recovered/recycled, and

[46] Metal prices taken as 2016 year-to date average in August.

also meets the definition of *removal* as the waste stream of the smelter allows monitoring to verify environmental safe treatment.

But it also means that certain other elements, such as aluminium, magnesium, lithium and also ferrous metals, are not recovered/recycled as these report to unusable slags. So, even if no disassembly is the economically preferred route, it is not necessarily the route with the highest recovery/recycling effect.

4.2.3 Electronic display(s) / units (indium)

Displays or better display units are predominantly of interest for WEEE because of the possible use of gas discharge lamps, more precisely cold cathode fluorescent lamps containing mercury as backlighting units. Present day displays have these lamps replaced entirely by LED-backlighting, making the WEEE requirement a legacy parameter - See the section on 'lamps' in this chapter.

Of more relevance is that LCD-displays contain a layer of Indium-Tin-oxide (ITO, 90 % by weight In_2O_3 + 10 % by weight SnO_2) which represents 84 % of indium's total demand[47]. Indium is also found in thin-film photovoltaic panels and in LEDs (InGaN). Indium is a critical raw material.

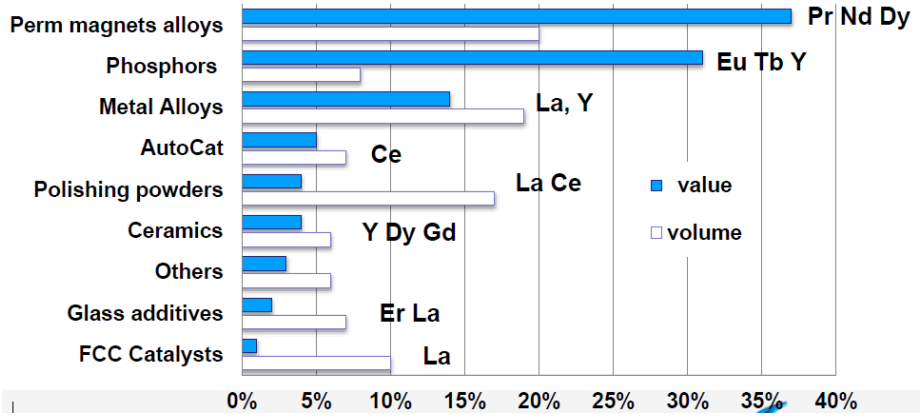
Recovery of Indium is possible through the Korea Zinc process. Korea Zinc is one of the few (global) companies that can recover Indium (and gold, silver and lead) from zinc concentrate[48]. Umicore's Cu/Ni process also recovers Indium, but not from post-consumer scrap displays, but from 'targets' that are used for conductive coatings: *"Recovery of indium from dissipative uses like flat panel displays and photovoltaics remains very challenging"*[49].

Indium is therefore not recovered in Cu/Ni smelt-refine operations and thus the display needs to be separated from the electronics for it to undergo a special lithium-recovery process. The upcoming display technology, OLED, also uses a layer of indium tin oxide as the anode. There are however initiatives that aim to find an alternative for ITO[50].

4.2.4 Lamps and motors/drives (REE in phosphors and magnets)

Most REE are applied in magnets (Pr, Nd, Dy) and the next largest market segment for REE is that of phosphor powders (12% by weight) that allow fluorescent lighting and LEDs (and even CRTs) emit lights of specific colour(s): such phosphors may contain lanthanum, yttrium, cerium, terbium, europium and gadolinium. Other applications of REE are batteries (La), in printed circuit boards, in displays.

Figure 17. Size of the market (value, volume) for REE, 2014 [51]



So far, no economic processing infrastructure exists for recovery of REE from post-consumer scrap. Although recovery is technically possible, with hydrometallurgy identified as most promising route, the dissipation is so vast that large scale economic recycling is not yet possible. The profitability of the RE recycling is mostly dependent on 'virgin' REE prices, which again depend on the (re)opening of mines. Solvay La Rochelle plant is the only facility outside of China able to separate all REE including HREE, and focuses on recovery from La Rochelle historical loss of yield, NiMH batteries, REEs from lamps.[52]

[47] Source: Metal Recycling – opportunities, limits, infrastructure, Figure 51 (p. 123)
[48] http://pulsenews.co.kr/view.php?year=2016&no=68230
[49] http://www.umicore.com/en/about/elements/indium/
[50] https://spectrum.ieee.org/tech-talk/semiconductors/materials/a-15yearold-polymer-may-challenge-indium-tin-oxide-in-oled-displays
[51] SOLVAY latest developments in Rare Earth Recovery from Urban Mines, Nov 2015
[52] http://ec.europa.eu/DocsRoom/documents/14043/attachments/1/translations/en/renditions/native

4.2.4.1 Lamps (gas discharge and LED)

Both gas-discharge lamps as well as LEDs (and old CRT) use phosphors to convert radiation in the invisible spectrum to the visible spectrum. This conversion often relies on phosphors that contain REE due to their optoelectronic properties. The rare earth elements used in such phosphors are mainly Yttrium and Europium (Terbium is more used in fluorescent only).

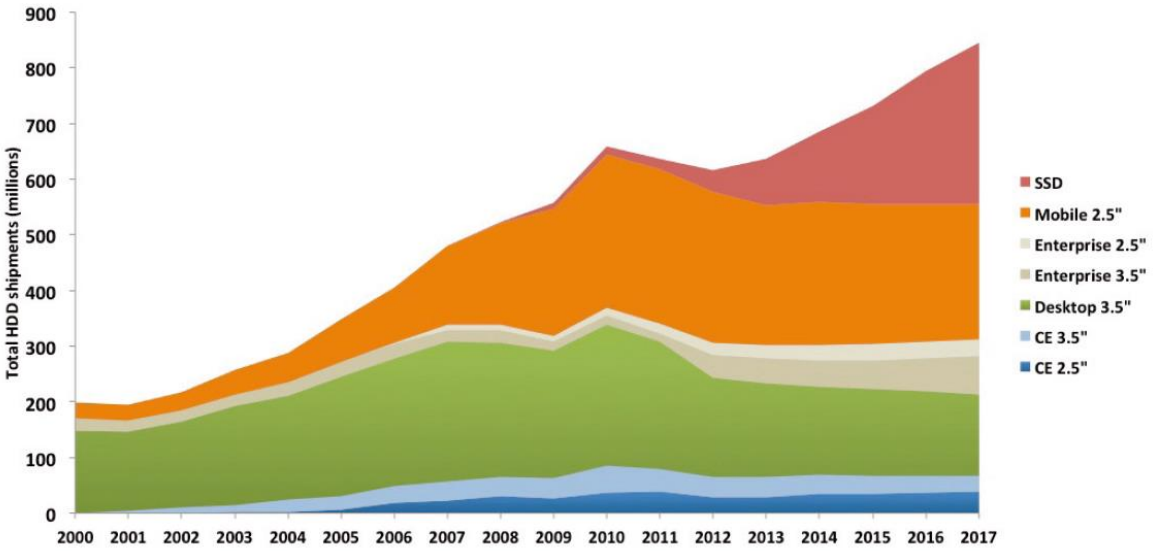
As gas discharge lamps are slowly being moved out of the market by LED lighting, the consumption of phosphors per lamp unit may reduce, but the total number of lamps, using LEDs, is expected to continue to grow. Still analysts predict an infliction point in global REE use for lamps: A T8 fluorescent bulb can contain up to 2 g of phosphor, whereas for an LED, at similar output, this would be closer to 0.07 g[53].

The recycling of REE used in lamps is in itself not problematic and follows the hydrometallurgic technology developed for REE. The problem is probably how to get sufficient phosphors to the few locations that are able to recover REE. Again, for recovery of Yt and Eu removal of LED (and other phosphors) is required. Current metallurgical technology does not allow the simultaneous recovery of the silicon of the LED.

4.2.4.2 Permanent magnets (HDD, e-motors)

Hard disk drives contain permanent magnets (in the read/write voice coil assembly and the spindle electric motor). Although HDDs are increasingly replaced by SSD technology in domestic and desktop environments, the use of HDDs is expected to continue to grow in the enterprise sector (cloud data) as the cost/performance ratio is yet not matched by SSD in this sector[54].

Figure 18. HDD production (plus SSD)



Note to figure: Mobile 2.5" drives are used in laptops. Enterprise drives are used in servers or PCs in a business context. Desktop 3.5" are predominantly used in personal computers. Consumer electronics (CE), such as game consoles and digital video recorders may also contain HDDs. Production of solid-state drives (SSD) that do not contain magnets has been included for reference.

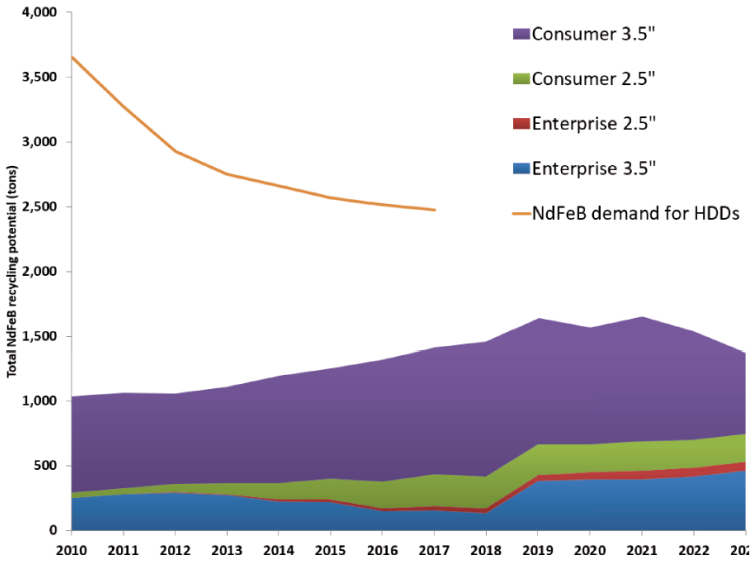
Simply shredding a complete device, including the HDD, may allow recovery of the large aluminium housing and ferrous parts, but Nd-magnets are lost, as well as significant fractions of precious metals in printed circuit boards. The Materials Innovation Institute in Delft, Netherlands, found that shredding hard drives for recycling resulted in a 90 percent loss of neodymium.[55]

Recovery of Nd poses several challenges: First of all the product must be identified to contain HDD and the location of the HDD in the product must be known before it can be removed. Direct pyrometallurgic treatment of an integral HDD may recover the elements for which the pyrometallurgic process was designed (usually Fe, Cu or Al) but will not recover the Nd. Hydrometallurgic processing could recover the Nd, but is quite extensive before Nd is returned to its metallic elemental form. The best recovery option is the liberation of magnets and processing up to secondary material (a compound similar to magnet production) or primary material (Nd in elemental form).

[53] Impact of Light Emitting Diode Adoption on Rare Earth Element Use in Lighting Implications for Yttrium, Europium, and Terbium Demand by Anthony Y. Ku, Anant A. Setlur, and Johnathan Loudis. [http://interface.ecsdl.org/content/24/4/45.full.pdf]
[54] Sprecher, B., When materials become critical : lessons from the 2010 rare earth crisis, Leiden University dissertation, 2016-06-28
[55] https://ensia.com/features/rare-earth-recycling/

Manual liberation of Ne-magnets however is very extensive and considered not economic. According several studies the best route is hydrogen decrepitation which disintegrates the magnet material into dust, while leaving other materials unaffected. This dust can either be re-used in magnet production or processed further into elemental Nd.

Figure 19. Total NdFeB recycling potential (tons) from different HDD types/applications and NdFeB demand for the production of HDDs.



4.2.5 Non-PM motors

Electric motors usually contain significant fractions of copper, aluminium and steel. Depending on the type of motor, rare earth elements may also be present in permanent magnets – See previous section. And motors may be equipped with an integrated electronic motor drive (printed circuit boards) – See printed circuit boards.

The general recycling of electric motors depends on how they are delivered to the recycling facilities. If the motor is still contained in the (industrial) product, like a fan, compressor, or other torque or traction producing apparatus, the whole product is usually shredded (hammered) and processed using magnetic separation (for ferrous) and eddy current (for non-ferro scrap). The non-ferro may be further separated into lighter (aluminium) and heavier (copper) fractions. As electric motors have intricate joining methods, a certain percentage of materials is lost (windings not completely liberated and sorted from the stator, magnets end up in Fe-processing).

This is probably the scenario that applies to motors incorporated into various domestic products (vacuum cleaners, washing machines, kitchen appliances, DIY tools, etc.) as well. Based on contemporary dry liberation technologies (shredding = shearing, hammering, etc. that produce a certain distribution in particle size) the chances that small electric motor parts end-up in the right waste fraction are smaller if the motor is smaller (a small steel encapsulated brushed DC motor will probably end up at Fe scrap because of its magnetic properties, which reduces copper recovery).

Figure 20. Simple electric motor, but difficult to liberate and sort

If the motor is discarded as a result of an exchange of a motor (and this only applies to relatively large motors), the rotor and stator may be separated to increase recovery value. Several types of machinery have been developed, most involving

removal of the motor shaft and then splitting the remaining stator in half and removing the copper wiring loom. This usually involves several steps and handling. The MORE project concluded that recycling of electric motors is already profitable due to their copper content[56].

4.2.6 Heat exchangers

Aluminium and copper are often used as materials for heat exchangers as they have good thermal conductivity and can be shaped relatively easy. Many fan-coil heat exchangers consist of copper tubes, onto which aluminium fins are attached. The ductility of both metals however may cause the product, in liberation processes involving hammering / repeated blows, to be transformed into a particle from which aluminium and copper cannot be liberated anymore by mechanical means (unless very fine shredding is applied).

4.2.7 Design guidelines for metal recycling/recovery

Conclusions for design and treatment are therefore:

1. Avoid inseparable combinations of Cu, Fe and Al as these should follow separate recovery routes;
2. If printed circuit boards are present (contains precious metals Pd, Pt, Au, Ag) design the product/treatment so that the part ends up in Cu/Ni recycling;
3. If batteries are present, lithium batteries in particular, allow the battery to be processed in special battery recycling and avoid processing in Fe/Al/Cu routes;
4. If LCD displays are present, allow the part to be recovered in the Cu/Ni route (and subsequent processing) for recovery of indium, and avoid Fe/Al routes;
5. if phosphors and/or magnets are present (contain rare earths), these should be removable as dedicated rare earth processing routes are the only available recovery processes. This may be possible for certain dry phosphors (e.g. in fluorescent lamps) and magnets, but difficult for REE present in trace amounts in LEDs and other electronic components, etc. (for REE in batteries, see 'Batteries');
6. if vibration motors are present or other parts that contain significant amounts of hard-metals (presence of tungsten and/or tantalum) these should allow separation from other metal rich streams so that dedicated processing can occur.

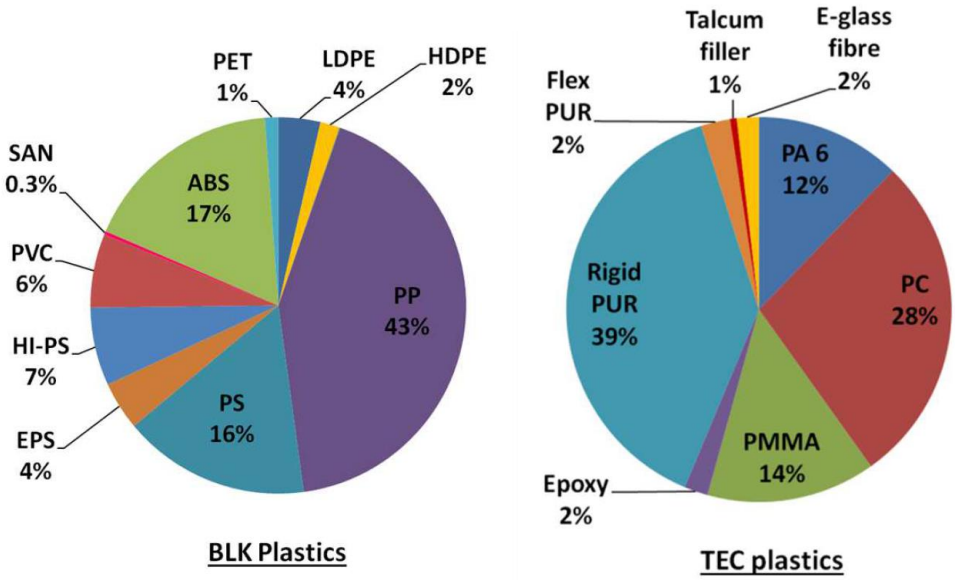
4.3 Plastics

Since the invention of Bakelite in 1907 the use of plastics (= synthetic polymers) in consumer products and ErP in general has only grown. Not only has the weight fraction of plastics in products generally increased, also the variety of resins / grades and their final applications (with additives like flame retardants, fillers, fibres and coatings based on metals or other plastics) have increased tremendously. Additionally, plastics can blended, co-extruded/–injected, laminated, possibly including non-plastics as well.

The VHK Special Report material Consumption 2016 calculated that, within the group of products covered by ecodesign, the use of PP, ABS and PS is the most prominent in the group of bulk plastics. Over half of these bulk plastics are placed on the EU market in the form of vacuum cleaners, refrigerators, electronic products and display products (televisions).

of the 'tec plastics' (engineering plastics) the use of rigid PUR, PC, PMMA and PA 6 stand out, and these are mostly found in refrigerators, display products, electronic products, vacuum cleaners and water heaters (especially PUR).

[56] Bast, U. Recycling von Komponenten und Strategischen Metallen aus Elektrischen Fahrantrieben: MORE (Motor Recycling). Final Research Report. 2014. Available online: http://edok01.tib.uni-hannover.de/edoks/e01fb15/826920594.pdf



Subsequently the recovery and recycling of (post-consumer) plastics has become a bigger challenge over the years. Current recycling involves separating plastics from mixed fractions from ErP, usually by liberation through shredding or crushing and subsequent sorting based on wet (sink/float) or dry methods (spectroscopic such as near or mid-IR, X-ray, etc.).

Proper sorting of plastics is key but liberation and sorting techniques for plastics have their limitations: plastics with similar densities are difficult to separate using density-based techniques, especially considering that plastic densities are affected by additives and grades. Plastics using carbon black as pigments (black PET dishes for packaging of fresh foods) cannot be recognised by IR-based sensors. Presence of BFRs in plastics can be recognised by X-ray but this is expensive and has lower throughput.

Other forms of recycling are depolymerisation (as mentioned under thermosets) where plastics are broken down into their monomers to be used again for a polymerization (chemical recycling). Other techniques involve creating a so-called syngas (through pyrolysis or hydrogenation), which can either be combusted (energy recovery) or be used to create monomers (chemical recycling).

4.3.1 Thermoplasts

Mechanical recycling of thermoplasts[57] is common practice in the packaging world and the current recycling rate is close to 30% of which 80% are packaging plastics[58]. Still, some 40% of plastics are incinerated and over 30% are landfilled. Plastics used in ErP are first of all much smaller in overall volume (say 30% of the total EU plastic demand) and as the variety of plastics involved is much, much higher, the recycling of it is much more challenging.

The biggest challenge is the proper sorting of a mixed waste plastic stream. Wet and dry sorting techniques are quite capable of sorting clean plastic flakes, but there are some conditions that pose challenges:

4.3.1.1 Black plastic

Near infrared radiation (NIR) is a well-known technology for sorting plastics, but carbon in black pigmented plastics absorb NIR, obstructing recognition.

4.3.1.2 Restricted substances (BFRs)

Most plastics contain additives to suppress flame propagation or to enhance certain mechanical properties. A certain number of such additives are however suspected to be hazardous, such as brominated flame retardants and several types of plasticizers (some can also aid in flame suppression).

BFRs hold a 19.7% market share of commercialized chemical flame retardants. The RoHS (recast) Directive 2011/65/EU restricted the use in products of certain brominated flame retardants, in addition to certain toxic metals. This list was expanded by Commission Delegated Directive 2015/863 of 31 March 2015 to include certain phthalates.

[57] Standard plastics (PE, PP, PVC, PS, EPS, PET (bottle grade)) + Engineering plastics (ABS, SAN, PA, PC, PBT, POM, PMMA, Blends, and others including High Performance Polymers).
[58] Plastics_the_facts, Plastics Europe, 2016

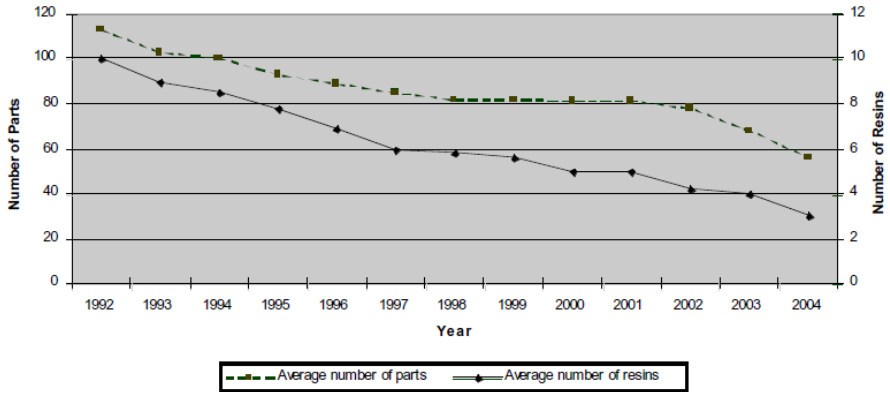
The candidate list of the REACH Regulation contains more suspect substances that may be prohibited in the future. Plastics that are placed on the EU market today increase their chances of recycling if no (potentially) restricted substances are present.

4.3.1.3 Compatibility

As only a limited number of plastics have material properties such as melting point, viscosity during processing, etc. that are compatible and combinations of which are accepted by the market. If not properly sorted mixed plastics usually undergo considerable down cycling (mixed plastic fractions used to produce park benches, road paving material, etc.) or are simply incinerated for energy recovery.

Enhancing the compatibility goes hand-in-hand with reducing the number of resins used. Manufacturers have shown that, in certain product groups or assemblies, the number of resins used could be reduced.

Figure 21. Parts and resins in HP monochrome LaserJet Print cartridges 1992-2004



4.3.2 Thermosets

Mechanical recycling of thermoset[59] plastics is generally not possible. There are however technologies available that break down the thermoset polymer back to monomers, or that grind them to fine sized particles which are then fed into the same thermoset production processes[60, 61]. These initiatives however have not yet resulted in a commercially viable infrastructure..

Thermosets are therefore currently not considered recyclable and energy recovery is the only economic recovery option.

4.3.3 Rubbers and foams

Rubbers, foams and other lightweight plastics normally have to be collected before shredding and commingling with other waste materials as proper sorting afterwards is often complicated. A relatively 'pure' fraction of rubbers or foams can be down cycled into flooring mats (rubbers) or sound dampening materials (e.g. flexible PUR) [62]. The foam in refrigeration equipment is shredded under controlled conditions and not mixed with other types of foams or materials and therefore results in a fairly clean flow.

If such materials are first shredded in a mixed waste product stream, they are likely to be contaminated with various materials, such as wood particle board, textiles and fabrics, and other materials / substances not suitable for recycling.

4.3.4 Design guidelines for plastic recycling/recovery

1. limit the number of plastic types or the variety of plastics applied in the product, as this reduces the efforts to achieve the purest recyclates;
2. avoid the use of black plastics using carbon black or other pigments that absorb IR radiation;
3. avoid the use of brominated flame retardants, phthalates or other substances that are on possible restricted substances lists, as these limit the possible number of reuses;

[59] Urea-formaldehyde foam, melamine resin, polyester resins, epoxy resins, etc.
[60] https://www.plasticstoday.com/recycling/yes-thermoset-resins-can-be-recycled/25571967424816
[61] http://science.sciencemag.org/content/344/6185/732
[62] https://polyurethane.americanchemistry.com/Polyurethane-Recycling/

4. avoid the use of stickers, coatings, laminates, co-injected/-extruded parts, as these hinder proper liberation and sorting (identification) of plastics, adding extra removal steps;
5. avoid the use of incompatible plastics in a single product: more compatible grades enhance the chance for reuse;
6. if recyclable foams are used, make these easy separable;

4.4 Natural and ceramic materials

ErP may contain various natural, bio-based, materials such as chipboard (wood) in loudspeaker cabinets or the top-plate of washing machines, cork, leather, cardboard, upholstery and textiles. Other materials may be sound dampening bitumen.

Ceramic materials (other than oxides of rare earths) may be applied as concrete counterweights in washing machines, (toughened) glass plates in refrigerators, electric insulating parts in electronics, heat and/or wear resistant parts in various products.

If the material is easily removable and can be collected in relatively pure form than recycling is often economic and an infrastructure exists (glass, paper/cardboard, clean wood). If the material is polluted with other incompatible materials the substances are recovered for energy at the most.

Sometimes removal is also required to reduce wear and tear on machinery (concrete counterweights may damage blades of shredding equipment and is removed prior to shredding, in hammering equipment removal is less often necessary).

4.4.1 Design guidelines for bio-based and ceramics recycling

1. allow the material (glass, concrete) to be easily removed from the product, avoiding liberation and sorting at a later stage which is probably more elaborate;

4.5 Other materials (gases, fluids, toner, etc.)

Although several hazardous substances are not allowed to be used in new products anymore, they may still be relevant in the recycling of older products and thus shape/determine the recycling infrastructure of today and the near future. The hazardous substances referred to in the WEEE Annex VII, that present day recyclers have to remove, are:

- **Mercury**: Primarily used in gas discharge lamps and (even older products) in electric switches. The use of gas discharge lamps is still allowed but the mercury content is regulated. Use of gas discharge lamps as backlighting in electronic displays has ended through replacement by LED lighting which poses several advantages. The REE in gas discharge lamps, and LEDS, can be recovered in theory – see 'Lamps' in 'metals'
- **PCBs** (polychlorinated biphenyls) and other POPs: PCB is an organic chlorine compound with the formula $C_{12}H_{10-x}Cl_x$ used as flame retardant in capacitor dielectrics. Regulation 850/2004 of 29 April 2004 on persistent organic pollutants requires that polychlorinated biphenyls (and many other POPs, including polybrominated diphenyl ethers) are not allowed to be placed on the market. Regulation 2015/2030 added short-chain chlorinated paraffins (SCCPs) to this list of POPs.
- **Asbestos** and **refractory ceramic fibres**: Since 1983 several EU regulations have regulated the use of asbestos to protect workers from risks, to prevent uncontrolled emissions when handling asbestos waste, and (more directly related to products) prohibit placing products on the market that contain asbestos through Commission Directive 1999/77/EC of 26 July 1999, Annex I to Council Directive 76/769/EEC. This directive bans the placing on the market and the use of products containing asbestos as of 2005. The use of asbestos in new products was also banned by Annex XVII of the REACH Regulation (EC) No. 1907/2006, which prohibits the marketing and use of products containing asbestos in the EU.
- **Refractory ceramic fibres**: These manmade fibres are identified to cause cancer (1B) and skin irritation (2) under Regulation 1272/2008 on the classification and labelling of hazardous substances (p. 919). Alumino-silicate is on the candidate list of REACH and the Registry of submitted SVHC intentions. Although their use in products is not yet restricted, the handling and disposal is.
- **Brominated flame retardants** [see 'restricted substance's in 'plastics'].
- **CFC, HCFC, HFC, and HC**: These are refrigerants and foaming agents primarily used in refrigeration equipment. The WEEE requires proper removal of these substances and appropriate treatment (destruction). Refrigerants are removed from refrigeration equipment using dedicated drill/suction equipment. Foaming agents are removed (extracted) in a shredding process under a controlled atmosphere.
- **Radioactive substances**: radioactive substances are primarily found in spent smoke alarms. These products should be removed from generic treatment (avoid shredding in a mixed waste stream) and be treated in appropriate facilities;

- **Toner cartridges, inks, and pastes**: Toners, ink and other imaging consumables are removed and sent to dedicated treatment facilities that recover the plastics and metals and, if possible, the pigment powder.

The removal of the abovementioned substances are mandatory activities and most likely not profitable, meaning that costs are passed on to manufacturers paying for proper disposal of WEEE.

4.5.1 Mercury in electronic displays

Due to the replacement of fluorescent lamps by LED lights direct environmental hazards resulting from treatment have reduced and removal of Hg-containing components is obsolete (for new products that is, not for current WEEE).

Electronic displays that may contain fluorescent lighting (containing mercury) are treated separate from other electronic devices. Often the mercury containing backlights are carefully removed. Some facilities may operate dedicated equipment that allow dust and gases containing mercury as emitted during crushing and sieving are collected and treated separately.

