iNEMI Repair and Recycling Metrics Project
End of Project Report

Co-Leaders:
Lisa Dender, IBM
Wayne Rifer, Green Electronics Council

Project Team:
Barbara Kyle, Electronics Take-Back Coalition
Max Marwede, Fraunhofer IZM
Kyle Wiens, iFixit

iNemi Project Manager:
Mark Schaffer, marks@inemi.org

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EXECUTIVE SUMMARY

"What's measured improves" – Peter F Drucker

The iNEMI Recycling and Repair Metrics Project was commissioned to assess the type and quality of metrics available to the electronics industry, and to determine if they are adequate to the needs of the industry. If not, the task was to make recommendations for changes and further study. It is generally believed that there are no agreed upon, quantifiable set of metrics or tools for measuring an electronic product's true *Recyclability, Reusability, Reparability* and *Refurbish-ability,* collectively called the 4Rs[1] in this report. These indicators, or metrics, are needed to assess the environmental impact of design choices and the progress being made in the electronics industry products to minimize the negative environmental impacts of electronic products. Stakeholders include customers, regional authorities, recyclers, environmental activists, and manufacturers, including their environmental department and product developers. How can product designers understand the choices they make without some system to evaluate results? They can't, which is why we need meaningful metrics to measure the impact of electronics industry and to achieve our desired result — more material recovered and fewer negative environmental impacts.

We did find mass-based metric standards that define calculations, terms, and methodology for RECYCLABILITY. The best example is International Electrotechnical Commission's Technical Report (IEC TR) 62635, which was developed in collaboration with and for the benefit of the electronics industry. The standard leverages ISO 22628, the automotive industry's calculation method for vehicles. While we did not find any standards regarding REUSABILITY, REPARABILITY and REFURBISH-ABILITY, we analyzed a system developed by iFixit—a company that develops repair manuals for the public. We found iFixit's system goes further than any other publicly-available system.

The mass-based[2] recyclability metrics are by far the most commonly used and easiest to calculate. However, this metric generally ignores the reality of liberation, separation and recovery of the materials, and the economic realities of the recycling process in the region where the product ends

[1] Note that this report does not address recoverability in the sense of materials destined for waste to energy. This is considered a disposal method. Where the term "recovery" is used in this report, it is referring to the recovery of material resources, not energy resources.
[2] Mass-based recyclability determines a product recyclability rate based on the masses of identified materials in the product and the recyclability rates of those materials. See section 5.2 for more details.

its life. Cost drivers and economics are the forcing function that determines if a product or material will be recycled.

Product designers have two other challenges with regards to liberation of materials and the recycle technologies available. At the time of design, there may not be any recycle technologies available to recover the product, which dramatically affects the environmental impact. An example[3] of this is the large screen LCD TVs that flooded the market and had to be landfilled, as there was no viable treatment available at recovery. While the component materials (plastics) are recyclable and would have resulted in a good mass-based recycle metric score, the reality is the materials could not be liberated. The second challenge is one of product use lifecycle. Some products have a very long life recovery cycle; demand, usage models, recycle capacity and capability can dramatically change between the time of product introduction and product retirement.

Another critical gap in recycling metrics is the failure to include the economic realities of recycling. A product or material's potential to be recycled or repaired does not mean it actually *is* recycled or repaired. There are striking differences in recovery rates based on economics. In regions where landfill is at a premium (for example, in Japan and Singapore), and/or where waste legislation is already in effect (as, for example, with European WEEE regulations), there is more innovation, technologies and investment in recovery. We found two main drivers of this economic reality:

- Value of the recovered material: Can the material be recovered? Can it be sold?
- Cost of liberation/separation: Can the materials be separated into clean streams? What does it take to liberate the materials (hazardous materials included)?

A 4R metric, whether integrated or unique to each 'R', should include actual performance of the 4R system in implemented practice, in addition to theoretical performance. Any metric that does not consider the economic realities is not likely to be a driver of informed choices and improvement.

Product designers do have control over a number of factors that improve the performance of the 4R metrics.

- Material Selection: choosing materials that are or can be recycled
- Product Design: designing the product for easy repair, disassembly, and ease of separation will benefit the creation of clean material streams at the end-of-life. This aspect will also improve the product's reparability, refurbish-ability, and reusability.
- Disclosure: providing needed information to consumers in order to facilitate repair and disassembly.

In conclusion, we find that the metric standards currently available are inadequate to the goal of measuring the environmental impact of product recycling, reuse, repair, and refurbishing. The industry has a good start in IEC TR 62635, which rewards a product designer for good material choices. Another benefit is that industry is already familiar with and, in some cases, is already using this standard. We recommend improving IEC TR 62635 with more details, covered later in this report. The industry needs a cost factor scoring system that reflects the economic realities of recovery and repair. This cost factor should include variables that can be translated into currency values, when needed. Examples are time and difficulty, special handling (such as protective gear to remove hazardous materials), special tools—all of which increase the cost of recovery and reduce the likelihood of recovery, regardless of the potential indicated by the mass-based metric. This factor rewards the product developer for good designs that facilitate materials separation, liberation, and reduction of hazardous materials. Finally, the industry needs an incorporated metric that reflects actual recovery rates of the product in the region where the product is sold. This recovery factor rewards the product developer for actual material recovery. When product designers deliver a

[3] Ardente, F., & Mathieux, F. (2013). 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. Joint Research Centre (JRC) Technical Report. Retrieved from http://bookshop.europa.eu/en/integration-of-resource-efficiency-and-waste

product to market, they can also provide the information for repair and disassembly, which facilitates the main objective of reducing the negative environmental aspects of the product.

INTRODUCTION

The purpose of this project is to identify a pathway to a common methodology for the calculation of a product's potential rate of reuse and/or recycling.

This methodology is intended to be used during the product's design and manufacturing stages, and it would project—based on decisions made in those stages—the resulting rate of a product's reusability/recyclability. It should thereby facilitate designers and selectors of materials in improving the product's performance when it reaches the end of its first life. The measure of success of that performance should be based on the hierarchy to first reuse, then recycle, and only finally dispose. Note that, in this formulation, energy recovery is considered as a method of disposal.

A central purpose of this metric's system is to project not only the theoretical rate of reusability/recyclability of the product, its components and its materials, but also, and even more important, to project what is practically to be achieved in the real world, using existing technologies, and recognizing the economic and practical constraints of practicing reuse and recycling organizations.

This later objective — the incorporation of practical reality, such as e-waste management practices in the country in question, into the calculation methodology — raises several very real complexities, and the result will inevitably be less precise and more variable over regions and time. But anything less than basing a calculation on practical reality may provide a highly misleading result.

The project team recognizes the following significant constraints and complexities of this goal to measure practical reality:

1. The product may be designed many years before it is available for reuse/recycling, and reuse/recycling technologies may change in that period. Any calculation based on the methodology should therefore identify its basic assumptions regarding reuse/recycling technologies, so far as they are relevant to the reuse/recycling rate. This report proposes that a database of recycling practices be developed in conjunction with the methodology to facilitate this.
2. The measurement of economic feasibility can change as costs and revenues change over time and region. The methodology should therefore be based on the factors that produce the costs, such as time or labor needed to achieve a given outcome. The report does not recommend that economic feasibility be measured in currency terms, but rather in terms that are the creators of cost. The database can also make this practical.

Note that this report is not intended to provide a methodology that achieves these goals. Such a methodology should be developed through a process that includes research capabilities and that engages input from stakeholders. Rather, this report is intended to define a pathway such a project could take, and thereby to make such project more feasible.

TASK 1: DEVELOPMENT OF A COMMON VOCABULARY

To facilitate effective discussions among team members, the first task was to develop a common vocabulary and understanding of the concepts of the "4Rs". For the purposes of our work, the 4Rs are **Reuse, Repair, Recycling and Refurbishing**, with a particular focus on Recycling and Repair.

1.1 Standards

The term "standards" is used throughout this report in a very inclusive way. Strictly, standards are formally developed and adopted through inclusive processes and following a defined set of practices. That is the correct use of the term. However, for simplicity, in this report the term is used to refer to standards, guidelines, technical reports, calculation heuristics, and other documented systems that provide methodologies for the calculation of reusability and recyclability of a product. Please excuse this drafting shortcut.

A formal standard is definitely a preferable document to be used in such calculations, over the others mentioned, because of the rigor and thoroughness of the adoption process. A formal standard will therefore receive much broader credibility and acceptance.

It should be the long-term goal to develop a standard for the calculation methodologies discussed in this report. However, there are some reasons that may not be practical in the near term. This report recommends the development of a product scoring system, together with a database of relevant data. The scoring system will need to be utilized and refined so that it accurately represents the true reusability/recyclability of Information and Communications Technology (ICT) products in the real world. This may require an initial technical report that is not developed into a standard for some time.