The current state-of-art is smelting the display module, together with electronic parts, in a TSL (top submerged lance furnace) where a copper-rich stream is treated in a TSL-reduction furnace and subsequent processes and the off gas/smelt is treated in a waste heat boiler, electrostatic separator to a zinc-rich residual stream which also contains In, Ge, Ga, Sb, As, etc. The display module could also be treated in a light-metal remelt/refine process, whereby the off gas is sent to an electrostatic separator for further recovery.

Conclusions for treatment: The display model (without large light metal parts) can be sent to the Cu/Ni processor and does not need prior liberation from printed circuit boards, but does require liberation from large light metal and steel parts, as these are lost in the Cu/Ni process. Indium is currently not economically recoverable from post-consumer scrap, although alternative routes are being developed.

To avoid the possible processing of large light metal/steel parts with the display module, the better recyclable products allows easy separation of these parts/components.

4.5.2 Design guidelines for recycling/recovery of other materials

1. avoid the use of the above mentioned substances;
2. design for easy removal of parts/components containing such substances (e.g. toners) prior to shredding;

5 Recyclability / recoverability methods

This Chapter presents an overview of methods developed to assess or include the recyclability of a product. The goal of such methods is to improve the design of the product so that the effort to recycle the product is reduced. The methods are assessed on the basis of how well the method results in designs that better meet the design guidelines identified in the previous chapter.

Improving the design of the products is however only one dimension of the problem of reducing material losses. The other dimension is legislative: The method should not only lead to improved designs, but should also allow a neutral, robust and reliable assessment of products, otherwise embedding in a regulatory context is meaningless. The assessment thus includes a legislative aspect as well.

5.1 Description of RR methods

In this chapter several methods for calculating the recyclability of a product are described and briefly assessed. The chapter is not comprehensive, as it can only focus on more well-known or tested methods. Although there may be more methods applied than described here, most of these methods share a common idea or basic concept.

The methods described are categorised by their distinctive feature (examples of method indicated):

1) Qualitative methods: These are based on a qualitative assessment of the product recycling performance. There is no
   a) EPEAT criteria;
   b) other criteria lists;
2) Semi-quantitative: These are called semi-quantitative because the outcome is a calculated score/rating/index, based on a qualitative assessment of the recycling performance of a product (based on poor, good, etc.):
   a) Cyclos
   b) Kirchner/Prumbohm
3) Mass -based quantitative methods: These are based on pure product composition, combined with values for recycling rates based upon literature:
   a) IEC/TR 62635
   b) VDE
4) Impact category -based quantitative methods: These are based on pure product composition, combined with an exactly defined waste treatment scenario, requiring input/output values for each step (resource use and emissions to land/air/water per impact category), based upon literature / commercially available databases:
   a) JRC method
      i) MEErP implementation
   b) Circular footprint formula

5.1.1 Criteria lists

5.1.1.1 EPEAT

EPEAT is an organisation that manages a system for environmental assessment of electronics. The system began in 2003 with a stakeholder process convened by the U.S. Environmental Protection Agency and has become a global environmental rating system for electronics. Managed by the Green Electronics Council, EPEAT currently tracks more than 4,400 products from more than 60 manufacturers across 43 countries.

The environmental criteria underlying the EPEAT system address the full product lifecycle, from design and production to energy use and recycling. EPEAT product assessment is based on ANSI-approved public standards developed through stakeholder consensus processes. Manufacturers' claims of compliance are subject to ongoing verification by qualified certification bodies. Products found non-conformant are removed from the EPEAT registry to ensure Purchasers worldwide can use the system with confidence.

EPEAT currently includes product ratings for PCs and Displays (including tablets), Imaging Equipment (which includes printers, copiers, scanners and multifunction devices) and Televisions. Standards for Mobile Phones, Servers and other electronic products are currently under development. A non-fiduciary Advisory Council provides input and advice about EPEAT expansion and other relevant issues.

Over 50 major electronics manufacturers currently have products registered at EPEAT.

The EPEAT system rates electronic products against a range of environmental performance criteria. Products must meet all required criteria to be registered in EPEAT at the Bronze level. They may then be registered as Silver or Gold based on the percentage of optional criteria they meet above that baseline.

The criteria cover the complete lifecycle, from selection of materials to energy use and end-of-life aspects. Recyclability or recycling aspects form a subset of the total criteria, and do not result in an index (the criteria are met with either yes/no, or require stating a percentage).

However, the criteria can be used as an inspiration for a more quantitative approach that does result in an index.

The table shows a selection of EPEAT criteria relating to material selection and recyclability (capita selecta of criteria for PC, displays, imaging equipment, televisions and mobile phones, not exhaustive):

Table 4. EPEAT criteria list (non exhaustive)

Selection of criteria	Required	Optional
Reduction/elimination of environmentally sensitive materials		
Compliance with provisions of European RoHS Directive upon its effective date	R	
Reporting on amount of mercury used in light sources (mg)	R	
Elimination / further reduction of intentionally added:		
– cadmium		O
– mercury		O
– lead		O
– hexavalent chromium		O
– DEHP, DBP, and BBP		O
– extractable nickel		O
– intentionally added SCCP flame retardants and plasticizers in certain applications	R	
– PVC content of external plastic casings	R	
Compliance with provisions of EU Battery Directive	R	
Batteries free of lead, cadmium and mercury		O
Materials selection		
Declaration of postconsumer recycled plastic content (%)	R	
Minimum content of postconsumer recycled plastic		O
Declaration of renewable/bio-based plastic materials content (%)	R	
Minimum content of renewable/bio-based plastic material		O
Declaration of product weight	R	
Design for end of life		
Identification of materials with special handling needs	R	
Elimination of paints or coatings that are not compatible with recycling or reuse	R	
Easy disassembly of external enclosure	R	
One recyclable plastic type per rigid plastic part > 25g		O
Marking of plastic components	R	
Identification and removal of components containing hazardous materials	R	
Reduced number of plastic material types		O
Moulded/glued in metal eliminated or removable		O
Preparation of product end-of-life characterization report	R	

Some 23 criteria (not only end-of-life related) must be met in order to be eligible, and depending on the score of optional criteria a rating of bronze, silver or gold is attained.

In the USA only, some 221 desktops are registered with EPEAT, with over half of them registered as 'gold'. The number of registered monitors is 609, with 2/3 registered as 'gold', and the number of notebooks is 474 of which over 2/3 is registered as 'gold' (complete overview at https://ww2.epeat.net/searchoptions.aspx).

The total number of registered computers and displays is 1595, imaging equipment is 1818, televisions is 73 and mobile phones is 15 in the USA.

However, the apparent success also has its criticasters which state that the criteria are under pressure by large manufacturers to be more easily attainable. A controversial episode involved the 2012 Apple MacBook Pro with Retina Display. Historically, the MacBook Pro line had been modular, repairable, and upgradeable. The 2012 Retina MacBook Pro, however, shipped with a proprietary SSD, non-upgradeable RAM, and a glued-down lithium-ion battery. Initially, the product did not receive the highest rating, but after Apple appealed and was able to convince the standards board to adjust the language around what elements made a product “upgradeable,” the laptop was marked with an EPEAT “Gold” rating[63]. Repair Association board member M. Schaffer states that tech companies are fighting to keep the requirements unchanged so that every new product can be easily labelled environmentally friendly without companies having to alter any aspect of the design or manufacturing process. Allegedly, products can be 'gold' certified and have a battery that is glued to the device.

5.1.1.2 Other criteria lists

The Cyclos report[64] describes several other methods that aim to address recycling issues or potential of products. These are:

1) Umweltzeichen Blauer Engel ("weil recyclinggerecht");
   a) The method is a list of criteria related to construction and materials. The criteria are either mandatory ('Muss' = must) or optional ('Soll' = shall, preferred but not mandatory). The criteria are to a large degree similar to those applied in the Kirchner/Prumbohm method.
2) ONR 192102 "Nachhaltigkeitsiegel für reparaturfreundlich konstruierte Elektro- und Elektronik-Geräte";
   a) This Austrian method is a list with required and optional criteria;
3) VDI-Richtlinie 2243 "Recyclingorientierte Productentwicklung";
   a) This method, developed in July 2002, is also a criteria-list, but is more elaborate and technical than others and offers more levels of assessment than just pass/fail. It also allows assessment of the improvement potential.
   b) The table of criteria:

[63] https://www.theverge.com/2017/8/3/16087628/apple-e-waste-environmental-standards-ieee-right-to-repair

[64] http://www.fachdokumente.lubw.baden-wuerttemberg.de/servlet/is/109472/?COMMAND=DisplayBericht&FIS=203&OBJECT=109472&MODE=METADATA

Technische Recycling-Kriterien	Bewertung	Optimierungs-Potenzial durch
Stoffliche Verwertbarkeit	recyclingfähig, gleiche Eigenschaften	keine Optimierung nötig
	recyclingfähig, mindere Eigenschaften	Einsatz höherwertigerer Werkstoffe prüfen
	nicht verwertbar, Beseitung nötig	recyclingfähige Werkstoffe verwenden
Verwertungs-kompatibilität	kompatibel, gleiche Eigenschaften	keine Optimierung nötig
	kompatibel, mindere Eigenschaften	eventuell Stoffvielfalt optimieren
	nicht kompatibel	verträgliche Werkstoffe verwenden
Identifizierbarkeit	eindeutig, einfach, maschinenlesbar	keine Optimierung nötig
	gut separierbar, keine Kennzeichnung	mindestens Kennzeichnung vorsehen
	nicht möglich, keine Kennzeichnung	vermeiden, Kennzeichnung vorsehen
Recyclingkritische Stoffe	nicht vorhanden	keine Optimierung nötig
	vorhanden, gekennzeichnet, gut separierbar	dauerhaft gute Lesbarkeit sichern
	vorhanden, unseparierbar, Beseitigung nötig	vermeiden, Kennzeichnung und Demontage vorsehen
Schad- und Gefahrstoffe	nicht vorhanden	keine Optimierung nötig
	vorhanden, gut separierbar	mindestens Kennzeichnung vorsehen
	vorhanden, unseparierbar, Beseitigung nötig	vermeiden, Kennzeichnung und Demontage vorsehen
Erkennbarkeit	eindeutig, sichtbar	keine Optimierung nötig
	nicht sichtbar, aber Hinweis	Kennzeichnung vorsehen
	nicht sichtbar, kein Hinweis	Hinweis und Kennzeichnung vorsehen
Zugänglichkeit	direkt zugänglich	keine Optimierung nötig
	indirekt zugänglich	eventuell Demontagetiefe verbessern
	nicht zugänglich	Änderung auf axiale Zugänglichkeit prüfen
Verbindungsarten	zerstörungsfrei lösbar	keine Optimierung nötig
	teilzerstörend, nur Verbindung	zerstörungsfreie Verbindung verwenden
	zerstörend, auch Bauteilbeschädigung	lösbare Verbindungen verwenden
Vielfalt der Verbindungen	eine/wenige, einheitliche Art	keine Optimierung nötig
	funktionsbedingt mehrere, standardisiert	eventuell mögliche Reduzierung prüfen
	unübersichtlich viele	Anzahl reduzieren
Demontage-Zeit	gering	keine Optimierung nötig
	vertretbarer Aufwand	eventuell mögliche Reduzierung prüfen
	sehr hoch, nicht akzeptabel	Zugänglichkeit verbessern, Modulbauweise anwenden
Recycling-Prozesse	optimaler Prozess vorhanden	keine Optimierung nötig
	aufwändige Prozessschritte nötig	Verträglichkeiten prüfen
	kein Prozess für Stoffe vorhanden	Werkstoffe ändern, vereinheitlichen

None of the above methods or projects resulted in an easy to apply method that allowed quantification of the recycling potential or recyclability.

5.1.2 Recyclability scores

5.1.2.1 Cyclos GmbH

Cyclos GmbH is a German specialist consultancy in the field of packaging, battery and electrical and electronic waste disposal, supporting clients in a practical and result-oriented manner on all aspects of waste and environmental management.

In 2013 the company developed a method[65] „Recyclinggerechte Produktkonzeption von Elektro(nik)geräten zur Förderung der Produktverantwortung“ for *Umweltforschung in Baden-Württemberg*.

Cyclos developed a new criteria-list, which takes into account design criteria based on the WEEE Directive and other design aspects:

1) Legal requirements;
2) Structure and joints – part A;
3) Structure and joints – part B;
4) Material selection and information/marking;
5) Selective treatment.

The comprehensive criteria-list is shown below:

[65] Bartnik, S.; Löhle, S.; Müller, M.; Kerkhoff, M.; „Recyclinggerechte Produktkonzeption von Elektro(nik)geräten zur Förderung der Produktverantwortung“; Final report; Funding code: L75 13001, Oktober (2013), 97 pages plus 258 pages appendix.

Nr.	Kriterium	Art*	gilt für	Ziel	mögliche Umsetzung
Konkrete rechtliche Anforderungen[1)]					
1	Sicherstellung der problemlosen Entnehmbarkeit der Batterien und Akkumulatoren (§ 4 ElektroG)	MUSS	Geräte gemäß ElektroG, die vollständig oder teilweise mit Batterien oder Akkumulatoren betrieben werden können	Schadstoffentnahme, Schadstoffentfrachtung	zerstörungsfrei, ohne Werkzeug zerstörungsfrei, mit Universalwerkzeug zerstörungsfrei, mit Spezialwerkzeug teilzerstörend (Verbindung) zerstörend (Bauteilbeschädigung)
zus.	sofern vorangehend "teilzerstörend / zerstörend": Erforderlichkeit einer ununterbrochene Stromversorgung aus Gründen der Sicherheit, der Leistung, aus medizinischen Gründen oder aus Gründen der Vollständigkeit von Daten?				ja nein
Baustruktur und Verbindungstechnik - TEIL A[2)]					
2	Lösbarkeit von Verbindungen, die im Rahmen der Demontage (ggf. Reparatur) getrennt werden müssen	MUSS	Gehäuse -> Baugruppen	Sicherstellung der Zugänglichkeit für Baugruppen für deren Entnahme / Austausch (u.a. im Rahmen der Wiederverwendung) bei Öffnung des Gerätes	zerstörungsfrei, ohne Werkzeug zerstörungsfrei, mit Universalwerkzeug zerstörungsfrei, mit Spezialwerkzeug teilzerstörend (Verbindung) zerstörend (Bauteilbeschädigung)
3	Gehäuseteile sind frei von Elektronikbaugruppen	MUSS	Gehäuse	Sicherstellung der Wiederverwendung und Trennung von unverträglichen Materialien	ja nein
4	Auffindbarkeit zu lösender Verbindungen	SOLL	gesamte Einheit	Sicherstellung der Zugänglichkeit für Baugruppen und Trennung von unverträglichen Materialien	vollständig erfüllt überwiegend erfüllt kaum erfüllt nicht erfüllt
→	Verhinderung der Wiederverwendung durch besondere Konstruktionsmerkmale (§ 4 ElektroG) (Auswertung Punkte 2 - 4, "nein", wenn alle MUSS-Kriterien positiv (grün/gelb) bewertet wurden)				nein ja
zus.	sofern vorangehend "ja": Erforderlichkeit dieser Konstruktionsmerkmale aus rechtlichen Gründen, aufgrund von überwiegenden Vorteilen im Hinblick auf den Gesundheitsschutz, den Umweltschutz oder auf Sicherheitsvorschriften				ja nein
Baustruktur und Verbindungstechnik - TEIL B[3)]					
5	Trennbarkeit miteinander unverträglicher Werkstoffe von Bauteilen	MUSS	Gehäuse -> Baugruppen	Sicherstellung der Trennung von unverträglichen Materialien bzgl. weiterer Verwertung	zerstörungsfrei, ohne Werkzeug zerstörungsfrei, mit Universalwerkzeug zerstörungsfrei, mit Spezialwerkzeug teilzerstörend (Verbindung) zerstörend (Bauteilbeschädigung)
6	Zerlegbarkeit in Einzelteile, die als Ersatzteile erhältlich sind	SOLL	gesamte Einheit	Sicherstellung möglicher Reparatur und Wiederverwendung	vollständig erfüllt überwiegend erfüllt kaum erfüllt nicht erfüllt
7	Vielfalt der Verbindungsarten	SOLL	gesamte Einheit	Reduzierung Demontageaufwand	wenige mehrere viele
8	Vielfalt der Demontagewerkzeuge	SOLL	gesamte Einheit	Reduzierung Demontageaufwand	wenige mehrere viele
9	Zugänglichkeit der Verbindungselemente (Arbeitsräume, Angriffspunkte für Demontagewerkzeug)	SOLL	gesamte Einheit	Reduzierung Demontageaufwand	vollständig / überwiegend erfüllt kaum / nicht erfüllt
10	Personaleinsatz bei Demontage	SOLL	gesamte Einheit	gesamte Einheit	eine Person mehrere Personen
Werkstoffwahl und Kennzeichnung[3)]					
11	Die Werkstoffvielfalt bei Kunststoffbauteilen vergleichbarer Funktion ist auf einen Werkstoff begrenzt	SOLL	gesamte Einheit	Sicherstellung der getrennten Erfassung / Verwertung	ja nein
12	Kennzeichnung von Kunststoffteilen > 25 g und einer ebenen Fläche von mindestens 200 mm² nach EN/ISO 11469 unter Beachtung von ISO 1043	SOLL	gesamte Einheit	Sicherstellung der getrennten Erfassung / Verwertung	vollständig erfüllt überwiegend erfüllt kaum erfüllt nicht erfüllt
13	Färbung von Bauteilen, die aus dem gleichen Kunststoff gefertigt sind	SOLL	gesamte Einheit	Sicherstellung der getrennten Erfassung / Verwertung	einheitlich/verträglich teilweise keine
→	Erleichterung der Demontage, Wiederverwendung und stofflichen Verwertung von Altgeräten, Bauteilen und Werkstoffen (§ 4 ElektroG)				ja nein
Selektive Behandlung[4)]					
14	Entnahme von Bauteilen und Werkstoffen gemäß Anhang III ElektroG (mit Ausnahme von Batterien und Akkumulatoren)	MUSS	gesamte Einheit	Selektive Behandlung, Schadstoffentfrachtung, Vorbereitung Umsetzung § 11 Abs. 2 ElektroG	einfach mittel schwer
15	Kennzeichnung/Identifikation von Bauteilen und Werkstoffen gemäß Anhang III ElektroG	MUSS	gesamte Einheit	Selektive Behandlung, Schadstoffentfrachtung, Vorbereitung Umsetzung § 11 Abs. 2 ElektroG	eindeutig, einfach teilweise keine
→	Gewährleistung der selektiven Behandlung von den im ElektroG Anhang III genannten Stoffen, Gemischen und Bauteilen im Verwertungsprozess				ja nein

Anmerkungen

* MUSS-Kriterien sind bzgl. der jeweiligen Anforderungen gemäß § 4 und § 11 Abs. 2 ElektroG mindestens zu erfüllen (grün/gelb)

1) in direkter Ableitung der Anforderungen gemäß § 4 ElektroG

2) in indirekter Ableitung der Anforderung, dass "die Wiederverwendung nicht durch besondere Konstruktionsmerkmale oder Herstellungsprozesse verhindert werden soll" (§ 4 ElektroG)

3) in indireter Ableitung der Anforderung, dass "Elektro- und Elektronikgeräte möglichst so zu gestalten sind, dass die Demontage und die Verwertung, insbesondere die Wiederverwendung und die stoffliche Verwertung von Altgeräten, ihren Bauteilen und Werkstoffen, berücksichtigt und erleichtert werden" (§ 4 ElektroG)

4) in Ableitung der Anforderungen gemäß § 11 Abs. 2 ElektroG und Anhang III bzgl. selektiver Behandlung

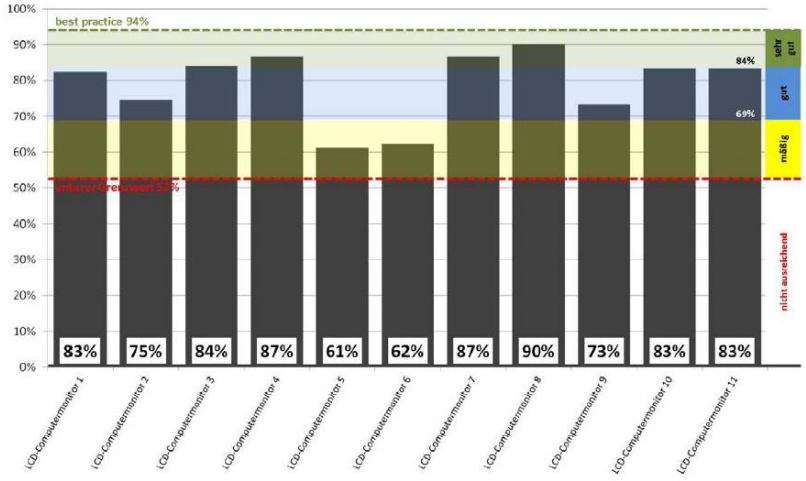
The study then identified product groups for testing of the method and acquired a number of test products (pieces indicated): smartphones (14 pcs.), cordless drills (8 pcs.), shavers (10 pcs.), LCD displays (11 pcs.). The products were tested at a facility of a WEEE operator.

The criteria are weighted in accordance with the goal of the assessment (can be limited to legal requirements only, or a full technical assessment). The weighing factors below are for a full technical assessment:

Nr.	Kriterium	Umsetzung	Gewichtung Umsetzung	Gewichtung Kriterium	Gewichtung Obergruppe
Konkrete rechtliche Anforderungen					
1	Sicherstellung der problemlosen Entnehmbarkeit der Batterien und Akkumulatoren	zerstörungsfrei, ohne Werkzeug	100%	100%	**15%**
		zerstörungsfrei, mit Universalwerkzeug	75%		
		zerstörungsfrei, mit Spezialwerkzeug	50%		
		teilzerstörend (Verbindung)	25%		
		zerstörend (Bauteilbeschädigung)	0%		
zus.	sofern Σ Gewichtung Kriterium = 0%, trifft Aussnahmeregelung zu?	ja	100%		
		nein	0%		
Baustruktur und Verbindungstechnik - TEIL A					
2	Lösbarkeit von Verbindungen, die im Rahmen der Demontage (ggf. Reparatur) getrennt werden müssen	zerstörungsfrei, ohne Werkzeug	100%	40%	**40%**
		zerstörungsfrei, mit Universalwerkzeug	75%		
		zerstörungsfrei, mit Spezialwerkzeug	50%		
		teilzerstörend (Verbindung)	25%		
		zerstörend (Bauteilbeschädigung)	0%		
3	Gehäuseteile sind frei von Elektronikbaugruppen	ja	100%	30%	
		nein	0%		
4	Auffindbarkeit zu lösender Verbindungen	vollständig erfüllt	100%	30%	
		überwiegend erfüllt	75%		
		kaum erfüllt	25%		
		nicht erfüllt	0%		
zus.	sofern Σ Gewichtung Kriterium < 50%, trifft Aussnahmeregelung zu?	ja	100%		
		nein	0%		
Baustruktur und Verbindungstechnik - TEIL B					
5	Trennbarkeit miteinander unverträglicher Werkstoffe von Bauteilen	zerstörungsfrei, ohne Werkzeug	100%	30%	**15%**
		zerstörungsfrei, mit Universalwerkzeug	75%		
		zerstörungsfrei, mit Spezialwerkzeug	50%		
		teilzerstörend (Verbindung)	25%		
		zerstörend (Bauteilbeschädigung)	0%		
6	Zerlegbarkeit in Einzelteile, die als Ersatzteile erhältlich sind	vollständig erfüllt	100%	30%	
		überwiegend erfüllt	75%		
		kaum erfüllt	25%		
		nicht erfüllt	0%		
7	Vielfalt der Verbindungsarten	wenige	100%	10%	
		mehrere	50%		
		viele	0%		
8	Vielfalt der Demontagewerkzeuge	wenige	100%	10%	
		mehrere	50%		
		viele	0%		
9	Zugänglichkeit der Verbindungselemente	vollständig / überwiegend erfüllt	100%	15%	
		kaum / nicht erfüllt	0%		
~~10~~	~~Personaleinsatz bei Demontage~~	~~eine Person~~	~~100%~~	5%	
		mehrere Personen	0%		
Werkstoffwahl und Kennzeichnung					
11	Die Werkstoffvielfalt bei Kunststoffbauteilen vergleichbarer	ja	100%	40%	**10%**
		nein	0%		
12	Kennzeichnung von Kunststoffteilen > 25 g und einer ebenen Fläche von mindestens 200 mm²	vollständig erfüllt	100%	40%	
		überwiegend erfüllt	75%		
		kaum erfüllt	25%		
		nicht erfüllt	0%		
13	Färbung von Bauteilen, die aus dem gleichen Kunststoff gefertigt sind	einheitlich/verträglich	100%	20%	
		teilweise	50%		
		keine	0%		
Selektive Behandlung					
14	Entnahme von Bauteilen und Werkstoffen gemäß Anhang III (ohne Batterien und Akkumulatoren)	einfach	100%	75%	**20%**
		mittel	50%		
		schwer	0%		
15	Kennzeichnung/Identifikation von Bauteilen und Werkstoffen gemäß Anhang III	eindeutig, einfach	100%	25%	
		teilweise	50%		
		keine	0%		

An important deciding factor for the overall score is whether a battery is easily removable for separate treatment. The scoring (Umsetzung) of technical characteristics depends on personal judgement of the test personnel (although guidelines can be given).

For all products the score was calculated. The example below is for LCD-displays:



The relatively low score for LCD 5 and 6 is because of poor separability of incompatible materials (LCD 5), poor removability of replacement parts (LCD 5), difficult removal of certain substances (LCD 5,6) and low score for identification of joints to be removed (LCD 6).

For other product groups similar profiles have been established.

The benefit of this method is its strong link to legal requirements. A drawback is the personal judgement involved which reduces reproducibility.

5.1.2.2 Kirchner, J.-S.; Prumbohm, M.

Kirchner and Prumbohm[66] developed a method for the quantification of the recycling potential of a product, resulting in a minimum 0% to maximum 100% score[67].

Parts and design solutions are awarded a score and a weighting: Generally applicable construction solutions are weighted with a factor 4, the effort required for recycling factor 2, improvement potential factor 4 and ability to allow combining factor. This results in a combined weighing factor G_i for each construction aspect.

For all applicable design solution result in a score $P_G = \Sigma G_i$ Each design solution is then awarded a score between 0 to 4, which is multiplied with a factor $\eta_r = G_i / (4*P_g)$

If applied to an Apple iPad the table below shows the original score and the score of an (theoretical) improved model.