SEE APPENDIX A FOR COMMON VOCABULARY ADOPTED AND/OR DEVELOPED BY THE TEAM.

TASK 2: EDUCATION ON EACH OF THE 4RS

The team started the process by brainstorming the uses of metrics and how information might inform decision-makers. Decision-makers range from the consumer selecting the best product profile to Product Designers choosing design and material features to improve their products' marketability. The lesser-known decision makers are those who provide recycle and reuse services, as some products and materials are easier to convert to profitable resale material. Finally political leaders and industry organizations use metrics to drive policy choices that solve large problems, such as waste management and pollution.

In order to advance the team's knowledge, we invited speakers from different parts of the electronics lifecycle process to educate us on what metrics they know, which are useful, and what considerations are missing from existing metrics. Team members also brought their technical experience to the project, adding to our technical warehouse of knowledge. The authors of the project Statement of Work (SOW) included a list of standards in the Is/Is Not Analysis as feeder stock to get the team going. Finally, we were able to use the Internet to search for obvious and obscure efforts toward repair/reuse/recycling.

The team would like to express their gratitude to those that provided educational content for us during our work, it was invaluable for conducting our assessments.

EDUCATIONAL SESSION SPEAKERS		
SPEAKER	ORGANIZATION	TOPIC
BILL HOFFMAN	UL ENVIRONMENT	IEC 62635 AND ULE 110
KYLE WIENS	IFIXIT	TEARDOWN/REPAIR AND METRICS FOR MEASURING DESIGN FOR DISASSEMBLY
JACO HUISMAN	UNITED NATIONS UNIVERSITY	ECO-POINTS/LCA/PRODUCT RECYCLABILITY
CRAIG BOSWELL	HOBI INTERNATIONAL INC.	ELECTRONICS RECYCLING AND PLASTICS RECYCLING
KARSTEN SCHISCHKE	FRAUNHOFER IZM	TABLET DISASSEMBLY
HOLLY GASTON, MATTEO KAUSCH	CRADLE TO CRADLE PRODUCTS INNOVATION INSTITUTE	CRADLE TO CRADLE CERTIFICATION ™ PRODUCT STANDARD

Contributing Project Team Members	
Name	Organization
Wayne Rifer (Co-Leader)	Green Electronics Council
Lisa Dender (Co-Leader)	IBM
Barbara Kyle	Electronic Take-Back Coalition
Max Marwede	Fraunhofer IZM/Technical University of Berlin
Kyle Wiens	iFixit

Task 3: Develop a screening framework – Set Criteria for the evaluation of standards

The team used the information from early research and brainstorming to create a list of questions, designed to be answerable in one of three ways:

- Yes – meaning the standard provides metric or detailed information
- Yes, but – meaning the standard talks about, or alludes to, or attempts to describe the metric or gives detailed information. The answer wasn't clearly a "Yes" or "No"
- No – meaning the standard does not provide the metric or detailed information.

Our next point of differentiation is the type of metrics that we sorted by:

- Administrative Metrics – These questions illuminate the intention, availability, scope of products, type or scope of the metrics found, and geographic scope. This part of the analysis sheds light on the level of acceptance and ease of use of the standard.
- Quantification of Recycling and Repair – These questions provide granularity on the details of the metrics such as identification of hazardous components or materials, need for selective treatment, disassembly where destructive means point to the inability to return the product to service (repair and reuse), liberation methods such as manual (by hand) or shredding (by machine). We put considerable detail into the topic of 'ease of disassembly,' because it is clear that time and/or effort required to liberate clean stream materials is critical to the economic realities of reusing products or materials.
- Recycling Metrics - Here we explore the nuts and bolts, no pun intended, of the traditional recycling functional steps, such as Material Liberation and Separation, Closed Loop Recycling, Material Choice, and Design Guidance.
- Reuse and Repair Metrics – Here we focus on returning the product to use in a similar, if not exact same manner, as the product was designed and used prior to entering the waste stream. The focus of repair and reuse drives the need for service manuals or information, and information or materials that facilitate return to service — like parts, software versions, durability of the materials and design.

This defined the screening framework against which all standards would be evaluated. More details on the screening criteria can be found in Appendix B.

Task 4: Standards and Tools to be evaluated

We discovered that there were many ways to calculate recycling metrics and no standard applied way to do so. The most common method of calculation is mass-based metrics that compare the weight of the defined categories with the total weight. Each category, such as metal or plastic, is given a designation of recyclability that for these materials is usually pretty high. This metric is found in IEC TR 62635, ISO 22628, as well as voluntary standards like the Cradle to Cradle Certified™ Product Standard. Generally, the only criterion for judging recycling is the 'ability to recycle the selected material somewhere in the world'. No weight is given to cost considerations, availability of the recycling service in the region where the product is placed on the market, or the market for the recovered material — all of which serve to downgrade the actual recovery from such a product.

Therefore, we also looked for guidance from other sources, such as recyclers, university programs and projects, private enterprise, and NGOs.

The main categories of standards and evaluations are:

Technical Standards – examples include IEC TR 62635,

Voluntary Standards or Systems – examples include Blue Angel, Austrian White Goods, Cradle to Cradle Certified ™ Product Standard, UL110, ISO 22628, IEEE 1680.1-1680.3, PAS 141

Proprietary Tools/Guidance – the best example we were able to review, based on the inclusion of Kyle Wiens on the team, is the iFixit Scorecard. Multiple other experts presented to the team their modeling assumptions and tools, but none of them were explicitly evaluated. VDE Lab Recyclability calculations also were reviewed.

Regulatory Driven systems – examples include WEEELabex, Eco-Design Directive

Other – the best example of this category is the Journal of Cleaner Production's paper, dated 8 August 2014, 'Identification and assessment of product's measures to improve resource efficiency: the case study of an Energy using Product by Fulvio Ardente and Fabrice Mathieux. StEP and ECMA were also given a quick review.

A brief synopsis of each standard and evaluation of relevancy for our work is below:

Austrian White Goods (ONR 192102)

Recently-updated label of excellence for durable, repair-friendly designed electrical and electronic appliances. It includes various requirements for ease of disassembly, but does not have a calculation metric of reparability. Not relevant to our task.

Blue Angel

German eco-label for a variety of products. Includes ease-of-disassembly requirements, but does not provide any method of calculation for either reparability or recyclability. Blue Angel affects product design, but does not provide a comparable measure and is therefore not relevant to our task.

Cradle to Cradle Certified™ Product Standard

Cradle to Cradle Certified™ Product Standard is based on a system designed by the Cradle to Cradle Products Innovation Institute founders, William McDonough and Dr. Michael Braungart, in 2002. This system is very elegant in design, encouraging the reuse of all materials used in the manufacture of a wide range of products (including factory scrap). While the system has been used for solar panels, it is not easily applied to electronics. A future standard might include electronics. This system does not address the economics of recycling. It also doesn't evaluate any interim steps — such as repair, reuse, or repurposing of materials — but rather judges the input against the final disposition of the materials. One excellent feature of this standard is the requirement of product producers and designers to 'walk the talk' in order to receive the higher levels of certification (gold and platinum) by developing an end-of-life strategy for their products through a take-back program or similar efforts and setting recycling targets and implementation goals.

IEC TR 62635

IEC TR 62635 provides metrics and calculations for electronic product recyclability based on the mass of materials and the recyclability, by region, for those materials. It is the most thorough and relevant system to that end. However, it does not provide metrics for repair or reuse, nor does it include metrics for the practicality of material liberation or the economics of recovery. Section 5.3 provides more details on the relevancy of this standard.

IEEE 1680.x (1,2,3)

The IEEE 1680.X family of standards requires manufacturers to declare product recyclability percentages and to generally include a minimal recyclability rate based on requirements of the EC

WEEE Directive. The standards do not develop a detailed methodology, though some reference IEC TR 62635.

iFixit Scorecard

The scorecard provides categories for grading the level of difficultly in the disassembly and reparability of a product. It includes availability of service manuals, types of tools needed, variations on fastener use, use/non-use of adhesives, time required to disassemble, ease of battery replacement and other components. It is a subjective scoring system based upon the experience of the repair technician. It only provides a 1-10 grade for the ease of reparability; it does not provide a method for independent calculation.

ISO 22628

ISO 22628 is a very concise and explicit standard with definitions, formulas and methodology for defining metrics and recyclability rate (mass-based). The standard is designed to support automobile and vehicle recycling. While the methodology and terms have been transported into IEC 62638, the core function does not support electronics recycling. There is also a worksheet to facilitate calculating the metric by organizing the applicable data.