[66] 3.6.1 Kirchner, J.-S.; Prumbohm, M., Bewertung der recyclinggerechten Gestaltung von Konstruktionen und Produkten, Clausthal University of Technology (CUT), Clausthal-Zellerfeld, Germany, 2016
[67] https://dokumente.ub.tu-clausthal.de/receive/clausthal_mods_00000377

Figure 22. Kirchner/Prumbohm assessment

Original design

Tabelle 1: Vorgehensweise zur Bewertung der Recyclingeignung eines frei im Handel erhältlichen Tablet-Computers

G_i	Titel der Maßnahme	Punkte	η_r	Ergebnis
Produktrecycling				
38	Verwendung lösbarer Verbindungselemente	1	0,013	1,33
33	Reduzierung der Anzahl von Verbindungselementen	3	0,011	3,48
39	Erleichterte Zugänglichkeit von Verbindungselementen	0	0,013	0
36	Verwendung alterungs- und korrosionsbeständiger Verbindungselemente	3	0,012	3,78
41	Standardisierung von Bauteilen und Verbindungselementen	2	0,014	2,88
34	Aufbau von Baugruppen auf einem Basisbauteil	3	0,011	3,57
42	Bildung von variantenneutralen Baugruppen	3	0,014	4,41
34	Leichte Separierbarkeit wiederverwendbarer Baugruppen	1	0,011	1,19
28	Leichte Separierbarkeit unvermeidbarer Gift- und Gefahrstoffe	1	0,009	0,98
37	Bereitstellung von Demontageinformationen und Informationen zur Wiederverwendung	0	0,013	0
31	Ermöglichung der Bauteilaufarbeitung	1	0,010	1,09
	Zwischensumme Produktrecycling:			22,71 %
Materialrecycling				
39	Einheitliche und geradlinige Füge- und Trennrichtung	4	0,014	5,48
43	Abwägung zwischen Integral- und Differentialbauweise	3	0,015	4,53
38	Erleichterte zerstörende Demontage	2	0,013	2,66
36	Verwendung stofflich verwertbarer und nachwachsender Materialien	3	0,013	3,78
43	Verringerung der Werkstoffvielfalt	1	0,015	1,51
33	Vermeidung unverträglicher Werkstoffkombinationen	1	0,012	1,16
40	Verwendung von Rezyklaten	2	0,014	2,8
47	Bereitstellung von Werkstoffinformationen	1	0,016	1,65
	Zwischensumme Materialrecycling:			23,57 %
	Gesamtsumme Recyclingeignung der Konstruktion:			46,28 %

Improved design

Tabelle 2: Bewertung der Recyclingeignung eines überarbeiteten Entwurfs für einen recyclinggerechten Tablet-Computer

G_i	Titel der Maßnahme	Punkte	η_r	Ergebnis
Produktrecycling				
38	Verwendung lösbarer Verbindungselemente	**4**	0,013	5,32
33	Reduzierung der Anzahl von Verbindungselementen	3	0,012	3,48
39	Erleichterte Zugänglichkeit von Verbindungselementen	**3**	0,014	4,11
36	Verwendung alterungs- und korrosionsbeständiger Verbindungselemente	3	0,013	3,78
41	Standardisierung von Bauteilen und Verbindungselementen	2	0,014	2,88
34	Aufbau von Baugruppen auf einem Basisbauteil	3	0,012	3,57
42	Bildung von variantenneutralen Baugruppen	3	0,015	4,41
34	Leichte Separierbarkeit wiederverwendbarer Baugruppen	**3**	0,012	3,57
28	Leichte Separierbarkeit unvermeidbarer Gift- und Gefahrstoffe	**3**	0,0098	2,94
37	Bereitstellung von Demontageinformationen und Informationen zur Wiederverwendung	**4**	0,013	5,2
31	Ermöglichung der Bauteilaufarbeitung	**2**	0,011	2,18
	Zwischensumme Produktrecycling:			41,44
Materialrecycling				
39	Einheitliche und geradlinige Füge- und Trennrichtung	**3**	0,014	4,11
43	Abwägung zwischen Integral- und Differentialbauweise	3	0,015	4,53
38	Erleichterte zerstörende Demontage	**3**	0,013	3,99
36	Verwendung stofflich verwertbarer und nachwachsender Materialien	3	0,013	3,78
43	Verringerung der Werkstoffvielfalt	**2**	0,015	3,02
33	Vermeidung unverträglicher Werkstoffkombinationen	**3**	0,012	3,48
40	Verwendung von Rezyklaten	2	0,014	2,8
47	Bereitstellung von Werkstoffinformationen	**4**	0,016	6,6
	Zwischensumme Materialrecycling:			32,31
	Gesamtsumme Recyclingeignung der Konstruktion:			73,75 %

A drawback is that the method is tuned towards disassembly as recycling technology, with an emphasis on removability of components ("Produkt recycling"). It does not fully consider the limitations of current end-of-life treatment technologies.

5.1.2.3 iNEMI – International electronics manufacturing initiative

iNEMI, the International Electronics Manufacturing Initiative[68] is developing a recyclability metric under its umbrella program dealing with sustainable electronics[69].

In July 2015 the first phase of the Repair and Recycling metrics resulted in a report that presented the following key findings:

1) Mass-based Recyclability Metrics (IEC 62635 and ISO 22628) are inadequate to the goal of measuring the environmental impact of product recycling. Missing are:
   a) Cost Drivers and Methodologies that determine IF a product or material will be recovered:
      i) Value of the recovered material (Can it be recovered? Can it be sold?)
      ii) Cost of Liberation/Separation (Can it be separated into clean streams?, What does it take to liberate the materials?)
      iii) Leading Edge technology introduces products that might not have a recycle technology available (LCD TV's)
      iv) Product Useful Life can create a long recovery cycle where demand, usage models, recycle capacity and capability, and market demand for the material can change dramatically (glass)
   b) Recyclable potential does not mean a product or material IS recycled.
2) No Metrics or Guidance for Reusability, Reparability, and Refurbish ability.

[68] iNEMI is a not-for-profit R&D consortium of approximately 90 leading electronics manufacturers, suppliers, associations, government agencies and universities. iNEMI's mission is to forecast and accelerate improvements in the electronics manufacturing industry for a sustainable future

[69] http://community.inemi.org/env

Phase I of the project found a mass-based recycle metric in an IEC Technical Report:

- Depends on data which is not readily available (BoM, RRR rates)
- Does not specify the costs/revenues of reuse
- Does not specify the ability to practically separate and liberate the components and materials

After concluding phase 1, the project on Reuse and Recycling Metrics continued with Phase 2. The interim findings of Phase 2 were presented to the public on 5 December 2017 and present the following[70]:

The objective of Phase 2 was to develop a 'Value Scoring' system for electronics that includes design, economic, liberation and regional factors.

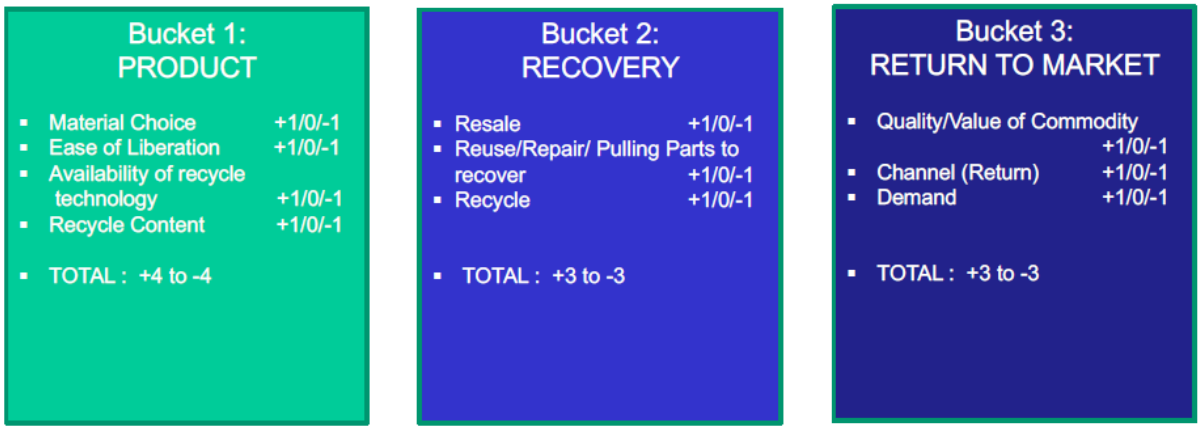
The project goals are:

- Develop a design score to measure and improve material choice, material and component liberation value (materials + liberation + circular economy impacts) to support highest net value at EOL.
- Identify product-related cost factors influencing economic feasibility of reuse and recycling
- Identify weighting factors
- Develop a metric system that can be applied to different electronic products
- Get ahead of regulations

The desired deliverable is a simple set of metric(s) that includes the calculations, scoring and value factors, tables (estimated if actual data is not available) that take into consideration: technology forecasts, price forecasts, design forecasts.

The proposed metric follows a 'bucket structure' in which scores for Product Design Assessment, Recovery (Recycle, Repair, Reclamation, Reuse) Assessment and Market Assessment are combined.

Figure 23. Bucket structure in iNEMI's Phase 2 of Reuse and Recycling Metrics project



The scoring structure is kept extremely simple:

Scores of +1/0/-1 are awarded where:

- +1 is assigned to the best in class examples – Rewards good product designs or recycle methods
- 0 is assigned as the default – Acts as the Baseline for the feature being assessed
- -1 is assigned to examples of what not to do – Punishes features that significantly damage the value of the materials being reclaimed.

Examples are provided below:

Figure 24. Bucket 1: Product Design Assessment

[70] http://community.inemi.org/reuse_recycling_2. This information was added after 5 December 2017

Feature	+1	0	-1
Material Choice	High Quality Recycle Materials (list from Return to Market Category) Biodegradable Dioxin Free Materials?	Most Commonly Found Materials Beryllium copper	Radioactive Materials, Hazardous Materials, Banned or Controlled Materials Exterior leather use Fluorinated Gases
Ease of Liberation	pull tab adhesive snap fit	screws	Fused or joined desperate metals Specified adhesive technology
Availability of Recycle Technology	TBA	Baseline	TBA
Recycle Content	TBA	Baseline	TBA

Figure 25. Bucket 2: Recovery Assessment

Feature	+1	0	-1
Resale	Product that is still desirable even after newer products have hit the market	Can product go back out without having to do much to the product?	Product that has been replaced and considered obsolete.
Reuse, Repair, Pulling Parts	Product needs little work for reuse.	Is there a secondary market for the existing product?	Product is obsolete Liberation of parts are time consuming / no value.
Recycle	Materials being removed are recyclable. • Gold, Aluminum, Stainless Steel, Brasses, Copper, Copper/Berylium	Materials used has no other function other than back to it's original commodity.	Materials used have a cost to dispose. (Smelting, Universal Waste, Waste to Energy)

Figure 26. Bucket 2: Return to Market Assessment

Feature	+1	0	-1
Quality or Value of Commodity	Magnets Precious/Semi-precious Metals/Commodity Metals	Value = process costs	Unrecyclable/Unrecoverable Materials Hazardous Materials
Return Channel	Incentive program to return product (free or incentive)	Drop-off location/Take back collection scheme	No organized method for pickup No collection scheme No mandate for collection
Demand	high need	Speculative purchases/storage for market fluctuations	few buyers

For the next phase iNEMI will take the following steps:

- Refine the Categories/Features in The Bucket Structure
- Design and Test The Scoring Structure
- Development of the overall metric
    - Start mass-based (from IEC TR 62635/Phase 1) and determine how to include weighting factors based on the Bucket List
    - Needs to be transparent, simple to use and repeatable
    - Validate metric
    - Dynamic Updating of Data (like value of materials, recycle capabilities, best in class)
- Continue Design Thinking Methodology (Empathy Map)
    - Are we addressing the key needs for Product Design, Reuse and Recycling? What are the pressure points?
- Research Data like Recycle Capabilities by Region, value of materials and/or components/assemblies etc.

5.1.3 Whole product recycling rate

5.1.3.1 IEC/TR 62635

The IEC/TR 62635:2012 describes a recyclability rate calculated on the basis of mass of parts and the recycling rate of parts. JRC followed up on this method and applied it in their REAPRo and Reference study and therefore both approaches are considered to be identical.

IEC/TR 62635 and JRC describe a 'recyclability rate', defined as:

Equation 1. Whole product recycling rate

$$R^*_{cyc} = \frac{\sum_{i=1}^{P} \left(m_{recyc,i} \cdot RCR_i \right)}{m} \cdot 100 \qquad [\%]$$

Where:

R*cyc = Recyclability rate [%]

m = total product mass [kg]

$m_{recyc,i}$ = mass of the ith recyclable part [kg]

RCR_i = recycling rate of the ith part [%]

P = number of recyclable parts

The calculation assumes that parts can be identified to which 'part-specific' recycling rates apply. In practice, as seen in the application by JRC in the Reference study, the part is interpreted as the fraction of a specific material, and the RCR is interpreted as the material-recycling rate as known from various sources (in the JRC study the RCR is based on information from WF-Reptool).

The method, although referred to as 'recyclability rate' is therefore essentially a 'whole product' recycling rate, composed of specific material recycling rates, weighted by their respective mass fraction.

Concluding, the IEC 62635 mass balance approach drives designs towards an increased use of easily recyclable metals (steel, iron, aluminium) but ignores the presence of precious metals and polluting substances, nor does it address (with the current availability of data) the present-day difficulty in separating and sorting of materials, such as plastics with brominated flame retardants.

Proponents of the IEC methodology warn against inclusion of elements that introduce an assessment of product design and how this interacts with a certain waste treatment technology (or combinations thereof), by adjusting certain recycling rates. They fear such elements could hinder innovation and lead to suboptimized products as treatment technologies continue to evolve and may render product designs optimised for a specific treatment obsolete. Then again, it may take quite some time before such treatment is completely eradicated from the EU waste treatment facilities.

In such cases, with unknown risks, the EU is accustomed to apply the precautionary principle ("better safe than sorry"). In the above discussion this could mean that products have to be optimised for as much as possible treatment methods, or more specific: both automated and manual methods.

The RE parameters by JRC-IES provide a methodological framework but hardly any input values for that framework. The number and nature of inputs required, and the possible conflicts that these inputs will cause means that the implementation at the level of preparatory Ecodesign studies will be very costly and Commission and Member States will need to find/allocate budgeting for extensions of Ecodesign preparatory studies or for specific RE studies in parallel to Ecodesign preparatory studies.

5.1.3.2 VDE Implementation of IEC 62635

The German electrotechnical association VDE (36,000 members, 1,300 companies) develops its own standards for electric and electronic devices and has developed a "VDE Recyclability Report" which "follows the suggestions of draft standard IEC 62635 on “End of life recyclability calculation for electrical and electronic equipment"[71]. The method comprises 5 steps:

1. The first step is a disassembly of the product into so-called "functional units", described as "A functional unit [is] defined as a part of a device that can either not be disassembled further (plastic parts, metal parts, PWBs) or

[71] Recyclability Report by VDE Testing and Certification Institute, Date: July 2017, VDE Testing and Certification Institute, Germany

takes a long time to do the disassembly at minimal gain of recycled share i.e. if the product weight share of the functional unit and recoverable recycling share is less than 10 % (for example speaker, vibra call motors, etc.).". The resolution of the assessment is thus based on disassembly (as opposed to destruction using automated processes, where materials may not be optimally liberated and/or sorted[72]). It thus assumes that bolted/screwed connections are unfastened whereas this may not be the case in automated processes.

2. In the second step the functional units undergo assay testing, which results in a detailed bill-of-materials. It even mentions the possibility for regulatory compliance assessment at the homogeneous material level i.e. REACH (which again assumes that liberation and sorting is at a very high level).
3. In the third step the results of the assay-tests are matched with 'recycling boxes' which is essentially an assessment of recyclability (and recoverability) depending on material type (yes/no) and material purity (if sufficient pure, it can be recycled. For plastics purity must be > 97% in most cases). This ignores the fact that in most treatment facilities most plastics are commingled and mixed and require extensive separating and sorting treatment to result in a possible useable fraction (and involves losses at various stages as well)
4. In the fourth step the recyclability (and recoverability) are calculated according a number of scenarios: Recycling optimal (recycling at highest level of disassembly), regulatory disassembly (removal of WEEE components), minimal disassembly (disassembly required to meet WEEE target levels) and no disassembly[73] (shredding and smelting). This is simply a check of the calculated values and the required values.
5. The fifth step is the creation of a report, presenting all findings.

This method deviates from the actual practice of recycling for the following reasons:

1. In step 1 the unit is manually disassembled without consideration of the actual technologies applied in recycling plants (shredding, sorting, etc.). The result of the VDE approach is a very long list of almost pure parts/materials[74], whereas in practice, after removal of some critical parts/substances, the product undergoes some form of automated liberation (shredding) during which material liberation (and sorting) is not optimal (examples by Van Schaik and Reuter): The VDE is too optimistic in separation of materials, as it assumes that during recycling the product disintegrates into almost pure metal, plastic, glass and other fractions.
2. By identifying 'recycling boxes' VDE appears to assume that 21 types of plastics can be recycled, regardless how they leave the recycling plant. It ignores the fact that plastics are leaving the facility as a mixed stream, with possible contaminations. The more contaminated the stream, the more difficult it is to sort. Sorting methods based on density or spectroscopy have limitations that are not reflected in the VDE calculations. It assumes that if a plastic can be disassembled, it will be recycled at a high level, regardless of its context (has it been liberated sufficiently and can it be sorted from other plastics?).
3. The recyclability indicator is expressed as % of total product weight, but no waste treatment facility will be able to achieve these values in real life, as it assumes that the product is completely broken down into the smallest functional units of pure material. In the example by VDE it is not clear how the recycling of a PWB (23% of weight) is considered. Currently only the precious metals are recycled, and the majority of the mass of the board (the plastic base board, resins of IC packages, etc.) are incinerated and not recycled. This argument also applies to certain battery packages and displays. The glass, which makes up 27% of the product, is assumed to be recycled, which is only true if indeed one takes the time to remove this from the phone and put it in the right (toughened) glass-waste bin. Steel parts make up 27% of the phone, and a high percentage of these parts are assumed to be recycled, whereas it is imaginable that many parts are connected to the main PWB or other parts with valuable elements in them and end up in a Cu/Ni smelter which recovers precious metals but not steel, aluminium, etc.

All in all, the VDE assessment is not considered to reflect current recycling results of waste treatment facilities.

5.1.4 Environmental benefit ratio

5.1.4.1 Environmental benefit ratio by JRC

Recycling experts agree that the recycling of 1 kg of steel has different environmental benefits than the recycling of 1 kg of gold: The production of some materials is much more polluting than that of others, and the benefits of recycling are therefore also different.

In an attempt to be more comprehensive as regards the benefits of recycling, the method currently known as the recycling benefit rate considers all the impacts: Both beneficial (avoided impacts of virgin production) as detrimental (additional impacts from the recycling processes, including a down cycling factor).

The recycling benefit can be calculated per single impact indicator (e.g. greenhouse gas emissions, acidifying emissions, toxic emissions etc.) as no comprehensive, holistic weighing method has been agreed at EU level. This means that multiple

[72] This is the material versus product-centric discussion as raised by Van Schaik and Reuter
[73] This scenario includes the battery in the list of materials, the other three scenarios don't.
[74] VDE, Test report WEEE ROHS REACH EXAMPLE, Product 1, test period 2011-11-11 - 2012-01-17

indicators must be assessed to provide a full picture of the impacts of recycling of a material and requires political interpretation of which impacts bear more weight.

The JRC studies describe a recyclability benefit rate, which requires an assessment of also impacts over the whole life cycle, and a simplified recyclability benefit rate, whereby the assessment of the life cycle has been removed, and also the down cycling index has been removed.

The (simplified) recyclability benefit rate[75] is defined as:

Equation 2. (Simplified) recyclability benefit rate

$$R'^{*}_{cyc,n} = \frac{\sum_{j=1}^{P}\sum_{i=1}^{N} m_{recyc,i,j} \cdot RCR_{i,j} \cdot \left(V_{n,i,j} - R_{n,i,j}\right)}{\sum_{j=1}^{P}\sum_{i=1}^{N} m_{i,j} \cdot V_{n,i,j}} \cdot 100$$

Where:

- $R'^{*}_{cyc,n}$ = simplified Recyclability Benefit rate for the n^{th} impact category [%];
- P = number of parts of the product;
- N = number of materials in the j^{th} part of the product;
- $m_{recyc,i,j}$ = mass of the i^{th} recyclable material of the j^{th} part [kg];
- $RCR_{i,j}$ = Recycling rate of the material i^{th} of the j^{th} part [%];
- $V_{n,i,j}$ = impact related to the n^{th} impact category for the production of the virgin material i^{th} of the j^{th} part [unit/kg];
- $R_{n,i,j}$ = impact related to the n^{th} impact category for the recycling of the material i^{th} of the j^{th} part[76] [unit/kg];
- $m_{i,j}$ = mass of the i^{th} material of the j^{th} part [kg];

Basically the calculation involves dividing the net avoided impacts by the total impacts, thus the value ranges between 0 (zero avoided impacts, no recycling benefit at all) to 1 (avoided impacts equal total impacts, a zero loss recycling situation).

Although the simplified recyclability benefit rate has removed the burden of doing a complete life cycle assessment, the method still relies on life cycle assessment for the production phase (virgin material impacts) and the end-of-life phase (recycling or recovery impacts). So far, there is no common source for this kind of information: Present life cycle inventory databases like Eco invent may contain much of this data but still rely on implementation using dedicated software like SimaPro or GABI to make calculations. The method currently depends on software implementations by third parties that are not controlled by European Institutions and introduces additional costs, a steep learning curve (especially for inexperienced manufacturers such as importers) and reduced robustness as there are many, many variables.

The method can only be applied by defining a very specific end-of-life treatment (to establish the recycling impacts) as is the case in all life cycle assessments, but the method lacks clear links to product design and specific treatment affecting recycling rates and impacts. The method is not clear or transparent in the way how an improved design leads to lower impacts and depends on 'expert' judgement.

Finally, the single most important point of the method is to resolve the issue of materials not having identical impacts during production and recycling. And although the method allows giving credit to i.e. recovery of gold, as opposed to the mass-based IEC 62635 method, it does not introduce new knowledge: The present day approach to ecodesign requires a life cycle assessment of products, prior to establishing policy options, which allows identification of material 'hot spots' as they happen. There is no urgent need to define a method that makes clear that precious metals and other materials with impacts larger than their weight-based presence suggests are prime candidates for recycling – this is already current practice. In addition, the results are expressed as (avoided) impacts per impact category. This does not allow for a simple overall conclusion on how to improve the product, also as no weighing of impact categories is available for EU law (the weighting is available in individual assessments, like Ecoindicator and Recipe).

In fact, waste treatment facilities see a continuous reduction in presence of valuable materials per tonne of waste products, as this reduces product prices. The effect is that the economics of recycling are under increased pressure as the value to be extracted reduces.

[75] Fulvio Ardente Fulvio, Fabrice Mathieux, Integration of resource efficiency and waste management criteria in European product policies – Second phase Report n° 3, Refined methods and Guidance documents for the calculation of indices concerning Reusability / Recyclability / Recoverability, Recycled content, Use of Priority Resources, Use of Hazardous substances, Durability (final), September 2012

[76] Includes impacts from sorting and processing into raw materials.

5.1.5 Circular economy based methods

5.1.5.1 Circular footprint formula

In the context of the development of product category rules for product environmental footprints[77] (PEFs) a "Circular Footprint Formula" (CFF) has been introduced, combining possible impacts of recycling, re-use and energy recovery. The formula reads[78]:

Figure 27. Circular footprint formula

material $$(1-R_1)E_V + R_1 \times \left(AE_{recycled} + (1-A)E_V \times \frac{Q_{Sin}}{Q_P} \right) + (1-A)R_2 \times \left(E_{recyclingEoL} - E^*_V \times \frac{Q_{Sout}}{Q_P} \right)$$

energy $$(1-B)R_3 \times \left(E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec} \right)$$

disposal $$(1-R_2-R_3) \times E_D$$

Where:

- A: allocation factor of burdens and credits between supplier and user of recycled materials.
- B: allocation factor of energy recovery processes: it applies both to burdens and credits.
- Q_{sin}: quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.
- Q_{sout}: quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.
- Q_p: quality of the primary material, i.e. quality of the virgin material.
- R_1: it is the proportion of material in the input to the production that has been recycled from a previous system.
- R_2: it is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R_2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant.
- R_3: it is the proportion of the material in the product that is used for energy recovery at EoL.
- $E_{recycled}$ (E_{rec}): specific emissions and resources consumed (per unit of analysis) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.
- $E_{recyclingEoL}$ (E_{recEoL}): specific emissions and resources consumed (per unit of analysis) arising from the recycling process at EoL, including collection, sorting and transportation process.
- Ev: specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material.
- E*v: specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.
- E_{ER}: specific emissions and resources consumed (per unit of analysis) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, …).
- $E_{SE,heat}$ and $E_{SE,elec}$: specific emissions and resources consumed (per unit of analysis) that would have arisen from the specific substituted energy source, heat and electricity respectively.
- E_D: specific emissions and resources consumed (per unit of analysis) arising from disposal of waste material at the EoL of the analysed product, without energy recovery.
- $X_{ER,heat}$ and $X_{ER,elec}$: the efficiency of the energy recovery process for both heat and electricity.
- LHV: Lower Heating Value of the material in the product that is used for energy recovery.

The CFF goes beyond the scope of a mere recyclability indicator as it covers material recovery (recycling, but also recycled content), energy recovery and disposal. The output of the method is the net impact (per impact category like global warming potential, acidification, etc.) of the whole EoL. If the value were to be divided by a reference (not recycled / recovered product) a benefit ratio would be the result.

[77] Recommendation 2013/179/EU, Annex V

[78] Product Environmental Footprint 1 Category Rules Guidance 2, Version 6.1 – xxxx 2017 (for questions: env-environmental-footprint@ec.europa.eu)

However, actual application of the method is not simple as the person making the calculations has to make various assessments to define parameters such as:

- the value 'A', which allocates burdens and credits between two subsequent life cycles to reflect market realities;
- the value 'B' which is an allocation factor for energy recovery processes, applicable to both burdens and credits,;
- the 'point of substitution' which corresponds to the point in the value chain where secondary materials substitute primary materials;
- quality ratios Q_{sin}/Q_p and Q_{sout}/Q_p to take into account the quality of both the ingoing and the outgoing recycled materials;
- plus various other rates, parameters, values, etc.

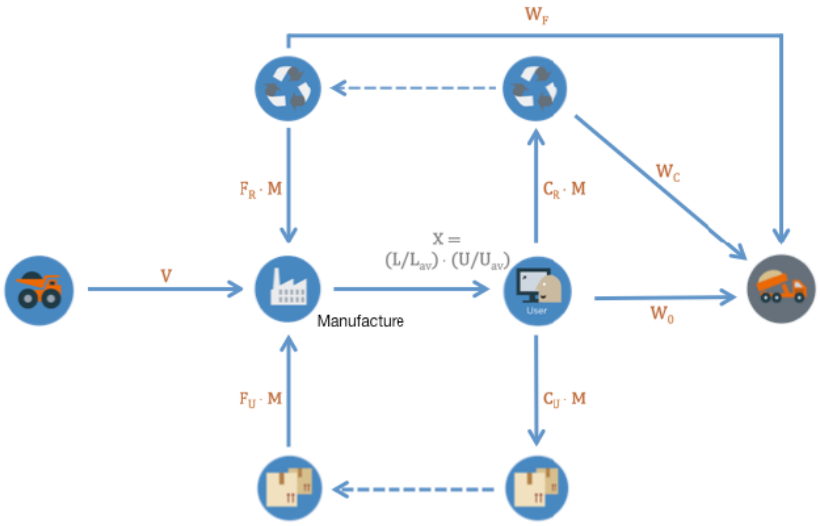
Values for R1, R2 and R3 are provided in an excel-sheet that accompanies the publication (not available in the public domain) but these are still very generic and seem to focus on construction materials mainly. So far, the drawbacks that apply to the previous methods also apply for this method.

5.1.5.2 MCI - Ellen McArthur

The material Circularity Indicator has been developed by Ellen MacArthur Foundation measures the extent to which linear flow has been minimised and restorative flow maximised for its component materials, and how long and intensively it is used compared to a similar industry-average product.

It therefore combines recycling, but also reuse and life time extension into a single indicator. Any product that is manufactured using only virgin feedstock and ends up in landfill at the end of its use phase can be considered a fully 'linear' product. On the other hand, any product that contains no virgin feedstock, is completely collected for recycling or component reuse, and where the recycling efficiency is 100% can be considered a fully 'circular' product. In practice, most products will sit somewhere between these two extremes and the MCI measures the level of circularity in the range 0 to 1.

Figure 28. Material Circularity Indicator



The Material Circularity Indicator is calculated as:

$$MCI^*_p = 1 - LFI \cdot F(X).$$, whereby the MCI cannot be negative

Where:

LFI = linear flow index, taking into account reuse of parts, and (waste from disposal, recycling and recycled content). Disposal includes incineration with heat recovery.

F(X) = utility index, taking into account lifetime and intensity of use

The method is quite unique in that it combines a material flow index with a lifetime/functionality (utility) index.

However, as the LFI part is very much based on a mass balance approach it has the same drawbacks as other mass balance approaches, in that if favours the optimisation (better recycling, more recycled content) in the direction of materials that have a strong effect purely because of their weight and high recycling rates. However, such an approach ignores materials (or substances) that have little weight, but have disproportional economic value (like gold, palladium) or environmental

impacts obstructing LFI optimisation (parts containing hazardous substances need to be separated from recoverable materials and treated appropriately).

Another drawback is that it assumes the required data (recycled feedstock, recycling collection rates, recycling process efficiencies, down cycling, lifetime and functional units of the product) is available. Maybe this is true at a very high aggregate level, it is certainly not available at product specific level (the ABS used in an electric hairdryer probably contains flame retardants, prohibiting recycling, whereas the ABS used in a low voltage motor driven electric shaver probably has no flame retardants, and both products may be treated in the same waste stream, leading to identical recycling rate values for the ABS).