PAS 141

Certification of a "reuse company" against the requirements of BSI PAS141:2011. Allowance of REEE mark (approved re-used electricals). PAS 141 is not applicable to our work.

REAPRo Method and Methodology for the Ecodesign of Energy-related Products (MEErP) (EU Eco-Design Directive)

The Joint European Research Center (JRC) developed the REAPRo method, which identifies a product's hot spots relevant to the following criteria: reusability/recyclability/recoverability (in mass and in terms of environmental impacts); recycled content (in mass and in terms of environmental impacts); and use of hazardous substances (Ardente & Mathieux, 2013)[4]. The method includes the calculation of a comprehensive set of lifecycle based indices, including some original indices, such as the "Reusability/Recyclability/Recoverability benefits rates" and the "Recycled content benefit rate".

The REAPRo method was partially implemented in the Methodology for the Ecodesign of Energy-related Products (MEErP). The MEEErP is used in so-called preparatory studies to create a basis for the development of appropriate requirements for every (new) product group in the European Union's Ecodesign Directive (Directive 2009/125/EC). The directive establishes a framework to set mandatory ecological requirements for energy-using and energy-related products sold in all 28 Member States. To assess the product groups, a spreadsheet-based tool, the EcoReport Tool, was developed (see Appendix C).

STEP Initiative

STEP conducts research on the entire lifecycle of electronic and electrical equipment and their corresponding global supply, process and materials flow. STEP is just an initiative without any developed metrics at this time. Not currently applicable to our work.

ULE 110

References IEC TR 62635 for recyclability calculation. No additional information provided for the ULE 110 standard beyond that for recyclability, repair or reuse calculations. Other than the reference to IEC TR 62635, the standard is not relevant to our task.

[4] Ardente, F., & Mathieux, F. (2013). 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. Joint Research Centre (JRC) Technical Report. Retrieved from http://bookshop.europa.eu/en/integration-of-resource-efficiency-and-waste

VDE Rapid Environmental Assessment Lab

An organization that performs disassembly reporting according to WEEE directive. Not applicable to our work.

VDI 2343

VDI 2343 is a German guidance document from 2001. The document is really more of a discussion paper which addresses some general information and guidance around recycling and reuse of electrical and electronic products, and provides some details as to what should be considered in planning recycling systems and treatment plans. It does include considerations for the economics of recycling, but does not provide much guidance on how the costs should be calculated. It was the only standard found to contain relevant information on the economics of recycling per our assessment.

WEEELABEX of WEEE 2

WEELABEX is a standard intended to govern the operation of European recycling facilities. It is intended to follow and implement the requirements of the WEEE Directive. It contains three separate standards for collection, logistics and treatment. Though peripherally related to our task, it is not directly relevant to it.

TASK 5: TECHNICAL ANALYSIS OF 4R INCLUDING CONCEPTS THAT IMPACT AND ENABLE RESOURCE EFFICIENCY

A research survey utilizing the developed spreadsheet was conducted, generally through reviewing available documents, of the many available standards that address the reusability/recyclability of products. The surveys examined many different dimensions of the standards.

The survey addressed both "theoretical" and "practical" aspects of reusability/recyclability. By "theoretical," this report means a measure of the reusability/recyclability of the components, fractions and material classes when they are separated into a marketable form. By "practical" this report takes into consideration, in essence, the economic constraints in liberating the components, fractions and material classes from the complex ICT product into marketable form.

Building on the thorough set of factors included in the spreadsheet, it is possible to conceive of a quantification system that first calculates a score based on the theoretical reusability/recyclability, and then includes a scoring system based on an assessment of the many factors that determine the practicality of the projected reuse and recycling.

Several standards include some of the factors identified by the team as desirable in a standard for measuring the reusability/recyclability of an electronic product. However, none of them come close to addressing the full suite of factors.

5.1 Identification of the most valuable standard

The consensus of the team is that the standard that is most productive in containing the essential factors is International Electrotechnical Commission's Technical Report (IEC TR) 62635. The ISO 22628, upon which the IEC TR is based, is explicitly a recycle metric for the automotive industry. In addition, IEC TR 62635 was developed through a lengthy, detail-oriented process conducted by an international IEC technical committee, which was a subcommittee of Technical Committee 111. The process involved many experts and manufacturers and other stakeholders reviewed the document through a formal process. The Technical Report is publically available. The chair of the Technical Committee (TC), Serge Theoleyre of Schneider-Electric, reports that the TC does not consider the committee's work complete and may consider further work on the report, which was tentatively scheduled to begin in October 2015.