5.1.6 Full metallurgical assessment

5.1.6.1 HSC Sim

As the recovery of valuable materials from waste bears much resemblance to the mining of ores, metallurgical experts have developed software to model the complete treatment of complex, electronic, products. This software takes into account liberation of parts and assemblies in current waste treatment equipment and allows for calculation of losses. Metallurgical liberation and sorting is modelled in great detail, and this method is probably the most refined approach to calculating the recycling to be achieved.

In order to be precise the method does require defining an end-of-life scenario, including the liberation technology (shredding or manual, etc.) applied. The conclusions are therefore relevant only for the defined scenario's.

Figure 29. Recycling scores of Fair phone 2, HSC Sim assessment

Recycling score (10 = max 100%)	Ag	Al	Au	Co	Cr	Cu	Dy	Fe	Ga	In	Li	Mg	Nd	Ni	Pd	Pr	Pt	Sn	Ta	W	Metals recycled	Metals + plastics + other recycled	Recycling + recovery (incineration)	variety recovered	Typical recovery of...
Route 1 direct smelter	10	1	10	10	1	10	1	1	10	10	1	1	1	10	10	1	10	10	1	1	14%	25%	36%	more precious	High recovery as plastics are fuel + oxidizers
Route 2 dismantle	8	2	10	9	1	10	1	1	10	10	10	9	1	10	9	1	10	9	1	1	19%	28%	31%	highest	More Li, Mg, (Al) Less Ag, Co, Pd, Sn
Route 3 shredder	9	2	10	9	1	10	1	8	9	9	10	10	1	9	1	1	10	7	1	1	22%	30%	31%	more bulk	More Fe, (Al) Less Pd, Ag, Co, Ga, In, Ni, Sn

5.1.7 Design Guidelines

The practical experience underlying the full metallurgical model resulted in design guidelines as set out below[79]:

1. Identify and minimize use of materials that will cause losses and contaminations in recycling due to material characteristics and behaviour in sorting:
    a. e.g. concrete in washing machines is difficult to dismantle and distributes over different recycle streams;
    b. glass plates in fridges (is tempered glass, not same as drinking glasses, jars or bulbs[80]);
    c. insulation materials (sound, thermal) are difficult to sort and may contaminate fractions;
    d. use of other than brown/green PCBs lowers sorting yield, increases losses.
2. Identify components/clusters in a product, which will cause problems and losses in recycling due to combined and applied materials:
    a. a compatibility matrix (for metals and plastics) helps to identify and avoid material combinations that affect possible recycling;
3. Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options e.g.:
    a. design critical components on separable or removable parts, e.g. avoid aluminium heat sinks on PCBs, put Fe-intensive functions on different part of PCB, put Ta-capacitors on an easy to remove part (or allow PCB to break in separation process);
4. Labelling of products/components so that they can be easily identified from recyclates and waste streams:
    a. harmonized colour and easy-to-break connections for Ta capacitors;
    b. harmonized identification of CFL (and LED) lamps for dedicated processing;
    c. harmonized identification of refrigerant and foaming agent, plus tapping point

[79] Guidelines in addition to fundamental DfR rules. See: http://www.nvmp.nl/uploads/pdf/nieuws/2013/2013%2010%2011%20Summary%20MARAS%20def3.pdf
[80] http://www.ferver.eu/en/sorting-tips

5. Be mindful of liberation of materials in design (Design for Liberation):
    a. avoid bolts/rivets of dissimilar or incompatible materials;
    b. minimize use of non-reversible adhesives, for incompatible materials (glass + steel, shrink film on CFL tube, sealed batteries, PUR glued to steel/aluminium/plastic;

These conclusions are supported by studies by Ruud Balkenende [81,82] who identified fairly similar design guidelines:

1. only use materials that can be recycled;
2. avoid use of (non-compliant) coatings;
3. limit the number of different / mixed materials;
4. disassembly of PCB in one piece (for smelting);
5. easy/fast detection of materials;
6. use of SMD components;
7. avoid fixed connections;
8. break down (by shredding/disassembly) into:
    a. pieces of uniform composition;
    b. pieces of relatively large size (>1 cm).

Also other work by the TU Delft points to methods that address the issue of how parts/materials are liberated in an automated waste treatment process and, if not liberated, whether they are compatible[83].

The Project "Materialeffizienz und Resourcenschonung (MaRess") resulted in guidelines for design for recycling:

1. avoid polluting substances;
2. mark components to indicate presence or absence of polluting substances;
3. avoid not- or poorly separable joints between incompatible materials;
4. reduce the number of materials applied;
5. apply, where possible, common materials;
6. make information available regarding reuse/recycling/recovery of the product.

5.2 Evaluation of RR methods

The section on practical feasibility shows that RR methods need to address both the design of the product and how it (is expected to) interact with recycling technologies. Furthermore the method needs to fit a legal framework

5.2.1 Criteria

A method based on just material quantities and recycling rates of materials is not sufficient – the method needs to take into account the actual differences in product design that make a product easier or more difficult to recycle/recover assuming real recycling/recovery technologies:

1. See the design guidelines for metals, plastics, natural and ceramic materials and other materials (previous Chapter)

On another level the method needs to address issues relevant for embedding the method in a legal context: For this to happen the method should allow neutral, robust and reliable results of the recyclability of the product. The method and supporting data must allow to be defined in the regulation itself (all manufacturers have to use the same dataset – compliance should not be depending on an arbitrary selection of data). Having data available in the product standard is not sufficient as the use of a (harmonized) standard is not mandatory for proof of conformity (interpretation by market surveillance necessary).

The following criteria are defined:

1. is the method reproducible (will a second assessor, at a different location and time, come to the same results?)
2. is the method transparent (is it clear where data comes from and how it influences results? If the method relies on software, can supply be guaranteed?)
3. is the method consistent with European Law (WEEE, RoHS, REACH, Ecodesign, etc.) and priorities (critical raw materials)?
4. is the method consistent with international law (WTO rules)?
5. is the method enforceable (no excessive costs or overly complex, can be assessed on product data only, excluding production process data);

[81] http://www.io.tudelft.nl/nl/over-de-faculteit/afdelingen/design-engineering/research-areas/circular-product-design/
[82] http://www.hitech-projects.com/euprojects/greenelec/deliverables/vtt_webinar_ruud_balkenende.pdf
[83] https://www.researchgate.net/publication/268193307_Design_Focused_QuickScan_Recyclability_ Assessment_Method

6. can the method be used as basis for variable EPR fees?
7. is the method suited for product specific standards? (not generic)

International law

The aspect of international law is based on WTO rules that prohibit the introduction of barriers to trade. Requirements (such as limit values under Ecodesign, or information requirements under Labelling) could be considered a potential barrier to trade where they address parameters of non-product related process and production methods. These are measures that relate to processes that do not impart any distinguishing characteristics to the final product: For example process emissions, or process energy use, or the sourcing of materials, which cannot be shown in the physical product itself.

One could argue that references to waste treatment processes (such as emissions from a specific treatment process, but possibly also the recycling rate of materials established using WF Reptool data) are references to production processes that are not a distinguishing characteristic of the final product. This clearly applies to the Benefit ratio method, but possibly also to the recycling rates (as established by WF Reptool or similar sources and not directly linked to the specific product and its features).

It must be noted that this topic is heavily debated in international law as one can argue that the mere fact that certain production processes were involved (or avoided) this alone may result in consumers responding differently and the products could be considered not-like, thus allowing such requirements. The jurisprudence however evolves on a case-by-case basis.

For this assessment it is assumed that requirements that include references to process and production parameters that do not impart any distinguishing characteristics to the final product are not allowed under international law.

5.2.2 *Assessment of methods*

Table 5. Assessment of methods[84]

A. Design guidelines	Criteria lists	Recyclability scoring	Whole product recycling rate	Benefit ratio or Circular footprint formula	Full metallurgical assessment
	EPEAT	**Cyclos GmbH**	**IEC/TR 62635**		
Metals					
inseparable Fe/Cu/Al combinations?	partly considered:	yes			yes, considered
printed circuit boards separable before shredding?	indication of handling needs	yes			yes, considered
batteries separable before shredding?	disassembly of enclosure	yes	no, the method has no penalties for poor removability	no, the method does not consider poor removability	yes, considered
LCD displays separable before shredding?	moulded/glued in metal eliminated or removable	yes			yes, considered
REE (phosphors, RE magnets) separable?	(not considered)	yes (although not specific for REE)	(not considered)	(not considered)	yes, considered
vibration motors separable?	(not considered)	yes	(not considered)	(not considered)	yes, considered
Plastics					
penalties for higher number of plastics?	yes	yes	no		no
penalty for carbon black plastics?	no	no	no		unknown
penalties for BFR/phthalate plastics?	yes	no	no (but could be implemented)	unsure whether these are counted as recyclable	unknown
penalties for stickers, coatings, etc.?	yes	no	no		unknown
penalties for incompatible plastics?	no	no	no		unknown
are recyclable foams separable before shredding?	no	yes	(not considered)	(not considered)	unknown
Natural and ceramic materials					
are recyclable materials separable before shredding?	only indication of presence	yes	(not considered)	(not considered)	yes, considered
Other materials					
penalties for presence of restricted substances	yes	no	no (but could be implemented)	no (but could be implemented)	unknown

[84] The iNEMI method could not be incorporated due to its availability by 5 December 2017, very close to finalisation of the present RR project.

A. Design guidelines	Criteria lists	Recyclability scoring	Whole product recycling rate	Benefit ratio or Circular footprint formula	Full metallurgical assessment
penalties for necessary use of dedicated equipment	no	no	(not considered)	(not considered)	probably not
	does address PVC content does address recycled content preparation of report marking of plastics	marking of plastics			
B. Legal framework					
is the method reproducible?	depends, results may vary by interpretation of 'easy' etc..	not sure, depends on assessor	yes, if dataset is consistent	limited, due to complexity of assessment	yes
is the method transparent?	yes	depends on assessment	yes, if source dataset is known	yes, but access is costly	method described in papers, but requires closed software
is the method consistent with EU law/priorities?	mostly, except for CRM	yes	no: depollution, liberation / sorting aspects and CRM missing	no: depollution, liberation / sorting aspects and CRM missing	for metals: yes for plastics: unknown
is the method consistent with international law (WTO)?	Not mandatory	Not mandatory	Not mandatory	Not mandatory	Not mandatory
is the method enforceable?	depends, on reproducibility many claims depend on statements and 'paper trails'	depends on reproducibility	yes	in principle yes, but practical constraints	in principle yes, but practical constraints
can the method be uses as basis for variable EPR fees?	in principle, yes	in principle yes (if adapted to recycling criteria only)	no	no	yes
is the method suitable for product specific standards?	yes	yes	currently no product specific datasets	currently no product specific datasets	yes

5.2.3 Conclusions

Chapter 2 on 'how we recycle' and Chapter 4 on 'what we recycle' make clear that it is quite difficult to bring all the materials in a complex ErP to their optimal final treatment destinations. This Chapter 5 looks at present methods that ultimately aim to change this situation, in the context of product design (the methods are not intended to change waste treatment facility operations as this is outside the sphere of influence of product manufacturers).

So how well do the methods fare in changing product design so that recycling is more effortless? And can the methods be applied in a legal setting, with all its requirements?

Criteria methods like the EPEAT, and simpler versions like the Blue Angel, are versatile and include criteria that, if met, steer the design of products into a direction that should make recycling easier (apart from some incompleteness regarding REE etc.). EPEAT is a well-known international method and tried-and-tested in the real world, with various documents that explain how verification should be done.

The biggest issue we see is that the requirement for parts to be 'easily removable' etc. allows room for interpretation – this is the same issue that caused the row between Apple, EPEAT and critical followers (IFixit, Repair Association). This makes the method less applicable in a legal setting, and could cause issues with enforcement.

For the purpose of only assessing recyclability and recoverability the present EPEAT is too elaborate, but that is not a deal breaker. As EPEAT is set up for assessment of electronic products, the list of criteria would need to be adapted to cover other product groups (the adaption could be relatively small and not complex).

Recyclability scoring methods as developed by Cyclos GmbH show good coverage of design guidelines with a lot of emphasis in liberation aspects. The current implementation is however not very specific as it comes to sorting aspects, especially for plastics.

The method does rely on expert judgement of recyclability aspect (similar to criteria methods) which makes it less robust for a legal context: How does one ensure that the same product, if assessed by different persons, results in an identical score?

Overall, the method does a good job in identifying relevant design aspects, and it is expected that products showing higher scores are indeed easier to recycle.

Whole product recycling rate methods like the IEC/TR 62635 offer a large benefit through their simplicity: One only needs an elaborate bill-of-materials (material type and mass) and a dataset of recycling rates per material to calculate the score (whole product recycling rate). The dataset of recycling rates should ideally be at product group level. Possible source data such as by WF Reptool is however only available at product category level (large household, small household, cold appliances, etc.).

The method is currently unfit to deal with the recovery of elements like PGM and CRM that are only present in minute traces: Especially for PGM their relevance for recycling vastly exceeds their relative mass, and this is not reflected in the method. The method also has no consideration of (mandatory) depollution i.e. the removal of parts containing hazardous substances prior to shredding.

Furthermore, the concept of using recycling rates based on rates from existing waste treatment plants, makes the method less suitable for product specific assessments. When calculating with a plastic recycling rate of (for example) 70% this implies a loss of 30% somewhere in the recovery chain, but it is not known what causes this loss nor where it happens: Is it that 3 out of 10 products cannot be recycled, or is it because 3 tons of material are lost in other streams when processing 10 tons? One can imagine two products with identical BOMs but where materials of one product are much easier to liberate fully. In practice these would show different recyclability rates, but this is not possible to accommodate in the method as it is. The ideal method would use recycling rates that are linked to a certain specific product design aspects, so that differences in design become apparent.

Summarising, the IEC/TR 62635 may have been quite appropriate to deal with simple products that contain steel, some non-ferro and a limited number of plastics, but is not suitable for assessing complex products, in which toxic, precious and/or critical materials are joined in a complex manner, all requiring a specific form of treatment.

If applied in a legal setting it would need to be adapted to consider mandatory depollution and political priorities regarding CRM. It also requires a vast dataset of recycling rates, but as this same dataset is to be used by all manufacturers, the chances that the method results in improved designs are slim. At most it would foster a change towards materials with higher shares of materials with higher recyclability rates (adding extra steel?) without the confirmation these are actually easier to recycle.

The **Environmental benefit ratio** method resembles a limited life cycle analysis covering the end-of-life phase only. The **Circular footprint formula** goes further and adds several other aspects related to creating material circles, such as use of recycled content, and includes recovery and final disposal.

Both methods are as simplistic in their approach to recycling issues as the mass-based methods, but add extra layers of information regarding the environmental impacts. This way the methods do focus on the environmental relevance of recycling precious metals and other materials with significant impacts. This is however not essential as the environmental relevance of most materials is already known (and, for precious metals at least, reflected in the value of the secondary material) or follows other criteria such as relevance for society and supply risks (as for CRM).

The methods are however complex, as they require access to a database of life cycle inventories (the impacts per unit assessed) and agreed methods for classification and characterisation (and possibly normalisation and weighing). The required databases and software are mainly commercially available, the exception possible the MEErP method (Ecoreport recyclability). Interpretation of the results is complex as the EU has not agreed on the weighing of various impacts.

The methods rely, just as the simpler mass-based methods on generic recycling rates per material and do not assess in detail the effect of the actual design on liberation and sorting results. Furthermore, the method must define a fixed end-of-life scenario as otherwise impacts from processing of waste cannot be included. This makes the outcome particularly dependent on the EOL-scenario assumed, which is not a parameter the manufacturer can influence.

The approach is however well suited for calculating the benefits (or impacts) of a minimum recycled content, provided sufficient data is available (on the impacts of the recycled material, and possible changes in design to accommodate recycled material).

Full metallurgical assessment (HSC SIM) is the most developed and exact method currently available. It includes various modelling parameters that allow consideration of liberation and sorting aspects and has a detailed modelling of metallurgical handling.

The method provides a useful basis for checking assumptions regarding effectivity of changes in design and a source of inspiration. Whether the model is as elaborate for plastics (consideration of carbon black pigments, presence of BFR, etc.) is not known.

The method is not suitable for use by non-experts, which limits the general access to it and reduces its use in a legal framework, as it cannot be described in regulatory documents, nor can commercial software be made mandatory as design tool.

***

If anything, the above evaluation shows that the **criteria method** has a good score for the variety in aspects addressed: liberation of components, plastics identification, presence of hazardous substances, etc. But the scoring is dependent on the personal judgement of the assessor. This dependency is also the major drawback of the **scoring method**.

The **whole product recycling rate** is considered inadequate for assessment of complex products, and the **benefit ratio** and **circular footprint formula** are overly complex for the goal of improving recyclability.

The **full metallurgical assessment** is undoubtedly the most exact method for assessment of recycling, although it appears to lack precision in the plastics assessment and results rely on a precisely defined recycling scenario.

All methods lack suitability for use in a legal framework and more attention needs to be given to increasing the value (quality) and volume (yield) of recyclates as this will increase the 'real' recycling rate.

6 A new RR method

6.1 Starting points

The new method for recyclability & recoverability is a basically a scoring method, in which expert judgement on removability of components is replaced by a technical assessment with relevance to liberation and sorting aspects, without creating a disassembly assessment (although in execution both are very close). The assessment includes typical recycling challenges per activity/material (depollution and valorisation) and results in four scores for: depollution, metals, plastics, and a miscellaneous group which comprises ceramics and bio-based materials.

The basic concept of the method is that if no recycling challenges are present in the product, i.e. no hazardous materials present or design features that limit the recycling potential, a perfect score of '10' is awarded. For each feature that introduces a certain recycling challenge, the ideal score is reduced (the minimum being near zero).

Depending on the specific challenges, the method focuses on liberation aspects or the compatibility of materials that are liberated but does so without prescribing a certain technology or defining a specific end-of-life scenario.

The scores for 'depollution' and recovery of 'metals' are primarily determined by liberation aspects, as the main challenge is getting the specific component into the correct route for final treatment, which is more difficult if component-specific liberation is more difficult. The method looks at the types of joints with which the component is joined to the rest of the product, and the disassembly depth.

For 'plastics' the score depends on the challenges to correctly sort a stream of mixed plastic waste and awards the avoidance of plastics with halogenated flame retardants or other polluting substances and the compatibility of plastics in the mix.

The score for 'other' materials depends on the removal and potential recyclability of the specific materials.

The overall recyclability score is the weighted total of the individual scores for depollution, metals, plastics and other.

The new method developed for this study overcomes the drawbacks of existing methods, by offering:

1. an objective assessment, based on technical parameters and characteristics of the product, that can be verified by product inspection, and performance standards;
2. consideration of applicable policies (WEEE, RoHS, REACH) and political priorities (CRM);
3. consideration of the limitations of waste treatment technologies;
4. an index that visualizes the improvement in recyclability (recoverability) scores of alternative designs;
5. a not overly complex method that:
    a. avoids use of software or datasets from third (commercial) parties;
    b. requires a minimum of data to be supplied by the manufacturer;
    c. requires a minimum of tools for the assessment.

Higher scoring products should lead to higher recycling rates (volume and value) of materials (rather than just increasing the share of materials with high recycling rates). This supports the supply-side of recyclates.

The method allows for the use of differentiating the EPR tariff to be paid for WEEE compliance (products increasing recycling receive lower tariffs).

6.2 Depollution and metals score

As depollution and valorisation of metals is mostly linked to proper removal (first liberation, then sorting) of components containing specific substances, this section of the method includes an assessment of how 'easy' it is to remove hazardous or metal parts. The basic assumption is that this requirement applies to those parts that should not be treated in shredders or hammers as that could entail occupational health issues (dispersion of dangerous substances like Hg, batteries, asbestos, etc.) and/or could lead to unacceptable loss of value (shredding high grade printed circuit boards) or hinder subsequent recovery from the mixed waste stream (permanent magnets with REE, displays with ITO layer). Still, the use of such methods is not forbidden – the score is only reduced if such methods are the only way to treat the product.

The method describes the parts or materials relevant for the product and looks at 'how deep' the part or material is embedded in the product and what kind of joining method is used. This is both relevant for manual disassembly as well as automated disassembly.

Van Schaik and Reuter have assessed the degree to which different joined materials are liberated to mono and multi-material particles during shredding and/or dismantling, and identified the following design properties that determine liberation characteristics[85]:

- The combined material properties (e. g. brittle, ductile) of the connection/product/component.
- The type of the material joints and connections (e. g. bolted, rivet, shape, glue, surface coating).
- Characteristics of the connection/joint, e. g. size of the connections in relation to particle size distribution after shredding.
- Complexity and homogeneity or heterogeneity of the product/component/connection (e. g. spatial distribution of the connections in the product, number of materials connected per connection).
- The thermodynamic compatibility among metals, alloys and metal compounds.

The method developed here has simplified the above design properties to allow a simplified assessment of 'joint-types'. Depending on the joint types used, and the level of embedding, a 'liberation-score' can be determined.

Table 6. Joint-types in the new method

Joint-type	Description	Verification
weak	'weak' means the joint can be broken by hand (slide-to-open battery lid, tearing off glued parts)	The joint should be accessible by hands and the maximum force for removal (pinch-pull) should not exceed 80 N in the most optimum direction for removal of the part.
standard	'standard' means the joint can be broken by standard phillips, torx, etc, screwdriver tools, or by a hammer blow (impact test).	Standard tools tips as described in tool standards. Other tools such as pliers, scissors, etc. also allowed. Hammer blow to be verified by impact tests
strong/complex	'strong / complex' means the joint is not 'weak' or 'standard': Removal may require cutting, machining, grinding, sawing using motorised equipment and/or the joint-type requires dedicated tools/substances for removal (e.g. refrigerant extraction from refrigerator, heater for softening glue) or special conditions (shredding of mercury lamps requires controlled environment, placing in oven or vacuum chamber, etc.).	If the methods for 'weak' or 'standard' fail to free the part, or if dedicated (non-standard) equipment is to be used, the joint-type is 'strong/complex'

Weak/simple joints are more likely to result in total liberation, whereas standard joints (screws) may result in some material still joined with another material, and strong/complex joints (glued, or requiring specialised tools) are most likely to result in the least liberation or highest effort required. Each joining method receives a weighting which is decided upon by the experts that finalise the method (if indeed developed as EN standard).

The assessor also counts the number of parts (layers) that need to be removed in order to free the component, with the joining method used. The combination of the number of layers to be removed (counts) and the joint-type are combined into a single score by raising the joint-type weight by the number of layers (counts) this joint-type occurs. This results in a multiplier for each type of joint.

The multipliers for the three joint-types are multiplied with each other and result in an overall score. Multiplying by 10 results in a score between 1 and 10, like in school reports.

The assessment based on liberation is applied to parts relevant for depollution and parts relevant for valorisation of metal containing parts.

6.2.1 Depollution score

Materials/parts/assemblies to be removed

The method starts with the identification of the materials/parts/assemblies to be removed from the generic waste stream, to avoid pollution of the work place and/or waste stream.

A logical starting point is the list of components to be removed according Annex VII of WEEE Directive 2012/19/EU.

[85] Box 8, p.97 in UNEP (2013) Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M. A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C.

Depending on the specific product group, parts may be added or removed from the list(e.g. products containing no refrigerants): As the WEEE list applies to old products currently discarded, it refers to parts that are no longer relevant (e.g. PCB capacitors, asbestos and CFCs are banned, etc.) for new equipment or have been considered ineffective.

The review of the first WEEE Directive 2002/96/EC of 2007 proposed to delete external electric cables, capacitors and LCD displays from the list of parts to be removed.[86]

Table 7. Items to be deleted from list of parts to be removed,

Annex II I item to be deleted	Explanation
External electric cables	There is no need to keep the entry on external cables (12), because the original reason, the labour aspects are because of the way of transport and treatment improved. The possible substances of concern are also in internal cables, which are not subject to specific rules. Furthermore, removal is also contra productive for the re-use possibility of the appliances.
Electrolyte capacitors (>25 mm)	The entry on electrolyte capacitors, containing substances of concern (15) is not necessary, because until now there are no other substances of concern found than PCB's, which is already prescribed in entry 1.
LCD displays	The entry on LCD's (11) is not necessary, because when backlights are used, it will be covered by the entry on mercury (2) because of the mercury content of these backlights. When no backlights are used, there is no need for specific removal, because no hazardous items are found in these LCD's. Liquid Crystals (LC's) are not toxic, neither are they mutagenic, suspicious of carcinogenicity and are not toxic to aquatic organisms. LC's may be irritant or sensitising and some are not readily biodegradable. (Information from Merck: Toxicological and ecotoxicological investigations of liquid crystals and disposal of LCD's; Becker e.a. febr. 2003)

This study and the method it describes, keeps LCD displays as items that affects recyclability, as the Indium it contains is listed as CRM, and final treatment for Indium differs from that for Cu/Ni or other carrier metal infrastructures.

The groups 'Printed circuit boards of mobile phones and/or greater than 10 cm2' and 'liquid crystal displays (together with their casing where appropriate) of a surface greater than 100 cm2 and all those back-lighted with gas discharge lamps' have been moved to the section 'Metals'. This could also apply to 'batteries', but as the calculation of bonuses is easier under Depollution, this was not implemented.

The group 'Plastic containing brominated flame retardants' has been moved to 'Plastics'.

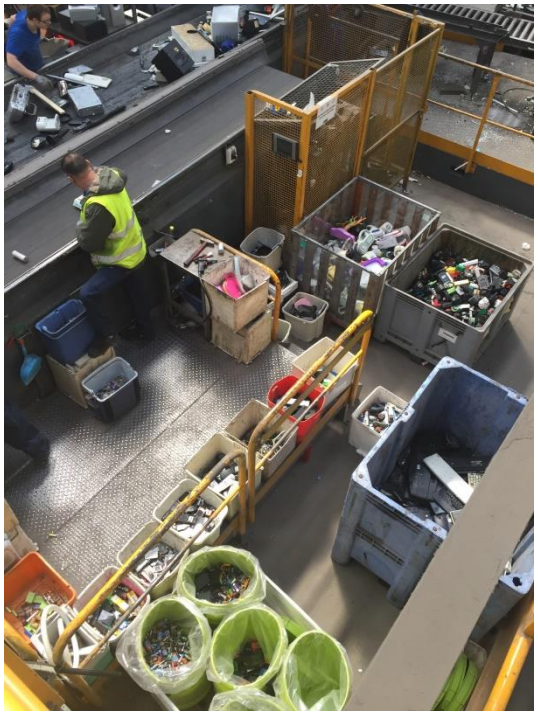
Table 8. Original list of items to be removed according Annex VII of 2012/19/EU and possible updated list

List in WEEE Directive 2012/19/EU		'Updated' list, for <u>new</u> products placed on the market
i.	PCB containing capacitors	(obsolete)
ii.	mercury containing components (e.g. switches, lamps) – includes removal of Hg from lamps	CFL lamps, as some still contain mercury. Almost obsolete
iii.	batteries	batteries
iv.	printed circuit boards of mobile phones and/or greater than 10 cm2	(see metals)
v.	toner cartridges, liquid and paste, as well as colour toner	toner cartridges / inks / etc.
vi.	plastic containing brominated flame retardants	(see plastics)

[86] 2008 Review of Directive 2002/96 on Waste Electrical and Electronic Equipment – Study No. 07010401/2006/442493/ETU/G4

vii.	asbestos waste and components which contain asbestos	(obsolete)
viii.	cathode ray tubes – includes removal of coating	(obsolete)
ix.	chlorofluorocarbons (CFC), hydro chlorofluorocarbons (HCFC) or hydro fluorocarbons (HFC), hydrocarbons (HC) – includes treatment of ozone depleting gases	refrigerants (HFC, HC, ammonia, carbon dioxide, etc.), thermal oil
x.	gas discharge lamps	(see Hg containing ...)
xi.	liquid crystal displays (together with their casing where appropriate) of a surface greater than 100 cm2 and all those back-lighted with gas discharge lamps	(see metals)
xii.	external electric cables	(not relevant)
xiii.	refractory ceramic fibres	(obsolete)
xiv.	radioactive substances	radioactive substances, in smoke alarms
xv.	electrolyte capacitors containing substances of concern (..)	(obsolete)

Figure 30. Manual depollution station



Calculation rules

The Depollution score D_P represents the effort required to remove a number of substances/materials/parts from the product. It is calculated depending on the type of joint to be broken for liberation of pollutants and the depth of dismantling required. The tools can be distinguished between weak (T_{wk}), standard (T_{std}) and complex (T_{cpx}). In addition, a bonus applies, if product information is available (T_{inf}) indicating presence of polluting substances and their location.

The method takes into the strength or exclusiveness of the bond and each action needed for achieving the goal is noted and summed into a total number of actions. Each joint-type to be broken is assigned a weight (ω_{smp}, ω_{std}, ω_{cpx}) which is raised to the power by the number of actions (T_{smp}, T_{std}, T_{cpx}) required for removing the pollutant/part.

The pollutants/parts to be liberated are identified in general or product-specific legislation (Directive 2012/19/EU on waste electric and electronic equipment, or any other mandatory or voluntary list of restricted substances)

T_{smp}, T_{std} and T_{cpx} are expressed as number of actions that need to be performed in order to liberate the respective part.

Equation 3.Depollution score

$$D_P = \frac{{\omega_{wk}}^{T_{wk}} + {\omega_{std}}^{T_{std}} + {\omega_{cpx}}^{T_{cpx}}}{{\omega_{inf}}^{T_{inf}}} * 10$$

Where:

Dp = depollution score (between 0-10)

ω_{wk} = the weight for a weak joint-type, e.g. 0.95

ω_{std} = the weight for a standard joint-type, e.g. 0.9

$\omega_{cp}x$ = the weight for a strong/complex joint-type, e.g. 0.85

ω_{inf} = the weight for a presence of information, e.g. 0.95 (should not be less than for 'weak')

T_{wk} = the total count of weak joint-types (value depends on complexity of product)

T_{std} = the total count of a standard joint- types (value depends on complexity of product)

$T_{cp}x$ = the total count of a strong/complex joint- types (value depends on complexity of product)

T_{inf} = the total count of presence of information, either 0 or 1 (value depends on presence)

The weight of the action (ω_{smp}, ω_{std}, ω_{cpx}) shall be assigned a value between 0 and 1, where higher values represent less effort (or less complexity) of separation and lower values represent more effort (or complexity) of separation. The weight for 'simple' actions (ω_{smp}) shall be higher than that for 'standard' actions (ω_{std}), which again is higher than 'complex' actions (ω_{cpx}) e.g. ω_{smp} = 0.95, ω_{std} = 0.9, ω_{cpx} = 0.85).

> Note: Ideally the weights are defined depending on the complexity of the product (type of actions and number of actions required) and can be chosen so that an average product (product representative of the group to be assessed and not designed with excessive attention to recyclability etc.) achieves an average score.

Values for Tools (T_{std}, T_{cpx}, T_{inf} analog):

Equation 4. Count of action/layers

$$T_{smp} = \sum_{1}^{i} t_i$$

Where:

t_i = each part or assembly that needs to be removed (layer), per joint-type, in order to free the required part/material counts as '1'. (t_i being the action required for liberation of one part)

In order to take into account the possible beneficial effects of providing product information (e.g. on the battery chemistry used) a correction may be applied on the total score.

The 'effort' for recycling (the numerator in D_p) is divided by a multiplier that takes into account the presence of information regarding presence or absence of polluting substances (denominator for D_p). Such information can help streamline recycling activities, as products can be sent through dedicated or specialised (or in case of absence of substances) generalised treatment routes.

For each polluting part or substances present (see list above) u_i is increased by 1. The information parameter is also assigned a weight ω_{inf} the value of which shall not be less than ω_{smp} (as otherwise D_p may exceed 10),

Example: if only one polluting part/substance is present and it is easily removed (1 action) the numerator is ${\omega_{smp}}^1$. If the presence was indicated properly the denominator is ${\omega_{inf}}^1$. If $\omega_{inf} < \omega_{smp}$, then Dp would be > 10, therefore $\omega_{inf} \geq \omega_{smp}$.

Values for information (T_{inf}):

Equation 5. Count of information

$$T_{inf} = \sum_{1}^{i} u_i$$

With u_i being the instances of information provided per pollutant/part to be removed.

In the case that no pollutants are present in an ErP, D_P is calculated to be '10'

6.2.2 Metals score

The assessment of the valorisation of metals presumes the most beneficial treatment is made possible. The methodology awards easier removal of parts that should not be treated in a generic waste stream.

Materials/parts/assemblies to be removed

The materials/parts/assemblies to be removed from the generic waste stream are 'printed circuit boards > 10 cm2 or from mobile phone' and 'displays' as these are replaced from depollution to metals recovery. The entry for printed circuit boards has been refined following recommendations by Umicore that high grade boards should not be shredded, and lower grade boards may be supplied to final treatment after shredding. A bonus is applied to low grade boards of standard colour to allow easier recovery from a mixed stream:

- Printed circuit boards > 100 ppm gold, as these should not be shredded to avoid losses of precious metals;
- a possible bonus for medium/low grade boards < 100 ppm gold if these are green/brown, allowing visual sorting after shredding;
- Displays > 10 cm2, as the indium may be recovered;

To these are added:

- LED lamps, as used for backlight, signal and general light, because of possible REE recovery;
- PM magnets, as found in HDD and PM motors, because of possible REE recovery;
- several combinations of Fe, Cu, Al and other light metals, as found in electric motors (non PM), heat exchangers/heat sinks and product housing, because of recovery of magnesium (CRM) and better recovery of Fe/Cu/Al;
- easy removal of memory banks / cards should be awarded as this increases options for economic recovery.

For electronic parts, the scrap value can be increased if it is sorted at higher degree. The differences in scrap value per component are shown below:

Table 9. Electronic scrap prices [87]

Electronic component	Scrap value (EUR/kg)	Extraction rate (kg/min, assuming 1 EUR/min labour costs)
CPU goldcap ceramic	95.00	0.01
CPU ceramic	45.00	0.02
Memory banks/cards gold	21.00	0.05
Slot cards	21.00	0.05
Memory banks/cards, silver	7.00	0.14
Stack cards	4.75	0.21
Motherboard, class 1	4.25	0.24
Printed circuit board, class A	4.25	0.24
Motherboard, unsorted	2.10	0.48
Printed circuit board, class B	1.20	0.83
HDD	1.20	0.83
Printed circuit board, class C	0.40	2.50
Server (outdated)	0.60	1.67
Desktop (outdated)	0.45	2.22
PC power supply	0.35	2.86
Old disk drives (floppy)	0.25	4.00

[87] KH Metals, Netherlands, Nov 2017

Although not required under WEEE, certain waste treatment facilities sort electronic scrap at very high level to increase its resale value.

Figure 31. Sorting of electronic components to get highest revenues[88]

Complex joined metals as in electric motors and in heat exchangers are also challenging to recycle as the materials involved are often ductile (soft steel, copper, aluminium) and the spatial distribution is complicated (the materials are intricately intwined / entangled).

Figure 32. Complex joining of ductile materials hinders liberation[89]

Electric motor before and after passage through a shredder. The mild steel encloses the copper

The brass rotor of this water pump is folded over the hard steel drive shaft.

Heat exchanger before and after passage through shredder. The aluminium encloses the copper tubing

Scrap metal rates reflect this: The copper content of an average basic electric motor may be close to 13 % (Lot 31 report, Task 5, figure 5.3), but the copper scrap price is 30 times the steel price. A motor scrap price reflecting these shares and rates would be 0.77 EUR/kg. However, the actual scrap price is only 0.30 EUR/kg, some 40% of the price based on material value.

Table 10. Metal scrap prices[90]

Metal type	Scrap value (EUR/kg)	Extraction rate (kg/min, assuming 1 EUR/min labour costs)

[88] Photo from North West European WEEE treatment facility, April 2017
[89] http://eco3e.eu/en/base/steel/
[90] KH Metals, Netherlands, Nov 2017

copper	4.20	0.23
steel	0.18	5.55
aluminium	0.80	1.25
old electric motors (75% steel, 12% aluminium, 13% copper)	0.30	3.33

Calculation rules

D_{VM} is assessed in the view of effort to liberate the ErP of metals. It is calculated depending on the tools needed. The tools can be distinguished between simple (T_{smp}), standard (T_{std}) and complex (T_{cpx}). In addition, a bonus (T_{bns}) can be achieved (similar to the 'information bonus' for depolluting), for example by the proportion of green PCB compared to brown PCB.

T_{smp}, T_{std} and T_{cpx} are expressed as number of actions that need to be performed in order to liberate the respective part.

Each variable (T_{smp}, T_{std}, T_{cpx}) is weighted (ω) individually, taking into accounts the individual design of certain product groups.

Equation 6. Metals score

$$D_{VM} = \frac{\omega_{m,wk}{}^{T_{m,wk}} + \omega_{m,std}{}^{T_{m,std}} + \omega_{m,cpx}{}^{T_{m,cpx}}}{bonus_{m,sort}} * 10$$

Values for Tools (Tstd, Tcpx analog):

Equation 7. Count of action/layers

$$T_{wk} = \sum_{1}^{i} t_i$$

Bonus

The denominator of D_{vm} contains a correction ('bonus') related to metal parts or substances that allow improved sorting, or reduce sorting difficulty.

For example: Simple, low grade, PCBs may be shredded together with the rest of the product (often after depollution), but still contain trace amounts of precious metals that are best treated in a precious metals smelter and should not end up in a steel or aluminium smelter/refiner. The current easiest way to recover PCB flakes from a mixed stream is by visual sorting. This works best if the PCB flakes have an easily recognisable colour, such as green or brown. Red, blue and other colours are more difficult to separate using visual sorting techniques. Therefore a bonus applies to those low grade PCBs that are green or brown.

The metal sorting bonus is calculated as:

Equation 8. Calculation of information bonus for metals

$$bonus_{m,sort} = base_{m,sort} - count_{m,sort}$$

With

$base_{m,sort} = value$ (Note: the value must exceed 1. If not, then a high $count_{m,sort}$ results in a malus). The value can be chosen so that a 100% green/brown PCB that is separable with 1 simple action results in an acceptable bonus, for example value = 1.12)

$$count_{m,sort} = \%\ green, brown * (base_{m,sort} - 1)$$

$\%_{green,brown}$ = the share (by weight) of low grade PCBs that are green/brown.

Calculation rules for count liberation for Dp and Dvm

When assessing the separation of polluting substances and metals, one can assume the least number of actions required (per type of action) for both depollution and valorisation of metals simultaneously. For example: if the removal of a battery (depollution action) requires removal of a printed circuit board (metal valorisation) the number of actions for removing the

battery is reduced (as these actions are already counted for the removal of the circuit board). There is no need to assume that an appliance is reassembled during depollution and metal valorisation.

Note: A low score on depollution (for a product that needs to be taken apart) results in a high score of metal valorisation (as the disassembly already happened, whereas the metal parts are still difficult to valorise). In hindsight (or for an improved version) it may be better to integrate depollution and metal valorisation in a single score.

6.3 Plastics score

Contrary to the depollution or metal valorisation parameters, the plastic valorisation calculation is based on the assumption that plastics are recyclable unless they have characteristics that make them less attractive for recycling (not recyclable because of presence of polluting substances, other unwanted substances, or result in poor compatibility, etc.).

Materials/parts/assemblies to be removed

The method starts with the identification of the materials that negatively affect the quality or value of the mixed waste stream.

Additives - These are plastics that contain hazardous or other restricted substances:

- contain intentionally added BFRs or antimony FR;
- contain intentionally added plasticizers that are substances of concern such as DEHP, DBP, DIBP and BBP;
- contain other substances of concern, e.g. certain foaming agents[91].

Sorting issues - Hamper correct identification in popular sorting techniques:

- contain carbon black as colorant;
- any combination of elastomers bonded with another polymer in a single part (co-extrusion, multi-material-injection);
- any combination of wrappers, stickers, adhesives not compatible with base polymer;

Incompatibility – as sorting technologies are rarely 100% effective, it could be that incompatible plastics are mixed::

- main plastic PA; combined with PC, PPE, PVC;
- main plastic PBT; combined with PVC;
- main plastic PC; combined with PA, POM, PVC;
- main plastic PE or PP (if density > 1.00 g/cm3); combined with ABS, ASA, PBT, PC, PET, PMMA, POM, PPE, PS, SAN;
- main plastic PMMA; combined with PBT;
- main plastic POM; combined with PC, PMMA;
- main plastic PVC; combined with PA, PBT, PC, PET, PPE;
- main plastic TPU; combined with PBT.

Final treatment – certain plastic types do not allow for recycling using regrinding:

- all thermoset polymers

Plastics that form the substrate for printed circuit boards shall not be included in this assessment as these receive a different final treatment.

Elaboration

The RoHS and REACH legislation have banned several types of **additives** from products, but several other types are still allowed. A panel of experts should decide on which other types of additives should be included in the 'non-recyclable' list. The inclusion of certain foaming agents does not mean that these plastics are unrecyclable. But if a manufacturer must choose between a physical blowing agent (usually nitrogen or carbon dioxide) and a chemical foaming agent, the solution that gives the least problems during recycling (assuming other performances are the same) should be preferred.

Chemical blowing agents are mixed into the plastic pellets in the form of powder or pellets and dissolve at higher temperatures. Above a certain temperature specific for blowing agent dissolution, a gaseous reaction product – usually nitrogen or CO2 – is separated and acts as a blowing agent. Due to the generation of undesired by-products and higher costs, chemical blowing agents are primarily applied for high-density materials. Examples are isocyanates (PUR), titanium hydride and azodicarbonamide.

[91] Plastic foams e.g.PS blown with pentane, as applied in many refrigerators, are shredded in a dedicated facility, that removes the gases and collects these.

Physical blowing agents are metered into the plastic melt during foam extrusion or injection moulded foaming or supplied to one of the initial products during polyurethane foaming. Physical blowing agents are used to create the often-requested low densities. Other advantages include a more homogenous foam structure, better process stability and significantly lower blowing agent costs[92]. Examples are pentane and butane, and other refrigerants (CFC are forbidden) and nitrogen, carbon dioxide. Inert gases like N2 and CO2 do not require specific equipment during recycling.

Sorting issues relate to the problems of correctly identifying a plastic using automated equipment. The problems with carbon black plastics and NIR sorting are mentioned before (although MIR could solve these). The presence of wrappers, adhesives, coatings and other surface modifications do not only hinder correct identification, but also add complexity in removing possible contaminations. This also applies to plastics that are intricately linked (co-extrusion, etc.).

Incompatibility of plastics is based on the table C.1 from ECMA 341[93].

Figure 33. Compatibility of various thermoplastics[94]

Mixture component \ Excess component	ABS	ASA	PA	PBT	PBT+PC	PC	PC+ ABS	PC+ PBT	PE	PET	PMMA	POM	PP	PPE	PPE+PS	PS	PVC	SAN	TPU
ABS	+	+	@	+	+	+	+	+	@	@	+	@	@	@	@	@	+	+	+
ASA	+	+	@	+	+	+	+	+	@	@	+	@	@	@	@	@	+	+	+
PA	@	@	+	@	@				@	@	@	@	@		@	@		@	+
PBT	+	+	@	+	+	+	+	+	@	@	@	@	@	@	@	@		+	@
PBT+ PC	+	+	@	+	+	+	+	+	@	@	@		@	@	@	@		+	+
PC	+	+		+	+	+	+	+	@	+	+		@	@	@	@		+	@
PC+ ABS	+	+	@	+	+	+	+	+	@	+	+	@	@	@	@	@		+	+
PC+ PBT	+	+		+	+	+	+	+	@	+	+	@	@	@	@	@		+	+
PE			@			@			+				+		@		@		@
PET	+	+	@	+	+	+	+	+	@	+	@	@	@	@	@	@	@	@	@
PMMA	+	+	@			+	+	+	@	@	+	@	@	@	@	@	@	@	@
POM	@	@	@	@	@				@	@		+	@	@	@	@	@	@	@
PP			@						@				+		@		@		@
PPE	@	@	@	@	@	@	@	@	@	@	@	@	@	+	+	+		@	@
PPE+ PS	@	@	+	@	@	@	@	@	@	@	@	@	@	+	+	+		@	@
PS	@	@	@	@	@	@	@	@	@	@	@	@	@	@	+	+	@	@	@
PVC	+	+							@		+	+	@		@	@	+	+	+
SAN	+	+	@	+	+	+	+	+	@	@	+	@	@	@	@	@	+	+	@
TPU	+	+	+		+	+	+	+	@	+	+	+	@	@	@	@	+	+	+

\+ Good compatibility over a wide range of mixtures
@ Limited compatibility for small excess component amounts
Incompatible

The plastics score is based on plastics that are incompatible according the above table. Blends with limited compatibility have been ignored as there is always uncertainty on how mixes behave: Even a mix of PE and PP, with good compatibility according the above table, is not always achievable as

Not surprisingly, in recent years there has been considerable advancement in the compatibilization of plastics.

Nonetheless, the inclusion of incompatible plastics reduces the variety of plastics used in products and reduces the need for extended sorting or upgrading.

Thermosets are also excluded from the total of recyclable plastics as only few methods are available, and simple sorting – cleaning-and reprocessing is not among them.

Calculation of the plastics score

The total mass of plastics (excluding those in PCBs) is calculated and from this total is subtracted those plastics that are 'compromised' as they contain hazardous substance, are incompatible polymer etc. The higher the amount of compromised plastics, the lower the score of D_{VP}.

NOTE: Each comprised amount of polymer needs only to be mentioned once.

The proportion of incompatible polymer fractions compared to the total mass of polymers in the product results in a mass fraction [%] of polymers m_{loss} lost during the recycling process. The valorisation of polymers index can be calculated as follows:

[92] http://www.lindeplastics.com/pdf/literature/1776E_Foaming_with_inert_gases_brochure_hires138_74264.pdf
[93] Standard ECMA 341 - Environmental Design Considerations for ICT & CE Products, 4th Edition / December 2010
[94] ECMA 341 states: The table was adapted from Table 5.3, page 632 of H. Saechtling, Kunststofftaschenbuch, Carl Hanser Verlag, München, 1998 (27th edition).

Equation 9. Plastics score

$$D_{VP} = (1 - \%_{loss}) * 10$$

with:

Equation 10. Summing compromised plastics

$$\%_{loss} = \sum \frac{m_{inc,pol}}{m_{total,pol}}$$

Where:

$m_{inc,pol}$ = the mass of a compromised plastic fraction

$m_{total,pol}$ = the total mass of polymers, excluding those contained in electronic parts (displays, circuit boards)

Calculation rule for multiple plastics

While calculating $m_{inc,pol}$ the same polymer should not be counted twice. So if a polymer is 'compromised' because it contains hazardous substances AND is compromised as it is incompatible with another polymer fraction, this polymer fraction is only counted once. The total of compromised polymer fractions may not exceed the total polymer fraction.

Bonus for polymer marking

Certain stakeholders, including EERA, have argued for better polymer marking to allow manual sorting of large items known to contain restricted substances. For this reason a factor correcting for the amount of plastics that are compromised is introduced, resulting in a 'bonus 'if plastics > 25 g (threshold can be discussed) are marked appropriately.

Simply reducing the amount of compromised plastics by a predetermined factor is the easiest way to introduce this bonus but ignores the fact that regardless whether these plastics are marked or not, they are 'compromised' and not recyclable.

The present method describes a bonus for marking of plastics by reducing a malus that applies to certain compromised plastics. The method assumes that a certain share of plastics (loss factor) is lost due to insufficient sorting technology. For example: In a sink/float tank the heavier plastics are usually considered suspect (contain x% brominated flame retardants) and are not recycled. This 'heavy' fraction may also contain plastics that do not contain hazardous substances but are still quite dense. So, a certain share of the not compromised plastics are lost as well. The bonus for marking reduces the %loss for this fraction.

Equation 11. Calculation of plastics marking bonus

$$\%_{loss,i} = IF(mass_{inc,pol} > 0, \frac{mass_{inc,pol} + (if\ marking\ \text{"true"}: 0, if\ marking\ \text{"false"}: mass_{loss})}{mass_{total}}, 0)$$

Where:

$mass_{loss}$ = $mass_{total}$ - Σ $m_{inc,pol}$ * loss factor

loss factor = value (for example 10%)

marking "true" = a polymer part > 25 g is marked according the algorithm described in Annex XX. At minimum the type of flame retardant and other additive is mentioned.

The marking of plastics should be in accordance with Annex E.

The effect of this correction is that large plastic parts that contain flame retardants are to be marked (or better: no flame retardants should be used).

6.4 Miscellaneous score

The score for miscellaneous materials is based on the effort of removing a substance, part or component that is relevant for the product group and does not belong to the groups depollution, metals or plastics.

Materials/parts/assemblies to be removed

Depending on the product at hand, the possible materials to be considered for the score may be:

- concrete, e.g. the counterweight in washing machines;
- glass tempered, e.g. the glass shelves in refrigerators or the glass plate in imaging equipment;
- other ceramics, e.g. ceramic housing;
- paper/cardboard, e.g. used as fillers;
- textiles / upholstery / foams, e.g. used in speaker cabinets;
- cork, e.g. used as dampener, insulator, etc.
- glass shaped, e.g. glass in furniture, bulbs;
- wood, e.g. particle board in domestic appliances, or speaker cabinets.

The list can be reduced/expanded depending the characteristics of the specific product group considered.

Calculation of the miscellaneous score

The score is calculated depending on the type of action needed and the disassembly depth (number of actions required for removal). Similar to depollution and metal valorisation the type of joint can be distinguished between weak, standard and strong/complex (ω_{wk}, ω_{std}, ω_{cpx}) and the number of actions ('layers') that need to be performed (uncovered) in order to liberate the respective part (T_{wk}, T_{std} and T_{cpx}). E.g. the glass in a washing machine door can be removed by undoing some bolts/screws (standard joint, layer count 1) and by pulling it from a rubber gasket (weak joint, layer count 2).

Note: actions do not need to be double counted: If depollution requires removal of an item in the miscellaneous category, the action allocated to it shall be counted once.

Note: Materials removed from the product are only counted if an infrastructure for recycling exists, as is the case for glass (toughened, float or container), paper/cardboard and clean wood. For mixed/polluted wood (particle board, chemically treated wood), or concrete the recycling infrastructure does not exist. For various textiles recycling programs exist, but these require a clean and dry supply of textiles, which is not the case in recycling facilities (where it is mixed with other materials of similar density, structure, characteristics).

The index for valorisation of miscellaneous materials can be calculated as follows:

Equation 12. Miscellaneous materials score

$$D_{misc} = \frac{\sum_{i=1}^{n} infra_i * \left(\omega_{smp}{}^{T_{smp}} * \omega_{std}{}^{T_{std}} * \omega_{cpx}{}^{T_{cpx}}\right) * mass_i}{mass_{total}}$$

With

$infra_i$ = a nominal value; if a recycling infrastructure for item i exists, the value is 1, if it doesn't exist, it is 0.

$mass_i$ = the mass (g or kg, as long as it is the same unit as $mass_{total}$) of item i;

ω_{smp}, ω_{std}, ω_{cpx} = the weight assigned to a simple, standard or complex liberation action. As the value of these materials is often low, complex liberation is often not worthwhile. Therefore, the weight of standard and complex liberation can be reduced, so that the recyclability score for miscellaneous is reduced as well. For example: 0.9, 0.45, 0.3 respectively

T_{smp}, T_{std}, T_{cpx} = the number of actions (disassembly depth) required for removal of the item i. Note that actions do not need to be double counted: If liberation of one part requires removal of another part, this action shall not be counted twice.

$mass_{total}$ = the mass of the product, excluding the mass of the depolluted, metals and plastics fraction.

6.5 Recyclability score

The overall product recyclability score is calculated as:

Equation 13. Recyclability score

$$R_{recyc} = \frac{w_P * D_P + w_{VM} * D_{VM} + w_{VP} * D_{VP} + w_{VMisc} * D_{VMisc}}{w_P + w_{VM} + w_{VP} + w_{VMisc}}$$

Where:

W_P = the weight of the 'depollution score'

W_{VM} = the weight of the 'metals score'

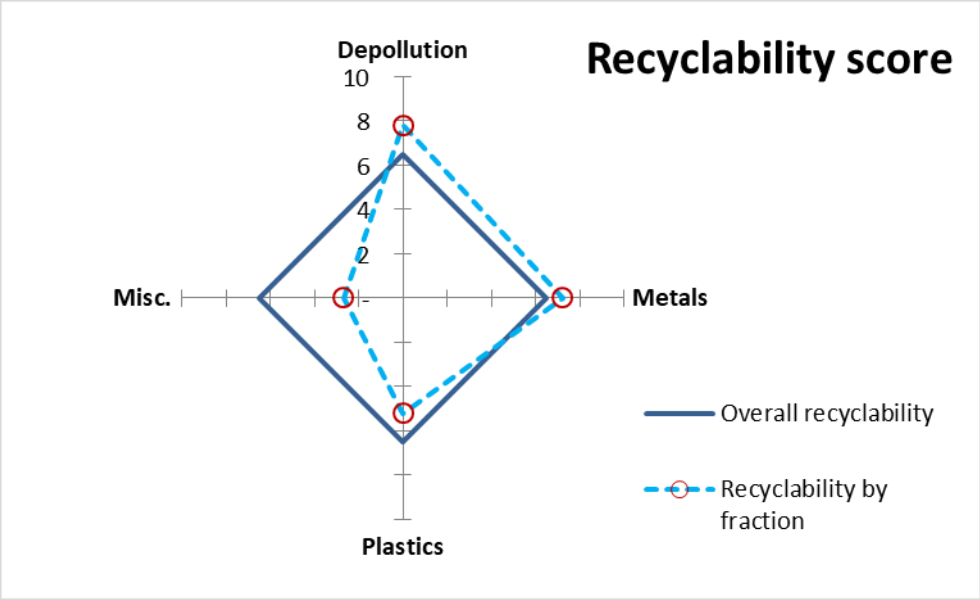
W_{VP} = the weight of the 'plastics score'

W_{VMisc} = the weight of the 'miscellaneous score'

The inclusion of weights allows differentiating the relative importance of the various fractions, depending on the product group considered.

6.5.1 *Visualization of recyclability*

The four scores can be visualized using a radar chart. In the below (fictive) example, the overall score is shown as a continuous blue line, and the individual scores as the dotted light blue lines (the overall score can be omitted of course, but is the only way to include the combined score in the same figure).



6.6 Recoverability score

Recovery includes various processes, of which recycling is one. Other processes considered to be recovery are: composting and backfilling, and energy recovery. If a material cannot be recovered, the only remaining option is 'disposal' which includes landfilling and incineration without energy recovery.

The recoverability score (R_{recov}) is constructed from four scores, related to recycling, composting, backfilling and energy recovery and is calculated as the weighted mean of the recyclable, compostable, backfillable and incinerable fraction R_{recyc}, R_{comp}, R_{back}, R_{incin}:

Equation 14. Recoverability score

$$R_{recov} = \frac{w_{recyc} * R_{recyc} + w_{comp} * R_{comp} + w_{back} * R_{back} + w_{incin} * R_{incin}}{w_{recyc} + w_{comp} + w_{back} + w_{incin}}$$

6.6.1 *Recyclable fraction*

This is the recyclability score, Rcyc, as established in 6.5

6.6.2 *Compostable fraction*

The compostable fraction score is calculated as:

Equation 15. Compostable fraction score

$$Rcomp = \frac{\sum_{i=1}^{n} polymer_{comp,i} + \sum_{i=1}^{n} misc_{comp,i}}{mass_{polymer} + mass_{misc}}$$

Where

$polymer_{comp,i}$ = the compostable mass of item i within the polymer fraction

$misc_{comp,i}$ = the compostable mass of item i within the miscellaneous fraction

$mass_{polymer}$ = total mass of polymer fraction

$mass_{misc}$ = total mass of miscellaneous fraction

Compostable means the item can be composted in accordance with EN 13432

6.6.3 Backfillable fraction

The backfillable fraction score is calculated as:

Equation 16. Backfillable fraction score

$$Rback = \sum_{i=1}^{n} \frac{polymer_{back,i} + misc_{back,i}}{mass_{polymer} + mass_{misc}}$$

Where

$polymer_{back,i}$ = the backfillable mass of item i within the polymer fraction

$misc_{back,i}$ = the backfillable mass of item i within the miscellaneous fraction

$mass_{polymer}$ = total mass of polymer fraction

$mass_{misc}$ = total mass of miscellaneous fraction

'backfillable' means the item can be used for backfilling purposes[95] in accordance with the Construction Products Regulation (EU) 305/2011[96].

6.6.4 Incinerable fraction

The incinerable fraction score is calculated as:

Equation 17. Incinerable fraction score

$$Rincin = \sum_{i=1}^{n} \frac{polymer_{incin,i} + misc_{incin,i}}{mass_{polymer} + mass_{misc}}$$

Where

$polymer_{incin,i}$ = the incinerable mass of item i within the polymer fraction

$misc_{incin,i}$ = the incinerable mass of item i within the miscellaneous fraction

$mass_{polymer}$ = total mass of polymer fraction

$mass_{misc}$ = total mass of miscellaneous fraction

Incinerable means the item can be incinerated safely and responsibly in an appropriate facility with recovery of energy. Appropriate means that the facility is capable of safely disposing hazardous substances possibly present in the item (such as

[95] http://ec.europa.eu/eurostat/documents/342366/4953052/Guidance-on-Backfilling.pdf/c18d330c-97f2-4f8c-badd-ba446491b47e
[96] http://ec.europa.eu/growth/sectors/construction/product-regulation/

halogenated flame retardants, or compounds, etc.). The item can be treated in accordance with recovery operation R1 as defined by Annex II of the Waste Directive 2008/98/EC and explanatory documents[97].

6.6.5 Weighting factors

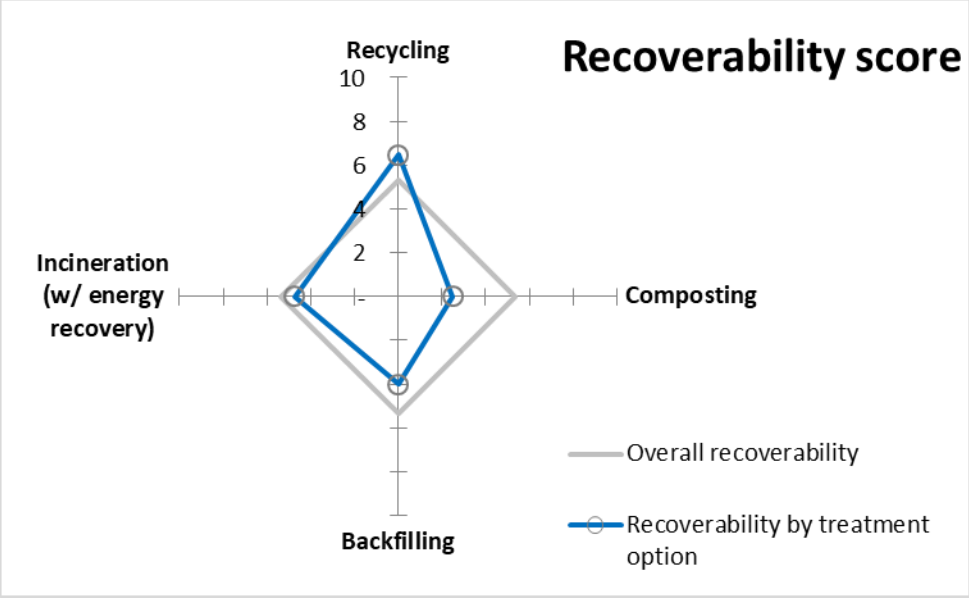
$w_{recyc}, w_{comp}, w_{back}$ *and* w_{incin} are weighting factors (any value).

If all weighing factors are set equal, the significance of recycling, composting, backfilling and incineration (with energy recovery) is equal. However, in most cases recycling is favoured over composting, backfilling and incineration, which can be reflected by a higher weight factor.

Additionally, if there are no compostable, backfillable and/or incinerable items present, the weights for these parameters may be set at zero respectively.

6.6.6 Visualization of recoverability

The four scores can be visualized using a radar chart. In the below (fictive) example, the overall score is shown as a continuous blue line, and the individual scores as the dotted light blue lines (the overall score can be omitted of course, but is the only way to include the combined score in the same figure).



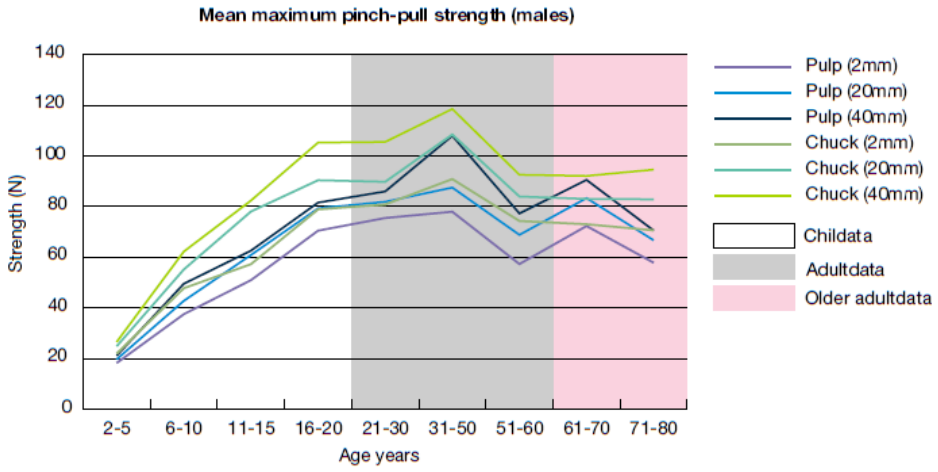
6.7 Notes regarding verification

6.7.1 Weak joints

The weak joint-type is defined as openable by hand. Ergonomic studies on the maximum force exerted by humans indicate a threshold level between 60-90 N in a pinch-pull test (results vary by gender and age). Maximum grip and push force can also be defined.

Figure 34. Maximum pinch-pull force [Ergonomics, DTI, UK]

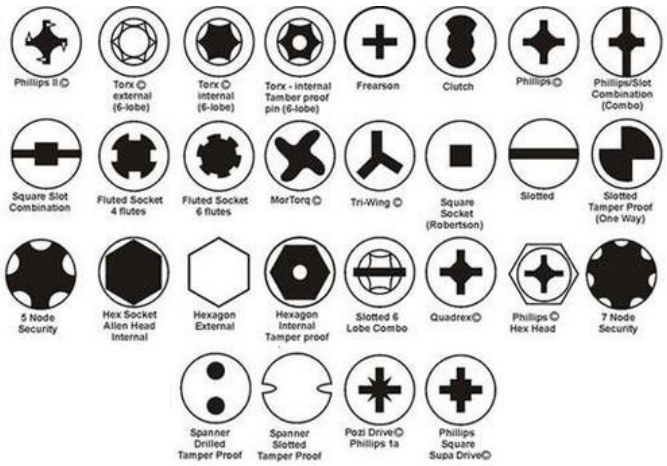
[97] http://ec.europa.eu/environment/waste/framework/pdf/guidance.pdf



6.7.2 *Standard joints*

The standard-joint type can either be liberated by using standardised tools (using tips such as pictured below) and/or by a blow by a hammer (impact test, expressed in joules).

Figure 35. Standardised tool tips



The proprietary 'pentalobe' tip used by Apple is not shown in the above figure.

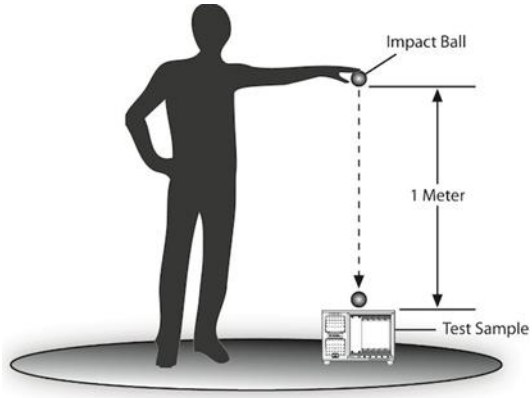
Other tools considered standard are spudgers (to remove cable assemblies), pliers, cable cutters, etc. (an elaborate list can be compiled by the Working Group experts dealing with the standard, if applicable)

Impact tests that could mimic a hammer blow are:

- IZOD impact test
- CHARPY impact test
- drop-weight impact test

The impact energy can be measured in Joules (for protective gear this is between 1-60 J)

Figure 36. Example of impact test



6.7.3 Strong or complex joints

- Either require specific equipment for removal of gaseous or liquid substances contained in the product (e.g. F-gas extraction);
- require a special conditioned atmosphere because of possible dispersion of airborne particles (asbestos fibres) or other than standard conditions (application of heat, application of solvents, etc.).
- and/or require cutting, grinding, sawing, machining, or other actions/machinery to separate a homogeneous material (this includes scraping, chiselling a glued battery) [i.e. does not meet the conditions for 'weak' or 'standard' joints?]

Figure 37. Extraction of F-gases

6.7.4 Recycling information

Recycling information can be added in the form of a QR-code. Depending on the physical size of the code, the marking can contain up to several thousands of letters/numbers. The specific format for information to be provided should be aligned with standards dealing with the provision of information.

Figure 38. Example of QR code

Manufacturer: "Example 1"
Model identifier: "model 1"
Depollution information:
Large capacitor - present: 1 * under motor hood;
Batteries - present: 1 * rear-side, 1 * PCB
Hg-part - present: 10 * lamps, in display
Metal-information: --
Polymer-information:
BFR or Sb-polymers - present: marked if >25g
Plast.-polymers - present: marked if > 25 g
Other materials:
Concrete - present: counterweight under motor hood
Cork - present: insulation motor

[created using: http://nl.qr-code-generator.com/#]

Information to be presented should be in conformity with the upcoming prEN 45559 Methods for providing information relating to material efficiency aspects of energy related products

6.8 Product cases

The equations and parameters described in the previous sections have been implemented in an Excel based model (actually, the model came first and was developed into a working prototype. The description in equations was added later).

[The product cases are described in the Excel-workbook supplied as second deliverable]

6.8.1 Selection of product cases

In consultation with the client the product cases focused on laptops. Two laptops, an old laptop with Hg-backlighting (ASUS Z9200, introduced 2006) and an fairly modern laptop with LED lighting and light metal housing (Apple MacBook pro 15", introduced 2012) were compared. The following components/materials have been identified for specific treatment:

1. Depollution
   - 1.1. Batteries
   - 1.2. Mercury backlight
2. Metals
   - 2.1. Printed circuit board, high grade
   - 2.2. Display module (containing ITO)
   - 2.3. LED module (if applicable)
   - 2.4. HDD
   - 2.5. metals:
     - 2.5.1. joined to electronics (housing)
     - 2.5.2. joined in motors
     - 2.5.3. joined in heat exchangers
3. Plastics
   - 3.1. Hazardous substances? (BFR, plasticizers, etc.)
   - 3.2. Sorting issues ? (carbon black, multi-material joints)
   - 3.3. Incompatibility issues ?
   - 3.4. Final treatment limitations ?
4. Miscellaneous
   - 4.1. any material worth recycling (not included above?)

6.8.2 Calculation of recyclability & recoverability

The teardown of the old laptop is presented in Annex F. The calculation of the scores is shown in the table below.

Table 11. Calculation of scores for old laptop

	Old laptop (ASUS Z9200)			RECYCLABILITY SCORE		(fictional product)	
					"effort" for liberating/sorting		
				0.975	0.95	0.9	0.8
1. Depollution (assumes manual liberation and sorting)		**Bonus applies if...**		**Product info bonus**	**weak**	**standard**	**strong/complex**
1.1	Batteries	if presence/absence declared AND chemistry indicated on OEM battery		1	1		1
1.3	Gas discharge lamps and/or other Hg-parts (includes FL lamps in backlight unit of LCD)*, Hg to be removed	if presence/absence declared			6	4	
				0.975	0.70	0.66	0.80
				Depollution score		**(10=best)**	**3.8**
Valorization (partly manual, partly automated)					"effort" for liberating/ sorting		
		Bonus applies if...		1.05	0.95	0.9	0.8
2. Metals	**Components holding precious metals, toxic metals and/or rare earth metals (Critical Raw Materials)**		**% green, brown**	**PWB bonus**	**weak**	**standard**	**strong/complex**
2.1	Removal of electronic board (PCB, PWB) > 10 cm2, or of mobile phone, or with gold content > 100 ppm*				2	3	
2.2	Removal of displays / screens > 100 cm2 (if not already removed in depollution)*						
2.3	Removal of LED modules						
2.4	Removal of HDD				1	1	
2.5	Removal of Al / Mg parts or components from high grade e-boards (housing, heat sink)					2	
2.6	Bonus for electronic board (PCB, PWB) < 10 cm2, or with gold content < 100 ppm	if PWB is green or brown, no bonus for red, blue, yellow, black, etc.	0%	0.000			
			1.00	1.000	0.86	0.53	1.00
				Score			**4.6**
					0.59874	0.34868	0.8
3. Plastics		**Bonus applies if...**	yes		**Compr. Plastic (kg)**		**Total polymer weight (kg)**
	Does the product contain polymers that ...?		no	**Loss factor**	(kg)		1.05
			Marked?	**10%**			**Plastics 'lost' (% of total plastics)**
3.1	contain intentionally added BFRs* or antimony FR	... if parts >25 g are marked according clause ..	yes	0.11			0.0%
3.2	contain intentionally added plasticizers that are substances of concern such as DEHP, DBP, DIBP and BBP	... if parts >25 g are marked according clause ..	yes	0.11			0.0%
3.3	contain foaming agents which are substances of concern and require separate treatment						0%
3.4	contain carbon black as colorant?						0%
3.5	PA combined with PC, PPE, PVC						0%
3.6	PBT combined with PVC						0%

3.7	PC combined with PA, POM, PVC					0%
	PE or PP (if density > 1.00 g/cm3) combined with ABS, ASA, PBT,					
3.8	PC, PET, PMMA, POM, PPE, PS, SAN					0%
3.9	PMMA combined with PBT					0%
3.1	POM combined with PC, PMMA					0%
3.1	PVC combined with PA, PBT, PC, PET,					
1	PPE					0%
3.1						
2	TPU combined with PBT					0%
3.1						
3	all thermoset polymers					0%
3.1	any combination of elastomers bonded with another polymer in a					
4	single part (co-extrusion, multi-material-injection)					0%
3.1	any combination of wrappers, stickers, adhesives not compatible					
5	with base polymer			0.1		10%
			Total (kg)	0.1	**% "lost"**	10%
			Polymer valorisation		**(10=best)**	**9.0**

4. Miscellaneous materials (not synthetic polymers, nor depolluted parts / metal parts)					**"effort" for liberating/sorting**		
					0.9	0.45	0.30
	(Examples)	**Existing recycling infrastructure?**	**Mass (kg)**	**Recycle-score per material**	**weak**	**standard**	**strong/complex**
4.1	clean wood	yes	0	0.90	1		
4.2	cork			0.00	1		
4.3	paper			0.00	1		
4.4	textiles / upholstery / foams			0.00	1		
4.5	concrete			0.00	1		
4.6	glass tempered			0.00	1		
4.7	glass float			0.00	1		
4.8	other ceramics			0.00	1		
			1 (kg available)	0.00 (kg recyclable)			
							100%
				Other material valorisation		**(10=best)**	-

5. Overall Recyclability score			**Overall recyclability**	**Weighting (optional)**	**Recyclability by fraction**
1.	Depollution		4.85	1	**3.8**
2.	Metals		4.85	1	**4.6**
		Total product weight (kg)			
3.	Plastics		4.85	0.33	**9.0**
4.	Misc.	3.2	4.85	-	-
5.				2.3	**4.8**

Table 12. Calculation of scores for modern laptop

	Modern laptop (Apple MacBook 2012)			RECYCLABILITY SCORE		(fictional product)	
					"effort" for liberating/sorting		
				0.975	0.95	0.9	0.8
1. Depollution (assumes manual liberation and sorting)		**Bonus applies if...**		**Product info bonus**	**weak**	**standard**	**strong/complex**
1.1	Batteries	if presence/absence declared AND chemistry indicated on OEM battery		1		2	
1.3	Gas discharge lamps and/or other Hg-parts (includes FL lamps in backlight unit of LCD)*, Hg to be removed	if presence/absence declared					
				0.975	1.00	0.81	1.00
				Depollution score		**(10=best)**	**8.3**
Valorization (partly manual, partly automated)					**"effort" for liberating/ sorting**		
		Bonus applies if...		1.05	0.95	0.9	0.8
2. Metals	**Components holding precious metals, toxic metals and/or rare earth metals (Critical Raw Materials)**		**% green, brown**	**PWB bonus**	**weak**	**standard**	**strong/complex**
2.1	Removal of electronic board (PCB, PWB) > 10 cm2, or of mobile phone, or with gold content > 100 ppm*					1	
2.2	Removal of displays / screens > 100 cm2 (if not already removed in depollution)*					2	
2.3	Removal of LED modules				1	2	
2.4	Removal of HDD				1	1	
2.5	Removal of Al / Mg parts or components from high grade e-boards (housing, heat sink)				1		
2.6	Bonus for electronic board (PCB, PWB) < 10 cm2, or with gold content < 100 ppm	if PWB is green or brown, no bonus for red, blue, yellow, black, etc.	0%	0.000			
			1.00	1.000	0.86	0.53	1.00
				Metal valorisation score		**(10=best)**	**4.6**
					0.857375	0.433467	1
3. Plastics		**Bonus applies if...**	yes		**Compr. Plastic (kg)**		**Total polymer weight (kg)**
	Does the product contain polymers that ...?		no	**Loss factor**	(kg)		1
			Marked?	**10%**			**Plastics 'lost' (% of total plastics)**
3.1	contain intentionally added BFRs* or antimony FR	... if parts >25 g are marked according clause ..	yes	0.11			0.0%
3.2	contain intentionally added plasticizers that are substances of concern such as DEHP, DBP, DIBP and BBP	... if parts >25 g are marked according clause ..	yes	0.11			0.0%
3.3	contain foaming agents which are substances of concern and require separate treatment						0%
3.4	contain carbon black as colorant?						0%

3.5	PA combined with PC, PPE, PVC					0%
3.6	PBT combined with PVC					0%
3.7	PC combined with PA, POM, PVC					0%
3.8	PE or PP (if density > 1.00 g/cm3) combined with ABS, ASA, PBT, PC, PET, PMMA, POM, PPE, PS, SAN					0%
3.9	PMMA combined with PBT					0%
3.1	POM combined with PC, PMMA					0%
3.11	PVC combined with PA, PBT, PC, PET, PPE					0%
3.12	TPU combined with PBT					0%
3.13	all thermoset polymers					0%
3.14	any combination of elastomers bonded with another polymer in a single part (co-extrusion, multi-material-injection)					0%
3.15	any combination of wrappers, stickers, adhesives not compatible with base polymer					0%
				Total (kg)	1	**% "lost"** 0%
				Polymer valorisation		**(10=best)** **10.0**

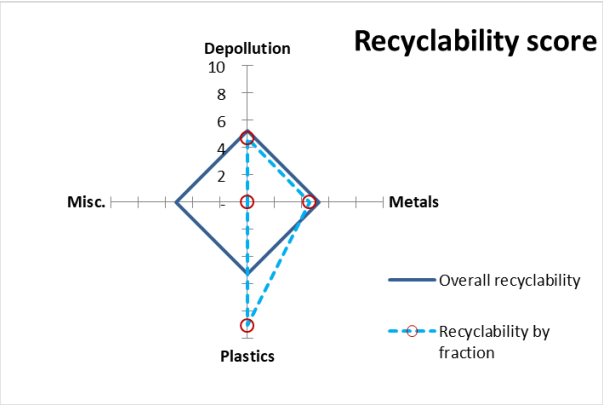
4. Miscellaneous materials					"effort" for liberating/sorting		
(not synthetic polymers, nor depolluted parts / metal parts)					0.9	0.45	0.30
	(Examples)	**Existing recycling infrastructure?**	**Mass (kg)**	**Recycle-score per material**	**weak**	**standard**	**strong/complex**
4.1	clean wood	yes	0	0.90	1		
4.2	cork			0.00	1		
4.3	paper			0.00	1		
4.4	textiles / upholstery / foams			0.00	1		
4.5	concrete			0.00	1		
4.6	glass tempered			0.00	1		
4.7	glass float			0.00	1		
4.8	other ceramics			0.00	1		
			1 (kg available)	0.00 (kg recyclable)			0%
				Other material valorisation		**(10=best)**	-

5. Overall Recyclability score		**Overall recyclability**	**Weighting (optional)**	**Recyclability by fraction**
1.	Depollution	5.25	1	**8.3**
2.	Metals	5.25	1	**4.6**
3.	Plastics	5.25	-	-
4.	Misc.	5.25	-	-
5.			2.0	**6.4**

Total product weight (kg): 0

Figure 39. Recyclability score 'Old vs. New'

Old laptop



Modern laptop

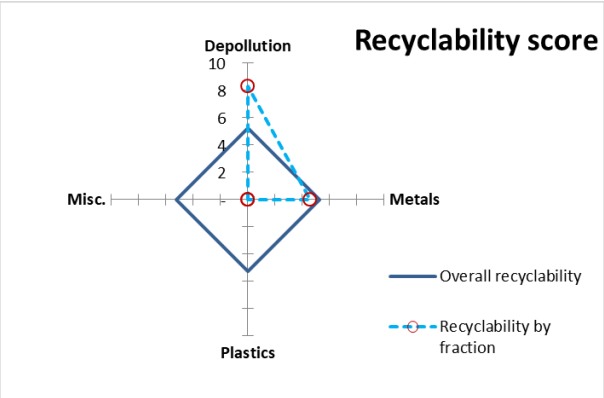
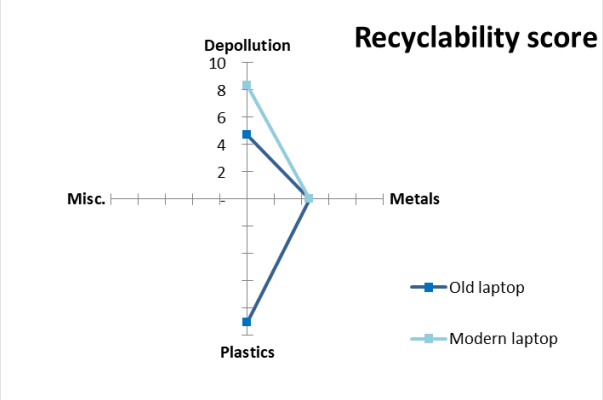


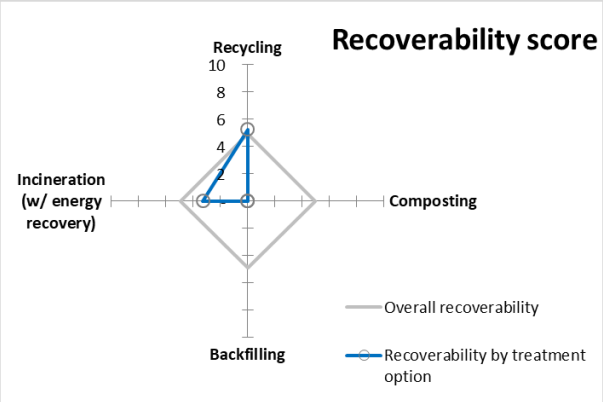
Figure 40. Recyclability combined in a single figure



The recoverability score of the old laptop is an average 4.6, as this is calculated on the basis of the recyclability and potential for incineration only. Weight for incineration was selected to be 1/5th of recyclability. For the new laptop it was 6.4 based on recycling only (no incineration or other recovery).

Figure 41. Recoverability score 'Old vs. New'

Old laptop



Modern laptop

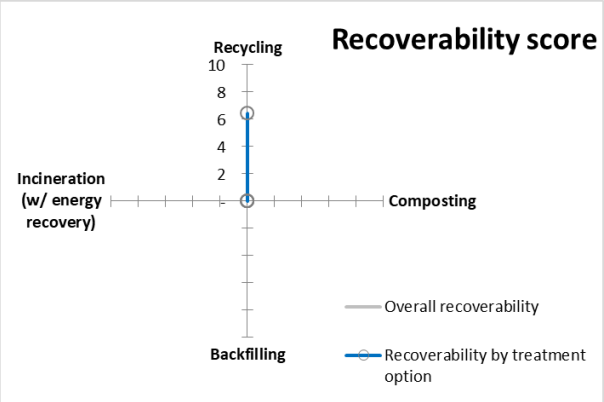
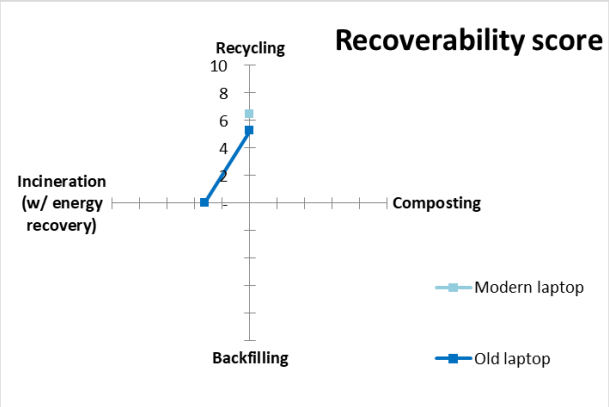


Figure 42. Recoverability combined in a single figure



6.9 Evaluation of the new method

After having performed several exercises with the method the following observations and recommendations are made:

6.9.1 The comparison of laptop scores

Identification of components relevant for assessment

The selection of components (assemblies/parts/materials) to be included in the assessment is very influential for the final outcome. The recyclability of the Modern laptop would increase from 6.4 to 7.1 if the removal of LED modules is ignored (coincidentally also the iFixit score). Likewise the recyclability of the modern laptop would reduce to 5.9 if not only the removal of LED modules is included, but also the removal of the display back cover. This all has to do with the number of layers to be removed and the weakness of the joints.

What if no plastics present for recycling?

The modern laptop has an aluminium unibody and virtually no plastic body parts (there are numerous plastics, but these are part of assemblies that are treated as a whole, i.e. the battery, the main board, etc.). For this reason the plastic score has been set to '-' (no entry) and is not counted in the overall recyclability score. The older laptop, with lots of usable plastic body parts has been given a good score (the carbon black issue is discussed below) – does that make this laptop a more recyclable laptop? In essence this depends on the recycling of the modern laptop body parts, for which they need to be liberated from the main board (otherwise they will end up in the Cu/Ni smelter) and the display (again in Cu/Ni smelter or Zn/Pb smelters for indium recovery, but neither recovers the aluminium). If this is included the recyclability score plummets below 6 although we can be fairly certain a demand for the aluminium exists, whereas this cannot be said for the plastic ABS+PC blend.

Carbon black and WEEE products

The recognition of carbon black plastics by NIR is difficult, especially when sorting black packaging plastics. But for WEEE the use of black plastic is quite common in consumer electronics, and other techniques exist to remove the black plastic from the mixed waste stream (visual sorting, density separation). As it is currently implemented, a lot of good recyclable plastics would not be counted as recyclable because of its colour.

Improvement options for the modern laptop are primarily the reduction of component depth (number of layers) and the type of joints.

6.9.2 Generic observations

Complex versus simple products

Very complex products (like multifunctional copiers, with network availability, etc.) would achieve very low scores with the method 'as is' as the number of layers can be quite deep. However, by reducing the weights per joint-type, the score (for depollution and metals) can be lifted so that average products can achieve an 'average' score. The method can thus be adapted to allow better comparison of compatible products. If however, one is interested in how much more difficult it is to recycle a copier versus a battery shaver, the weights should be kept constant.

Counting of joints relevant for both depollution and metals

The method assigns a score based on the assembly depth of the part and the type of joint. Naturally when liberating a joint to access a part, it could be that other parts or substances (both applicable to depollution and metals) are liberated as well. Of course this joint should not count twice. This can be solved by proper accounting of the number of joint-types encountered and the liberation of components.

However, it could result in counting all joints towards 'depollution' and leaving zero joints for 'metals' in case both are freed at the same time, but different weights apply to depollution and metals. It is possible to strategically distribute joints weights over the assessment so that an advantage is achieved.

The solution is to either split the total joint-count over both material groups (e.g. 0.5 joints to 'depollution' and 0.5 joints to 'metals'), or to combine both depollution and metals in a single score. The latter solution is easier for the counting of joints, but makes the correction for depollution information and metal information more complex. This issue has to be dealt with when further developing the method.

Acquiring information on plastics

The method has been designed so that assessment can take place with minimal reliance on external information: Just the bill of materials of the product should suffice, combined with a teardown to assess the joint-types.

But for plastics, the assessment relies on exact information on plastic type and grade, including additives such as BFRs and phthalates. Such information is not produced in a table-top assessment/teardown. Either the assessor has to acquire a detailed list of plastic types (going beyond most BOMs), additives and mass of the parts from the manufacturer directly, or create such a list by him/herself by weighing parts and applying polymer identification analysis. For certain additives this could entail expensive laboratory testing. The FairPhone assessments show that this level of information can be achieved, even for a final manufacturer, although he/she has to contact many (sub)suppliers. In case such information is not available, the score is less reliable.

Verification of undesirable plastic combinations

Both laptops have a keyboard assembly that consists of a plastics keys, connected to a metal base board. The plastics score does not include a simple rating of the joint type applied and thus whether the keys can be counted as recyclable or not (it is possible that a certain percentage is not liberated and sent to the Fe-smelter route).

7 Conclusions & recommendations

7.1 Conclusions

Recycling is what happens if one tries to recover materials from a waste product with the aim to reuse the materials again, possibly for their original purpose. This implies depollution, the removal of hazardous substances from the material to be recycled, so that these do not stand in the way of possible reuse or valorisation of materials and recover as much economic value from the waste product as possible.

The effort required to remove pollutants and extract value is determined by the combination of waste treatment technologies and the design of the product being processed. For certain materials/parts/assemblies certain recycling routes are preferable over others, as they allow better recovery of the materials. Whether these preferred routes are easy or difficult to establish depends on the design of the product for a great deal.

A more recycling friendly design of products may be brought about by introducing a simple scoring method, expressing the recyclability of a product. Such a scoring method could A) make manufacturers better aware of their decisions in product design that affect recycling, especially if such information is made mandatory, and B) could be used to differentiate the EPR fees paid by manufacturers so that an economic incentive is created to improve the design.

Several methods have been developed to calculate or express the recyclability of a product, but none of these fulfilled all requirements for the above goals: Methods did not adequately consider the interaction between product design and waste treatment technologies, rely on personal judgement of performance, or required complex calculations using software / datasets managed by 3rd parties, etc.

The new method described in Chapter 6 focuses on those parts, assemblies and materials that are the most challenging when recycling (recovering) the product. These recycling challenges can be identified for each product category or group so that the method can be tuned to specific product categories or product groups.

The method is set up to allow an objective assessment on the basis of the product only, without referring to external datasets, and be less susceptible to personal judgement. The weighing factors included in the method are to be established by experts and apply to all products equally (if confined to the same product group).

The assessment also avoids use of production-related parameters, as these could be considered as potentially conflicting with WTO rules.

The result of the method, a score between 0-10, is easily conveyed to the general public, and can be used as a basis for a differentiated EPR fee (for this to happen, a reference score has to be established).

7.2 Recommendations

7.2.1 Regarding the RR method

Before the new RR method can be employed as described above, it needs to be scrutinised by experts, preferably in the context of setting EN standards under Mandate M/534.

A proposal for its further development, by means of a new work item proposal, has been discussed by CEN/CLC TC10, WG5. This development should in particular identify materials/parts/assemblies relevant for product specific standards, and should establish the weighing factors applied in the calculation of the effort for liberation. The method then needs to be tested with a larger group of products and experts, including those that could be involved in market surveillance and/or providing proof of conformity.

Besides this, the development of other methods aiming for similar goals, should be followed as these could bring valuable insights. The work by iNEMI is of particular interest. Where such standards are being discussed, the aspect of legal implementation, and the focus on product characteristics, should be stressed, as otherwise its possible implementation will be voluntary at maximum. Method should avoid inclusion of 'production-related elements'.

7.2.2 Regarding implementation by the Belgian Federal government

As stated in Chapter 1 - Introduction the purpose of the method is to improve the understanding between product manufacturers and recyclers, and, based on this information (possibly made available under Directive 2009/125/EC), allow more differentiation in rates within extended producer responsibility (EPR) systems (under Directive 2012/19/EU).

Differentiation in rates EPR

The current collective producer responsibility schemes do not incentivize the (re)design of products to make recycling easier and/or more economical: Producers, or ultimately the consumers, pay upfront for the amount of waste placed on the market but the fees generally do not differentiate between easy to recycle or difficult to recycle products. An individual producer responsibility scheme could change this. Note: this does not mean that producers must organise the physical treatment of the waste products individually. This can still be done through collective facilities. It does mean that the producers bears the costs for the treatment of his own products.

Individual producer responsibility is covered in the WEEE Directive in recital (23) that states *".. Collective schemes could provide for differentiated fees based on how easily products and the valuable secondary raw materials that they contain could be recycled"* and Article 12.3 that refers to *"financing the operations ... relating to the waste from [the producers'] own products"*.

The implementation of the WEEE Directive by the Belgian regions[98, 99] allow the possibility of an 'individual producer responsibility' for products placed on the market after 13 August 2005. The fee structure however is decided by the organisations responsible for the collection and treatment of waste products. For WEEE, an example is the differentiation in handling fees is applied in Belgium, by Recupel, for the handling and treatment of ionizing (radioactive) smoke alarms, the fees of which are some 10 times higher than for other equipment[100]. In France the fees are modulated in accordance with product characteristics that influence the generation of waste, which ranges from availability of spare parts, to use of recycled material, or absence of paint and coatings incompatible with reuse of plastics, etc.[101].

Modulating or differentiating such fees is therefore deemed possible, but adds complexity as more information determines the fees. The French example shows that the extra information may not need to be limited to only the performance as regards recyclability and recoverability, but may also include parameters related to reparability, use of recycled materials, etc.

A recent Dutch study on extended producer responsibility included interviews with multinational producers in which they stress the need to avoid additional administrative costs, consideration of the cost-benefit ratio (increased complexity only if significant environmental gains can be achieved), and the need for more harmonization of EPR schemes in Europe. Furthermore, modulating fees should not disturb a level playing field and should be controlled to reduce free-riding (for instance if consumers buy directly from extra-EU shops).

The interviewee from Philips in the abovementioned study provided some specific boundary conditions:

- Implementation should be on the European level rather than the national level;
- criteria should be the same in all EU countries (harmonized);
- criteria should target a selection of priority issues that are updated every several years;
- the process should be coordinated by a standardization organization through a multi-stakeholder process;
- and, the differences between the modulated fees should be more substantial than in the current situation.

Some of these conditions can be met by using the Ecodesign Directive for the introduction of RR information.

Ecodesign requirements

The Ecodesign Directive 2009/125/EC allows the Commission to include recyclability and recoverability aspects in implementing regulations as long as this can be done within the rules set out in Article 15 of that Directive.

If an RR-score is to be included as requirement, the implementing regulation should start (in an annex on measurement and calculations) with identifying which materials / parts / assemblies should be taken into account in the assessment of the RR-score, and the regulation could even specify the weighing factors for the various joint-types and metal scores versus plastic scores etc. This allows a multi-stakeholder discussion of these aspects. The method (not the values for weighing etc.) would be described in a (harmonized) EN standard.

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[98] https://emis.vito.be/nl/actuele_wetgeving/23-mei-2014-besluit-van-de-vlaamse-regering-tot-wijziging-van-het-besluit-van-de

[99] http://www.ejustice.just.fgov.be/doc/rech_n.htm

[100] Maarten Dubois (EY Belgium), Diana de Graaf (EY Netherlands), Joachim Thieren (EY Belgium), Exploration of the Role of Extended Producer Responsibility for the circular economy in the Netherlands, June 27th 2016

[101] Technical report - Application of environmental contribution modulation criteria, by OCAD3E - Waste Electrical and Electronic Equipment Authorised Coordinator Agency (Ecologic, Eco-Systemes, recylum), 17/04/2015

The regulation could then implement generic or specific ecodesign requirements. Generic requirements relate to the provision of product information with relevance to the environmental performance. Requiring the (product-specific) RR-score as mandatory product information is a logical step and could serve three goals:

1) The RR information could help to influence possible buying behaviour of consumers, but the score then needs to be visible at the point-of-sale. This can in principle be done through a specific provision in the regulation (there is no article in 2009/125/EC that prohibits this[102]) but inclusion in the Energy label (if applicable) would be preferable. This however is not (yet) allowed as the energy label is limited to resource use during the use-phase.
2) The mandatory provision of RR information is also instrumental to the establishment of an individual producer responsibility scheme, where a producer pays fees in relation to the recyclability / recoverability of his/her own products. The benefits would be that the method would be harmonised across the EU, as it is described in an EN standard and the (politically sensitive) parameters are described in the legislation (parts/assemblies and weighing factors).
3) Additionally, the RR-score could also assist in making information regarding end-of-life treatment available to recyclers.

   Article 15 of WEEE Directive 2012/19/EU requires Member States to *"take the necessary measures to ensure that producers provide information free of charge about preparation for re-use and treatment in respect of each type of new EEE placed for the first time on the Union market within one year after the equipment is placed on the market. This information shall identify ... the different EEE components and materials, as well as the location of dangerous substances and mixtures in EEE. It shall be made available to centres which prepare for re-use and treatment and recycling facilities by producers of EEE in the form of manuals or by means of electronic media (e.g. CD-ROM, online services)."*

   Recycling facilities state that manufacturers do not supply this information in sufficient numbers[103]. Enforcement of this provision is also particularly challenging as the exact content and format of the information is not clear, and not required for being allowed placement on the market: the WEEE Directive is not a New Approach Directive and does not require CE marking for presumption of conformity.

   Implementing regulations under the Ecodesign Directive do require CE marking and enforcement follows known routes. At the moment most implementing regulations under the Ecodesign Directive include the provision of "information relevant to disassembly, recycling and disposal at end-of-life", but it depends on the applicable harmonised standards to give interpretation and meaning to this. In most cases the EN standards are not much more explicit than referring to proper treatment, without stating what this actually means.

   Ecodesign requirements can improve this situation by requiring more explicit information: regarding the identification of different EEE components and materials, as well as the location of dangerous substances and mixtures in EEE, and the manner through which this information is made available to those who need it, similar to the WEEE Directive. Ideally (candidate) harmonised standards should be aligned as well so that the requirement and the means to verify compliance are consistent.

   The RR method described includes a consideration of presence of product information, for example by means of a QR-code[104], which meets the above requirements coming from the WEEE. But the method can only be applied if there is an ecodesign requirement that prescribes the form and content of the information to be provided.

The use of the RR-score as a specific requirement means that the product must meet specific threshold values. The setting of specific ecodesign requirements must be according the method described in Annex II of Ecodesign Directive 2009/125/EC which requires a technical, environmental and economic analysis that supports the economic and technical feasibility, including a sensitivity analysis. The currently available information is insufficient for this purpose.

***

Implementing regulations under the Ecodesign Directive can require the recyclability / recoverability score as mandatory product information[105]. Such a mandatory RR-score would enable:

1) the possibility to show this information at point-of-sale (if indeed allowed under the Ecodesign Directive 2009/125/EC);
2) the possibility to use this information for differentiated or modulating EPR fees;

[102] Annex I, Part 2. Requirements relating to the supply of information of Directive 2009/125/EC states that "Implementing measures may require information to be supplied by the manufacturer that may influence the way the product is handled, used or recycled by parties other than the manufacturer". It also states that said information should be given on the product itself wherever possible. For distance-selling this means that the information could be required when showing the purchase price (similar to Energy Labelling).

[103] Personal comment by EERA representative N. Zonneveld and L. Stengs.

[104] A QR-code is an easy to create visual code that can be read by either dedicated or universal (smartphone) readers and displays the information contained (or links to information accessible through the web).

[105] Assuming the method is developed to sufficient level, and relevant materials / parts / assemblies and weighing factors can be identified.

3) the provision of information (as required under WEEE) in a more consistent and harmonized manner, also allowing easier enforcement.

ANNEX A: Definitions

The table below presents an overview of various terms used in this report and the definition preferred by the authors.

Table 13 Overview of definitions

Term	Defined as	Source / reference
Assembly	means a set of components assembled into a single part	Bram Soenen
Backfilling	means a recovery operation where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials	2008/98/EC
Component	means a part that cannot be taken apart without destruction or impairment of its intended use	Bram Soenen
Disposal	means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy. Annex I (of 2008/98/EC) sets out a non-exhaustive list of disposal operations;	2008/98/EC + IEC/TR 62635
Downcycling	A process of converting materials into new materials of lesser quality and reduced functionality	Ellen MacArthur Foundation
End-of-life	life cycle stage of a product starting when it is removed from its intended use-stage	IEC 62075:2008 [4], definition 3.4, modified
End-of-life treatment	any operation after a waste has been handed over to a facility for product and product part reuse, material recycling, energy recovery and residue disposal	IEC/TR 62635
End-of-life treatment scenario	description of an end-of-life treatment process and corresponding recycling rates of product parts and materials	IEC/TR 62635
Energy recovery	Energy recovery means the use of combustible waste as a means to generate energy through direct incineration with or without other waste but with recovery of the heat;	VHK, for this study
Energy recovery	production of useful energy through direct and controlled combustion or other processing of waste Note 1 to entry: Waste incinerators producing hot water, steam and/or electricity are a common form of energy recovery	IEC/TR 62635
Index	means a number giving the magnitude of a physical property or other measured phenomenon in terms of a standard	Oxford dictionary[1]
Manufacturer	organization responsible for the design, development and manufacture of a product in view of its being placed on the market, regardless of whether these operations are carried out by that organization itself or on its behalf	IEC/TR 62635
Material	means a substance or a mixture of substances of uniform composition throughout (homogeneous) or consisting of a combination of (different mixtures of) substances, that cannot be disjointed or separated by mechanical actions such as unscrewing, cutting, crushing, grinding and abrasive processes;	VHK, for this study, based on RoHS 2011
Material recovery	material-processing operations including mechanical recycling, feedstock (chemical) recycling and organic recycling, but excluding energy recovery	IEC/TR 62635
Material separation	operation to separate materials, including mechanical, chemical or thermal process (e.g. shredding, smelting, sorting , etc.) other than dismantling	VHK, for this study
Part	means a manufactured object assembled with others to make a product;	VHK, for this study

Post-consumer	means waste of products that have been used by the final user (consumer);	VHK, for this study
Pre-consumer	means waste that (when still a product) has not yet been used by the final user (consumer). It covers waste from manufacturing processes, or of products that have not been sold to final customers;	VHK, for this study
Product, also 'energy related product'	means any good that has an impact on energy consumption during use which is placed on the market and/or put into service, and includes parts intended to be incorporated into energy-related products covered by this Directive which are placed on the market and/or put into service as individual parts for end-users and of which the environmental performance can be assessed independently;	2009/125/EC
Recoverability	ability of a waste product to be recovered, based on actual practices	IEC/TR 62635
Recovery	means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II (of 2008/98/EC) sets out a non-exhaustive list of recovery operations;	2008/98/EC
Recovery rate	ratio of recovered products, product parts or materials mass to waste product mass reprocessed	IEC/TR 62635
Recovery rate	means the amount of materials that have been (or can be expected) to be recovered, divided by the amount of materials that have been offered to the first waste treatment facility or operator;	VHK, for this study
Recyclability	ability of waste product to be recycled, based on actual practices. Whereby recycling assumes that losses may occur due to technical, economical constraints or limitations of the product, the recycling processes and/or the combination of both;	VHK, for this study
Recyclability rate / index / score	ratio of recyclable product mass to total product mass	IEC/TR 62635
Recycler	organization with the facility to carry out recycling and/or recovery operations	IEC/TR 62635
Recycling	means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations;	2008/98/EC
Recycling rate	ratio of recycled products, product parts or materials mass to waste product mass reprocessed Note 1 to entry: A recycling rate is obtained by computing data obtained from recycling operations.	VHK, for this study
Removal	means manual, mechanical, chemical or metallurgic handling with the result that hazardous substances, mixtures and components are contained in an identifiable stream or are an identifiable part of a stream within the treatment process. A substance, mixture or component is identifiable if it can be monitored to verify environmentally safe treatment; Note: This means that feeding a complete smartphone into a copper smelter is a form of removal, as it separates (into identifiable streams) valuable materials (copper, gold, silver, etc.), compounds (incl. slags) and off-gases etc. Similarly, any handling resulting in separation into more streams than the input stream is a form of removal, if the streams can be monitored (for environmentally safe treatment).	
Reusability	means the ability of a product to reused;	VHK, for this study
Reusability rate	means the amount of materials that have been (or can be expected) to be reused, divided by the amount of materials that have been offered to the first waste treatment facility or operator;	VHK, for this study

Reuse	means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived	2008/98/EC
Reuse	operation by which a product, or a part thereof, having reached the end of one use stage is used again for the same purpose for which it was conceived	IEC/TR 62635
Substance	means a chemical element and its compounds in the natural state or obtained by any manufacturing process, including any additive necessary to preserve its stability and any impurity deriving from the process used, but excluding any solvent which may be separated without affecting the stability of the substance or changing its composition;	Regulation 1907/2006 ('REACH')
Total product mass	waste product mass reference which is inputted to the end-of-life treatment process	IEC/TR 62635
Waste	means any substance or object which the holder discards or intends or is required to discard	2008/98/EC

ANNEX B: Ecodesign requirements proposed

Proposal for ecodesign requirements – Electronic displays

The proposal for ecodesign requirements for electronic displays of summer 2016 introduces several waste phase related resource efficiency requirements. These are:

ANNEX III Resource efficiency requirements

From 1 January 2020:

1. Requirements on design for dismantling, re-use, recycling and recovery

Manufacturers shall ensure that welding or gluing other than through the use of double-sided adhesive tape are not used as joining or sealing techniques for the following components, when present

- batteries;
- PCB assemblies larger than 0.1 dm2;
- display panels larger than 1 dm2;
- mercury containing components;
- capacitors; and in addition;
- PMMA boards;
- internal power supplies.

Accessing components shall be ensured by documenting the sequence of dismantling operations needed to access the targeted components, including for each of these operations, the type and number of fastening technique(s) to be unlocked, and tool(s) required.

2. Marking of plastic parts

Plastic parts heavier than 50g:

2.1. Shall be marked by specifying the type of polymer using the appropriate standard symbols and abbreviated terms as specified in available standards. The marking shall be legible.

Plastic parts in the following circumstances are exempt from marking requirements:

- the marking is not possible because of the shape or size;
- the marking would impact on the performance or functionality of the plastic part;
- marking is technically not possible because of the moulding method.

For the following plastic parts no marking is required:

- packaging, tape, labels and stretch wraps;
- wiring, cables and connectors;
- PCB assemblies, PMMA boards, optical components, electrostatic discharge components, electromagnetic interference components, speakers;
- transparent parts where the marking would obstruct the function of the part in question;
- If there is not enough available appropriate surface area for the marking to be of a legible size to be identified by a recycling operator.

2.2. If flame retardants are present, they shall be marked according to available standards and using the following notation: ' x-FR-y'

where:

x= abbreviated term for the polymer used

FR = abbreviation meaning 'flame retardant'

y= standard code number of the flame retardant used.

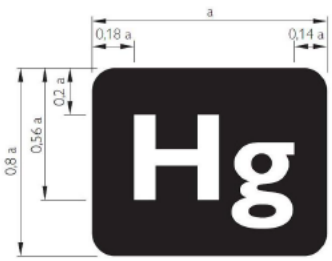
From 1 July 2018:

3. Mercury logo

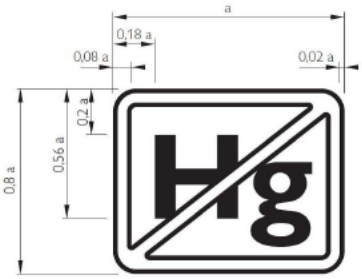
Electronic displays shall be labelled with the "Mercury inside" logo. The logo shall be visible without the removal of a cover, durable, legible and indelible. The logo shall be in the form of the following graphic.

A "Mercury free" logo may be used if no mercury is used in the backlighting system or other component.

Mercury inside



Mercury free



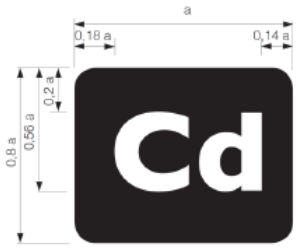
The dimension of “a” shall be greater than 9 mm and the typeface to be used is ‘Gill Sans serif’.

4. Cadmium logo

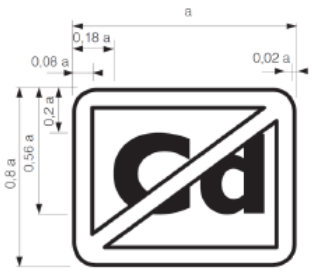
Electronic displays shall be labelled with the "Cadmium inside" logo. The logo shall be visible without the removal of a cover, durable, legible and indelible. The logo shall be in the form of the following graphic. The "Cadmium inside" logo shall be attached also internally, on the back of the LCD panel, in a position easily visible by a worker dismounting or manipulating it.

A "Cadmium free" logo may be used if no cadmium is used.

Cadmium inside



Cadmium free



ANNEX IV Information requirements

From 1 July 2018, the following information shall be kept available for at least 15 years from the day the last model of a product family was placed on the market and free of charge:

(1. General Information , 2. Technical information, and...)

3. Repair and end of life documentation and information

For each product family, suppliers shall provide information relevant for repair purposes including the information relevant for non-destructive disassembly and replacement of defective components.

For each product family, suppliers shall provide information relevant for dismantling, re-use, recycling and recovery at end-of-life including at least the following:

a) a diagram of the product showing the location of the components indicated in section 1 of Annex III, when present, and showing the location of plastic parts containing flame retardants, when present, using references of parts as given in the Table IV.2;
b) instructions on the sequence of operations needed to remove these components, including type and number of fastening techniques to be unlocked and tool(s) required;
c) the reason why certain, if any, plastic parts are not marked as per the exemption set out in section 2.1 of Annex III;
d) for the following toxic, ecotoxic or rare and precious substances: cadmium, lead, arsenic, mercury or their compounds and indium: the indication of the specific substance(s), the location of all component(s) containing each, its quantity (as X,X mg), and the advised recycling techniques, if any, to be applied;
e) if plastic parts (excluding the PCB assemblies) containing flame retardants are used, documentation in the format of Table I.

Table I - 'Flame retardant in plastic parts' index calculation table.

(All masses shall be expressed in grams)

Brand name and Product family:			
Part reference	**Polymer ***	**Flame retardant****	**Total mass (g)**
Reference *(1)*	…	…	…
Reference *(2)*	…	…	…
…	…	…	…
Reference *(j)*	…	…	…
A) Overall mass of plastic parts*** incorporated in the display that contain flame retardants *(g)*			
B) Overall mass of plastic parts***incorporated in the display *(g)*			
Total mass of the display *(g)*			
			Index (%)
Ratio of plastic containing flame retardants on the total mass of plastic (A/B)			
Ratio of plastic containing flame retardants on the total mass of display (A/C)			

* standard abbreviated term for the polymer(s)

** standard code number of the flame retardant(s)

*** PCB assemblies are excluded

ANNEX V Measurements

1. to 4. as in original document

5. Measurements of marking of plastic parts of electronic displays

Measurements of marking of plastic referred to in Annex III, point 2 shall be made using a reliable, accurate and reproducible measurement procedure, which takes into account the generally recognised state of the art measurement methods.

6. Mercury logos

Measurements of presence of mercury in components of electronic displays referred to in Annex III, point 3 shall be made using available standards, as those already used to check the compliance of product with the Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances.

ANNEX VI Product compliance verification by market surveillance authorities

10. Verification procedure for requirements established in Annex III

For the requirement set out in Annex III, market surveillance authority/member States' authorities shall test one single display unit.

The model shall be considered to comply with the requirements, if:

i. No fastening technique using welding or gluing, other than through the use of adhesive tape, is encountered in the sequence of dismantling operations leading to the extraction of the targeted components, as set out in Annex III point 1;
ii. All plastic parts of the display larger than 50 g, other than those exempted as defined in Annex III point 2, are marked with the proper symbols set out in Annex III point 2.1. Models with plastic parts larger than 50 g (other than PMMA board and display optical plastics) containing flame retardants shall be considered to comply with the requirements if marked with the proper symbols for flame retardant, as set out in Annex III point 2.2. For exempted plastic parts, the market surveillance authority shall check that a justification is provided in the end-of-life documentation, as in Annex IV point 3;
iii. The mercury logo and/or cadmium logo, as detailed in Annex IV point 3, are present for products containing these toxic metals; and
iv. The end-of-life documentation for the product family containing all information set out in Annex III point 3, as applicable, is made available on a website.

If the test results and requirements under sub points (i), (ii), (iii) or (iv) are not achieved, the model is considered not compliant.

11. Verification procedure for requirements established in Annex IV (Information requirements)

For the requirement set out in Annex IV, the Member States' authorities shall verify the information requirements for one single display unit.

The model shall be considered to comply with the requirements set out in Annex IV.1, if all the required information is present in the format and order listed in Annex IV.1, printed on paper or as PDF document provided on a suitable support, such as CD, DVD, SD card, USB memory stick of similar supports for which a reader is commonly available on the market.

The model shall be considered to comply with the requirements set out in Annex IV.2 and **Annex IV.3**, if all the required information is present in the format and order listed in Annex IV.2 and Annex IV.3, **accessible and correctly viewable using the last major release of at least two web browsers among the more common five web browsers available**.

Voluntary Agreement imaging Equipment

The Voluntary Agreement by the European imaging equipment seems to have drawn inspiration for the EPEAT criteria. The Voluntary Agreement version 5.2 of April 2015 has the following criteria related to recyclability aspects:

5.2. Design for recycling

For all product models first placed on the EU market after 1 January 2012:

- Plastic parts >100 g shall be manually separable into recyclable plastic streams with commonly available tools.
- Product shall utilize commonly used fasteners for joining components, subassemblies, chassis and enclosures.
- Non-separable connections (e.g. glued, welded) between different materials shall be avoided unless they are technically or legally required.
- Product plastics shall be marked by material type (ISO 11469 referring ISO 1043, resin identification code, SPI, DIN, or country specific). Marking requirement does not apply to plastic parts weighing less than 25 g or with surface area less than 50 cm^2; tape; plastic protective and stretch wraps and labels; or plastic pieces when due to shape marking is not possible. Exempted are plastic parts contained in reused complex modules.

5.3 Polymer composition

For all new TEC product models first placed on the EU market after 1 January 2015:

In order to limit the variety of materials used, plastic casing parts with a mass greater than 100 grams have to consist of one single polymer or a polymer blend.

All plastic casing parts may only consist of up to four separable plastics or polymer blends.

Large-sized casing parts must be designed in a way that the contained plastics can be used for the production of high-quality durable products by applying available recycling techniques.

The use of coatings for special parts is to be reduced to a minimum, unless it can be demonstrated that it does not alter recyclability. Galvanic coatings on plastic parts are not permissible.

5.4 Cartridges

For all new product models first placed on the EU market after 1 January 2015:

5.4.1 Any cartridge produced by or recommended by the OEM for use in the product shall not be designed to prevent its reuse and recycling.

5.4.2 The machine shall not be designed to prevent the use of a non-OEM cartridge.

The requirements of paragraph 5.4 shall not be interpreted in such a way that would prevent or limit innovation, development or improvements in design or functionality of the products, cartridges, etc.

5.5 Recycled plastic content

For all new product models first placed on the EU market after 1 January 2015, Signatories shall make information available to customers on the minimum percentage of postconsumer recycled plastic content, calculated as a percentage of total plastic (by weight) in each product.

The following may be excluded from the calculation of the percentage: printed circuit boards, labels, cables, connectors, electronic components, optical components, electrostatic discharge (ESD) components, electromagnetic interference (EMI) components, and bio based plastic material. Products that do not contain plastics can declare “Not applicable” for this criterion.

ANNEX C: Metal table

Table 14. Elements, their properties and recovery in basic metal infrastructure

Elements	Atomic number #	Symbol	Name	Toxic (heavy) metals	Critical raw material (3rd 2017 assessment)	Noble / PGM metal	Magnetism	Fe steel (BOF&EAF)	Al (remelt/refine)	Ti (pyrometall.)	Mg (hydrometall./remelt)	Li (hydro-/pyrometall.)	RE (hydrometall.)	RE (special batt. recycling)	Sn (smelt/refine)	Cu/Ni (smelt/refine)	Pb (smelt/refine)	Zn (RLE/fume)	Ni/Cr (stainless steel)	Mn (TRIP steel)	Possible applications (examples, indicative)
Metallic	47	Ag	Silver	Toxic/2nd		Noble/PGM	dia	6	3						1	1/4					contacts, switches, solders
Metallic	13	Al	Aluminium				para	7*	1/8*	2/8*	2/7*	7*	5/7*		7*	7*	7*	7*	7*	2/5/7*	
Halogen	18	Ar	Argon																		
Metalloid	33	As	Arsenic	Toxic/1st			dia	6					5		5	2					
Metallic	79	Au	Gold			Noble/PGM	dia	6	3							1	1	1			bonding wire, contacts, ICs
Metalloid	5	B	Boron								5/7	5/7									
Metallic	56	Ba	Barium		CRM			8*	8*	8*						8*					
Metallic	4	Be	Beryllium		CRM		dia														
Metallic	83	Bi	Bismuth		CRM			6							4	4	1	1			solders, capacitor, heat sink
Halogen	35	Br	Bromine					6				5/7				4					
Nonmetal	6	C	Carbon																		
Metallic	20	Ca	Calcium					7*	8*	8*	7*	7*	5/7*		7*	7*	7*	7*	7*	7*	
Metallic	48	Cd	Cadmium	Toxic/1st			dia	6	5							4	4	4			batteries (not allowed WEEE, Batt.Directive)
Metallic	58	Ce	Cerium		CRM/LREE		para	5/8*	8*	8*	2		1	4*	8*	6/8*					
Nonmetal	17	Cl	Chlorine					6	7*	7*	4	5/7				4				5	
Metallic	27	Co	Cobalt	Toxic/2nd	CRM		Ferro	2						1		4	4	4			rechargeable battery (cathode)
Metallic	24	Cr	Chromium	Toxic/2nd			para	2	6	2									1		
Metallic	55	Cs	Cesium																		
Metallic	29	Cu	Copper	Toxic/2nd		Noble/incl.	dia	6	2				5		4	1/7*	4	4			cable wire, connectors (electronics, motors)

Elements	Atomic number #	Symbol	Name	Toxic (heavy) metals	Critical raw material (3rd 2017 assessment)	Noble / PGM metal	Magnetism	Fe steel (BOF&EAF)	Al (remelt/refine)	Ti (pyrometall.)	Mg (hydrometall./remelt)	Li (hydro-/pyrometall.)	RE (hydrometall.)	RE (special batt. recycling)	Sn (smelt/refine)	Cu/Ni (smelt/refine)	Pb (smelt/refine)	Zn (RLE/fume)	Ni/Cr (stainless steel)	Mn (TRIP steel)	Possible applications (examples, indicative)
Metallic	66	Dy	Dysprosium		CRM/HREE		para	5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	68	Er	Erbium		CRM/HREE		para	5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	63	Eu	Europium		CRM/HREE		para	5/8*	8*	8*	2		1	4*	8*	6/8*					
Halogen	9	F	Fluorine					7*	5			5/7				5			7*	5/7*	
Metallic	26	Fe	Iron				ferro	1/7*	2		7*	7*		5*	7*	7*	7*	7*	1/7*	1/7*	
Metallic	31	Ga	Gallium		CRM		dia	8*					5			4*	1/4	1/4			In LED phosphors
Metallic	64	Gd	Gadolinium		CRM/HREE		ferro	5/8*	8*	8*	2		1	4*	8*	6/8*					
Metalloid	32	Ge	Germanium		CRM		dia									4	4	4			
Nonmetal	1	H	Hydrogen																		
Noble gas	2	He	Helium		CRM																
Metallic	72	Hf	Hafnium		CRM																
Metallic	80	Hg	Mercury	Toxic/1st		Noble/incl.	dia	6	5							4					
Metallic	67	Ho	Holmium		CRM/HREE		para	5/8*	8*	8*	2		1	4*	8*	6/8*					
Halogen	53	I	Iodine																		
Metallic	49	In	Indium		CRM		dia	8*					5		4(*)	4*	1/4	1/4			LCD glass, solder, semiconductor
Metallic	77	Ir	Iridium		CRM/PGM	Noble/PGM	para														
Metallic	19	K	Potassium					6	6/7*	7*		5/7		5		6					
Noble gas	36	Kr	Krypton																		
Metallic	57	La	Lanthanium		CRM/LREE			5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	3	Li	Lithium				para					1		4							battery cathode, electrolyte (Li-batt. in mainboard)
Metallic	71	Lu	Lutetium		CRM/HREE			5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	12	Mg	Magnesium		CRM		para	7*	2/8*	8*	1/7*	7*	7*		7*	7*			7*	7*	
Metallic	25	Mn	Manganese	Toxic/2nd			para		2		7*	7*			7*	7*				1	board-to-board connectors

Elements	Atomic number #	Symbol	Name	Toxic (heavy) metals	Critical raw material (3rd 2017 assessment)	Noble / PGM metal	Magnetism	Fe steel (BOF&EAF)	Al (remelt/refine)	Ti (pyrometall.)	Mg (hydrometall./remelt)	Li (hydro-/pyrometall.)	RE (hydrometall.)	RE (special batt. recycling)	Sn (smelt/refine)	Cu/Ni (smelt/refine)	Pb (smelt/refine)	Zn (RLE/fume)	Ni/Cr (stainless steel)	Mn (TRIP steel)	Possible applications (examples, indicative)
Metallic	42	Mo	Molybdenum					2		2						4					
Nonmetal	7	N	Nitrogen																		
Metallic	11	Na	Natrium					6	6			5/7				6					
Metallic	41	Nb	Niobium		CRM			2/8*		2					8*						
Metallic	60	Nd	Neodymium		CRM/LREE		para	5/8*	8*	8*	2		1	4*	8*	6/8*					As element in chemistry for powerful magnets
Noble gas	10	Ne	Neon																		
Metallic	28	Ni	Nickel	Toxic/2nd			ferro	2	2					1		1/7*			1		electronics (general, contacts), batteries (Ni-Cd)
Nonmetal	8	Os	Oxygen																		
Metallic	76	Os	Osmium		CRM/PGM	Noble/PGM	para														
Nonmetal	15	P	Phosphorus		CRM			6	6		7*	7*	5/8			6					electronics (general)
Metallic	82	Pb	Lead	Toxic/1st			dia	5	5						4	4	1			5	
Metallic	46	Pd	Palladium		CRM/PGM	Noble/PGM	para	3	3							1					multilayer capacitors, connectors
Metallic	61	Pm	Promethium		CRM/LREE			5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	59	Pr	Preasodymium		CRM/LREE			5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	78	Pt	Platinum		CRM/PGM	Noble/PGM	para	3	3							1	1	1			hard disk, thermocouple, fuel cell
Metallic	37	Rb	Rubidium																		
Metallic	75	Re	Rhenium		CRM/PGM	Noble/PGM/incl.															
Metallic	45	Rh	Rhodium		CRM/PGM	Noble/PGM	para	3								1					
Metallic	44	Ru	Ruthemium		CRM/PGM	Noble/PGM	para														Hard disk, plasma displays
Nonmetal	16	S	Sulphur																		
Metalloid	51	Sb	Antimony	Toxic/2nd	CRM		dia	6	6				5		5	2/5	1	1			flame retardants, CRT glass
Metallic	21	Sc	Scandium		CRM			5/8*	8*	8*	2		1	4*	8*	8*					
Nonmetal	34	Se	Selenium	Toxic/2nd			dia									1					electro-optic, copier, solar cell
Metalloid	14	Si	Silicon		CRM		dia	2/7*	2	2	2/5/7*	7*	5/7*		7*	7*	7*	7*	7*	7*	electronics (general)

Elements	Atomic number #	Symbol	Name	Toxic (heavy) metals	Critical raw material (3rd 2017 assessment)	Noble / PGM metal	Magnetism	Fe steel (BOF&EAF)	Al (remelt/refine)	Ti (pyrometall.)	Mg (hydrometall./remelt)	Li (hydro-/pyrometall.)	RE (hydrometall.)	RE (special batt. recycling)	Sn (smelt/refine)	Cu/Ni (smelt/refine)	Pb (smelt/refine)	Zn (RLE/fume)	Ni/Cr (stainless steel)	Mn (TRIP steel)	Possible applications (examples, indicative)
Metallic	62	**Sm**	Samarium		CRM/LREE		para	5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	50	**Sn**	Tin				para	6	2	2					1	4	1	1			solders
Metallic	38	**Sr**	Strontium					7*	7*	7*			7*			6*					
Metallic	73	**Ta**	Tantalum		CRM		n/a	2/8*							8*	8*					As Ta-capacitors
Metallic	65	**Tb**	Terbium		CRM/HREE		para	5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	43	**Tc**	Technetium																		
Metalloid	52	**Te**	Tellurium													1					CdTe solar cells, Te in flash memory
Actinide	90	**Th**	Thorium					8*			2					8*					
Metallic	22	**Ti**	Titanium					2/8*	5/8*	1/8*					8*	8*					
Metallic	81	**Tl**	Thallium	Toxic/2nd			dia									3					
Metallic	69	**Tm**	Thulium		CRM/HREE		para	5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	23	**V**	Vanadium		CRM			2	7*	2/7*					7*	7*					
Metallic	74	**W**	Tungsten		CRM		para	2/8*							8*	8*					Heating/lighting filament, vibration motor
Noble gas	54	**Xe**	Xenon																		
Metallic	39	**Y**	Yttrium		CRM/LREE			5/8*	8*	8*	2		1	4*	8*	8*					
Metallic	70	**Yb**	Ytterbium		CRM/HREE			5/8*	8*	8*	2		1	4*	8*	6/8*					
Metallic	30	**Zn**	Zinc	Toxic/2nd			dia	5	5		2/5				4	4		1		5	electronics (general)
Metallic	40	**Zr**	Zirconium					8*	8*	2/8*	2				8*	8*					
Other elements	84 - 118		(no details available related to ErP recycling)																		
For information only:																					
Other CRM		mineral	Borates		CRM																
Other CRM		mineral	Coking coal		CRM																

Elements	Atomic number #	Symbol	Name	Toxic (heavy) metals	Critical raw material (3rd 2017 assessment)	Noble / PGM metal	Magnetism	Fe steel (BOF&EAF)	Al (remelt/refine)	Ti (pyrometall.)	Mg (hydrometall./remelt)	Li (hydro-/pyrometall.)	RE (hydrometall.)	RE (special batt. recycling)	Sn (smelt/refine)	Cu/Ni (smelt/refine)	Pb (smelt/refine)	Zn (RLE/fume)	Ni/Cr (stainless steel)	Mn (TRIP steel)	Possible applications (examples, indicative)
Other CRM		mineral	Fluorspar (Fluorite)		CRM																
Other CRM		mineral	Magnesite		CRM (> magnesium)																
Other CRM		mineral	Natural graphite		CRM																batteries
Other CRM		mineral	Phosphate rock		CRM																
Other CRM			Natural Rubber		CRM																

Legend:

Reports to..	Further processing: recovered	alloy or EOL product	Lost (no economic recovery)
Carrier metal	1	2	3
Compounds	4	5	6
Sink		7	8

Interpretation:

1	Carrier metal / alloying element
2	Carrier metal / not detrimental
3	Carrier metal / lost
4	Compounds / recoverable
5	Compounds / useful as slag
6	Compounds / lost
7	Sink / useful slag
8	Sink / lost

ANNEX D: WEEE product categories, after 2018 and main components

Table 15. WEEE product categories, before and after 2018

WEEE 2012/19/EU Annex III / period 2018+ ↓	Annex I / period 2012-2018 →										ANNEX IV targets 2018+
	1. Large household appliances	**2. Small household appliances**	**3. IT + telecom equipment**	**4. Consumer equipment, PV**	**5. Lighting equipment**	**6. Electric / electronic tools**	**7. Toys, leisure, sports equipment**	**8. Medical devices**	**9. Monitoring + control equipment devices**	**10. Automatic dispensers**	
1. Temp. exchange equipment	fridge, airco, oil-filled heaters										recovery: 85% re-use/recycling: 80%
2. Screens, monitors, +100 cm²			laptops, tablets +100cm²	TV's, photo frame +100cm²							recovery: 80% re-use/recycling: 70%
3. Lamps					lamps						recycling: 80%
4. Large equipment (>50 cm, no 1-3)	washing machine, dryer, dishwasher, oven, space heaters (no temp. exch.)		large IT, telecom	PV, large A/V, music instr.	luminaires	large tools	large leisure, coin-slot	large medical	large monitoring	hot/cold/money dispensers	recovery: 85% re-use/recycling: 80%
5. Small equipment (<50 cm, no 1-3+6)		vacuum cleaner, kitchen, care, cleaning appliances		small A/V equipment, small music instr.	luminaires	small tools, power supplies	toys, small leisure	small medical	small monitoring (thermostats, scales)	small dispensers	recovery: 75% re-use/recycling: 55%
6. Small IT and telecom (<50 cm)			small IT, desktop, telecom, phones				video games (if connected)				recovery: 75% re-use/recycling: 55%
	excluded: large-scale stationary industrial tools										
ANNEX IV targets 2015-2018	recovery: 85% re-use/recycling: 80%	recovery: 75% re-use/recycling: 55%	recovery: 80% re-use/recycling: 70%	recovery: 80% re-use/recycling: 70%	recovery: 75% re-use/recycling: 55% gas-discharge: recycling 80%	recovery: 75% re-use/recycling: 55%	recovery: 75% re-use/recycling: 55%	recovery: 75% re-use/recycling: 55%	recovery: 75% re-use/recycling: 55%	recovery: 85% re-use/recycling: 80%	

Table 16. WEEE product categories and main components to receive specific treatment

WEEE 2012/19/EU Annex III / period 2018+ ↓	Components →									
	1. Depollution	**2. Batteries**	**3. Electronics (PCB, sensors, camera's, etc.)**	**4. Displays**	**5. Lamps**	**6. Perm. Magnets (HDD, motors)**	**7. Heat exchangers / sink**	**8. Plastics**	**9. Other / glass**	**10. Other / concrete/stone**	**11. Other / bio-based**
1. Temp. exchange equipment	v/refrigerants		v	v	v	v	v	v/BFR	v/ shelves		
2. Screens, monitors, +100 cm²	v/Hg in lighting		v	v	v		v	v	v/ screen		
3. Lamps	v/Hg in lighting	v/portable	v		v		v/heat sink	v/BFR, thermosets	v/ bulb		
4. Large equipment (>50 cm, no 1-3)	v/cap's, toner, insulation		v	v	v	v	v	v/BFR	v/ door	v/concrete counterweight	v/wood top
5. Small equipment (<50 cm, no 1-3+6)	v/cap's, insulation	v	v	v	v	v	v	v/BFR	v/ door		v/wood cabinet
6. Small IT and telecom (<50 cm)	v/toner	v	v	v	v	v	v	v/BFR	v/ screen		
Main resources to recover	HFCs, HCs, etc. oils, lubricants removal of haz. subst.	Lithium Cobalt Nickel Manganese REE	Precious metals (Au, Ag, Pd, etc.) REE	Indium REE	REE Hg	Copper Aluminium Steel REE in magnets (Nd, Pr, etc.)	Copper Aluminium Steel	thermoplasts			

ANNEX E: Marking of plastics

This annex is based on the following publication: **Plastic Part Marking Algorithm (15-March-2017),** Copyrighted in 2016 by HP Development Company, L.P.

The document provides a standard for the marking of plastic parts and products, to be used for subsequent decision-making during recycling, reuse, or disposal.

The marking is actually an algorithm for creating a code that includes the relevant information for the polymer type and additives. The code consists of:

1. material identification for basic polymers
2. flame retardant marking
3. filler and reinforced composition marking
4. plasticizer marking
5. recycled content marking
6. supplemental identification

Basic polymers are marked: >polymer<, where polymer is an abbreviation of the homopolymeric, copolymer or natural polymer. The list goes from >AB< for acrylonitrile-butadiene, to >VE< for vinyl-ester, and includes all well-known abbreviations such as PE-HD, PE-LD, PP, PVC, PET, PS, PC, PMMA, ABS, etc. The HP list contains over 130 entries.

Polymer blends are marked using a '+': >PC+ABS< (example), and laminates using a comma: >PVC,PUR,ABS<

Flame retardants are added as 'FR(code)' . The HP list has over 33 codes of possible FR substances, related to halogenated compounds, nitrogen compounds, organic phosphorous compounds, inorganic phosphorous compounds, metal oxides / metal hydroxides / metal salts, boron and zinc compounds, silica compounds and others. Polybrominated diphenyl ethers are coded '18'.

Fillers are added by their type, e.g. GF is glass fibre, MD is mineral powder, and fill mass percentage: Example: >PC-GF20<. Fillers are marked according their main material (A=aramid, B=boron ... G=glass, M=metal, T=talcum) and the form or structure (B=beads, balls, D=fines, powders, F=fibre, etc.).

Plasticizers are marked using 'P(abbreviation)': >PVC-P(DBP)<. HP identified some 94 possible plasticizers, from ASE (alkylsulfonic acid ester) to TXP (trixylyl phosphate).

Recycled content is marked using 'REC(content)': >ABS(REC85)<

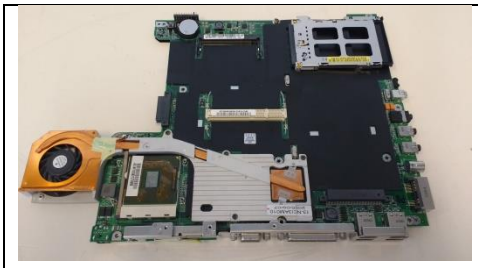
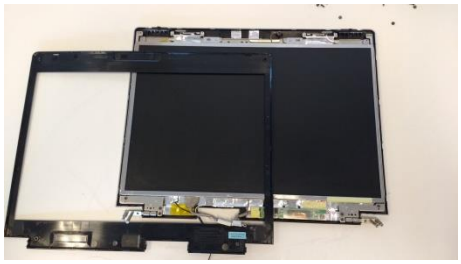
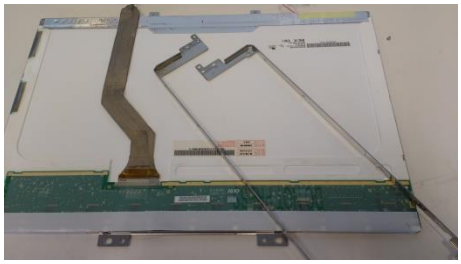
The document has the following references:

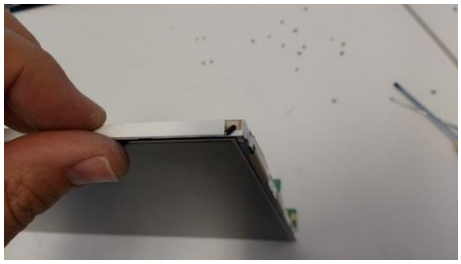
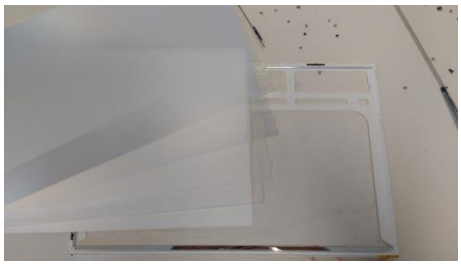
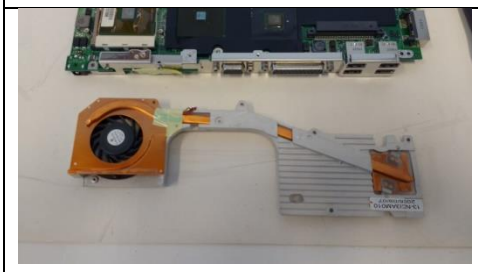
- ASTM D1600, Standard Terminology Relating to Abbreviations and Codes for Terms Related to Plastics.
- ASTM D1972, Standard Practice for Generic Marking of Plastic Products
- ISO 1043-1:2011(E) Plastics - Symbols. Part 1: Basic polymers and their special characteristics.
- ISO 1043-2:2011(E) Plastics- Symbols Part 2: Fillers and Reinforcing Materials.
- ISO 1043-3:2016(E) Plastics-Symbols and abbreviated terms Part 3 Plasticizers
- ISO 1043-4:1998 (E) Plastics-Symbols Part 4 Flame retardants.
- ISO 11469-2016 (E) Plastics - Generic Identification and Marking of Plastic Products.
- SAE J1344 Marking of Plastics Parts

ANNEX F: Laptop teardown

ASUS Z9200

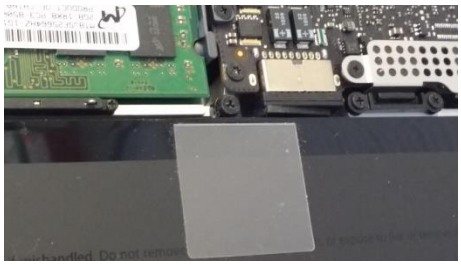
Foto	Description of layer / action	weak	standard	strong
	Ready for teardown			
Depollution and metals				
	Battery removal by hand (weak joint) Chemistry (Li-ion) indicated > Bonus (button cell removal at PCB board level)	1		
	HDD removal One lid (standard joint) manual removable (weak joint)	1	1	
 	PCB (high grade) removal Several screws need to be unfastened before the back cover comes off (standard joint) The keyboard needs to come off to reveal a hidden screw (weak joint + standard joint) The motherboard itself needs to be unfastened (standard joint) The motherboard contains a lithium button cell (weak joint), a heat sink assembly of two parts (see below) and several ferrometal parts that are not worth removing	2	3	

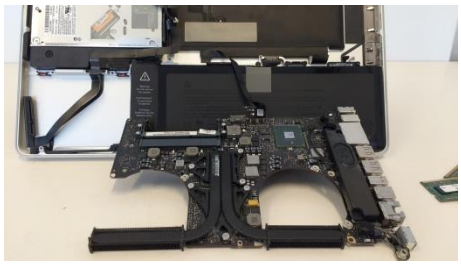
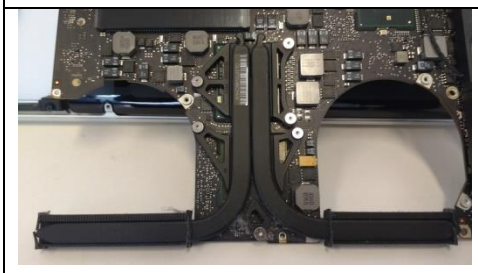
				
     	**Hg removal (overlaps with display module removal)** The screws for the hinges are unfastened (standard joint) The plastic front frame is removed (weak joint) The back frame is removed (weak joint) Several metal frames, adhesives and covers needed to be removed before the final CFL assembly is separated (2 standard joints / screwed, 4 weak joints / manual stripping)	6	4	

     				
	**Light metals removal from high grade PCBs** The heat sink consists of two parts and is unfastened (standard joint) and consists of a die cast light metal heat spreader (aluminium) and copper heat pipes, and a fan.		2	
Plastics				
	The body plastics are an ABS-PC blend, no known flame retardants. The display holds several light guide-plastics, probably of PMMA - no BFRs, plasticizers or other restricted substances - carbon black as colorant is possible - no compatibility issues confirmed - major parts have been spray-painted with copper or silver coatings - the keyboard is intricately linked to a ferrous metal back plate – this reduces the chances for 100% recovery			

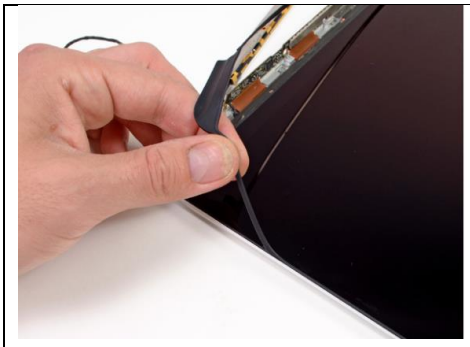
	The score depends on the penalty for black plastics and the plastic-metal keyboard combination. If carbon is allowed and keyboard assumed lost, the score is 9. If carbon is not allowed, the score is 0.			
Miscellaneous				
	Not relevant – score 0			

Apple MacBook 2012

Foto	**Description of layer / action**	**weak**	**standard**	**strong**
	Ready for teardown			
Depollution and metals				
 (tri-lobe) 	**Battery removal** First, the back cover needs removing (standard joint) The battery is attached using tri-lobe screws. Not available in workshop, but iFixit confirms the battery can be removed using these screws only (standard joint) Chemistry (Li-ion polymer) indicated > Bonus (no button cell at PCB board level)		2	

	HDD removal The HDD is loosened by 4 phillips screws (standard joint) and then manually removed (weak joint)	1	1	
  	**PCB (high grade) removal** Some 14 screws need to be unfastened before the motherboard comes off (standard joint)		1	
	**Light metals removal from high grade PCBs** The heat sink consists of one part and is unfastened (standard joint) and consists of a die cast light metal heat spreader (aluminium) and copper heat pipes, and a fan.		1	
	Display removal (overlaps with LED module removal) A part of the disk drive needed to be removed (standard joint) The hinges need unfastening (standard joint) At this point our tool tip failed (worn out as screws are tightly fastened) and the assessment of display removal is based upon iFixit teardowns [106, 107] The iFixit teardown shows that the screen lid is still secured to the display module (see removal of light metals from PCB)		2	

[106] https://nl.ifixit.com/Teardown/MacBook+Pro+15-Inch+Unibody+Mid+2012+Teardown/9515
[107] https://nl.ifixit.com/Teardown/MacBook+Pro+Retina+Display+Teardown/9493

	**Light metals removal from display** The screen lid is secured by various screws (standard joint) that hold antennas, and then requires removal of a rubber seal (weak joint) and a spudger (standard joint) to lift the display module	1	2	
	LED removal from display This is presented in the iFixit teardown (for a Retina display). Although the exact sequence could not be replicated, it appears the removal of antennas and camera requires loosening standard joints, and then some further manual disassembly (assumed 2 weak joints) and removal using a spudger tool (standard joint)	1	2	
Plastics	The body contains no plastics in relevant quantities – score 0			
Miscellaneous	Not relevant – score 0			

ANNEX F: Modulated WEEE fees in France

OCAD3E Technical report - Application of environmental contribution modulation criteria

Equipment in question	Contribution modulation criteria	Contribution modulation	Criteria application rules
Refrigerator/ freezer	Presence of refrigerant with GWP>15 **or** Failure to provide technical documentation for electrically authorised repairers **or** Unavailability of essential spare parts for equipment use	+ 20 %	If one (or more) of the 3 criteria applies/apply to the EEE, the contribution is increased by +20%
Washing machine	Provision of essential parts for equipment use for 11 years **or** Incorporation of post-consumer recycled plastic (minimum threshold of 10%)	- 20 %	If the EEE meets one of the 2 criteria or both, the contribution is reduced by -20%
Dishwasher	Provision of essential parts for equipment use for 11 years **or** Incorporation of post-consumer recycled plastic (minimum threshold of 10%)	- 20 %	If the EEE meets one of the 2 criteria or both, the contribution is reduced by -20%
Vacuum cleaner	Presence of plastic parts > 25 grams containing brominated flame retardants **or** Failure to provide technical documentation for electrically authorised repairers **or** Unavailability of essential spare parts for equipment use	+ 20 %	If one (or more) of the 3 criteria applies/apply to the EEE, the contribution is increased by +20%
Coffee maker / kettle / tea maker	Provision of essential parts for equipment use for 5 years **and** Provision of technical documentation for electrically authorised repairers	- 20 %	If the EEE simultaneously meets both criteria, the contribution is reduced by -20%
Computer (desktop or laptop)	Absence of paint and coatings incompatible with recycling and reuse on plastic parts >100g, **and** Incorporation of post-consumer recycled plastic (minimum threshold of 10%) **and** Product upgrade with standard tools, including memory drives, chips and cards	- 20 %	If the EEE simultaneously meets the 3 criteria, the contribution is reduced by -20%
Tablet	Presence of plastic parts > 25g containing brominated flame retardants **or** Lack of mutually compatible software updates, essential for the basic use of the device	+ 100 %	If one (or both) of the criteria applies/apply to the EEE, the contribution is increased by +100%
Printer	Complete disassembly capability with commercially available standard tools	- 20 %	If the EEE simultaneously meets

	and Provision of essential parts for equipment use for 5 years		both criteria, the contribution is reduced by -20%
Telephone	Lack of standardised connections (charger and other connections) **or** Lack of mutually compatible software updates, essential for the basic use of the device	+ 100 %	If one (or both) of the criteria applies/apply to the EEE, the contribution is increased by +100%
Televisions	Provision of technical documentation for electrically authorised repairers and essential parts for equipment use (electronic boards) for 5 years **or** Incorporation of post-consumer recycled plastic (minimum threshold of 10%)	- 20 %	If the EEE meets one of the 2 criteria or both, the contribution is reduced by -20%
Lamp	LED sources only	-20%	The contribution is reduced by -20% if the criterion is met
Electric drill / screwdriver	Failure to provide technical documentation for electrically authorised repairers **or** Unavailability of essential spare parts for equipment use	+ 20 %	If one (or both) of the criteria applies/apply to the EEE, the contribution is increased by +20%
Game console	Failure to provide technical documentation for electrically authorised repairers **or** Unavailability of essential spare parts for equipment use **or** Presence of brominated flame retardants in plastic body of equipment	+ 20 %	If one (or more) of the 3 criteria applies/apply to the EEE, the contribution is increased by +20%