IEC TR 62635 was developed for purposes very similar to those of this project. The Technical Report provides guidelines for both the calculation of a recyclability rate of ICT products and information exchange between manufacturers and recyclers regarding product characteristics and recycling systems.

The approach is mass-based. That is, it determines a product recyclability rate based on the masses of identified materials in the product and the recyclability rates of those materials. In addition to the formulas, the criteria in the report address a number of critical aspects of effective recycling, including:

- Criteria to determine end-of-life treatment scenarios
- Criteria to determine product parts to be dismantled before material separation and related information to be provided by manufacturers

The Technical Report includes the following sections:

- Terms and definitions
- End-of-life treatment processes
- Provision of information from manufacturers
- Provision of information from recyclers
- Variables and symbols
- Calculation method

And then five valuable annexes are provided:

- Indicative List of materials or parts to be identified for selective treatment
- Product information for use by recyclers or treatment facilities
- Synthesis of information from recyclers
- Example of End-of-Life Treatment Scenario
- Example of Recyclability Rate Calculation

The final annex is of special note, since it contains, as an example, data on recyclability rates for materials and components for Korean household appliances. This is a model for the kind of data that will be essential for calculating recyclability for products in a variety of countries. And then it includes a table that uses the data and formulas from the TR to calculate a product's recyclability rate.

5.2 Formulas for calculating product recyclability

The calculation method section of the TR provides the formulas for calculation of recyclability and recoverability (meaning, in this section, energy recovery as meant in the TR, but which is not addressed in this report) rates. IEC/TR 62635 calculates a product's recyclability rate using the following formula:

$$R_{\mathrm{cyc}} = \frac{\text{Sum of recyclable masses of each parts}}{\text{Total product mass}} \times 100\%$$

The recoverability rate is calculated as:

$$R_{\mathrm{cov}} = \frac{\text{Sum of recoverable masses of each parts}}{\text{Total product mass}} \times 100\%$$

IEC/TR 62635 contains tables that make general assumptions about the recyclability rate and recoverability rate for different types of materials and specific parts commonly used in electronics. To make recyclability or recoverability calculations, one lists a product's parts and materials and applies the rates from the tables for each part or material.

These formulas should be the basis of any further developed system. The priority at this time should be to develop some of the factors not included in the TR, as described in the following section.

5.3 IEC TR 62635 is lacking in some important factors

The IEC TR provides an excellent basis for calculating recyclability rates, but it needs to be enhanced with some additional factors to be fully comprehensive and adequate to the task.

5.3.1 An assessment of the practical recyclability based primarily on consideration of the practicality of material liberation

IEC TR 62635 provides a reasonable approach for a fairly simple, generic estimate of recyclability. But it does not provide a way to consider how design decisions and material selection choices will actually impact practical recyclability and recoverability rates. For example, it assigns rates to aluminum, copper, and steel. Then it assigns a 95% recyclability and recoverability rate to "other metals." In fact, the rates for "other metals" will fluctuate depending on how easy or difficult it may be to liberate those metals from other material. Are they alloyed to another metal? Are they glued or fastened to other parts?

While the report does an excellent job of providing metrics for "theoretical" recycling, it stops short of providing metrics for "practical" recycling. Nor does it adequately address metrics for reuse, including repair and refurbishment.

Note that IEC TR 62635 gives credit at one point: "parts with single recyclable material and easy to dismantle". So the report does recognize that "easy to dismantle" is an important quality. However, the term "easy" alone is completely subjective and the report provides no method of measuring whether something is "easy" or not.

Appendix B lays out the factors that the project team considers important for a complete standard for calculation of reuse and recycling rates. In addition to the mass-based approach of IEC TR 62635, it is essential that a methodology be developed to incorporate the factors that determine if the product will in fact be reused or recycled by companies operating in the real world under economic pressures.

5.3.2 Comprehensive regional data

This projected system, as does IEC TR 62635, requires the assembly of regional databases for calculations that are valid for the reuse/recycling systems available in those regions. The Technical Report recognizes that further research will be needed in this area.

The research will need to address several matters:

- Recycling technologies and practices available regionally
- Material recycling market capacities and values
- Product and component reuse market capacities and value

With such data, it should be possible to calculate reuse and recycling rates regionally — as was done in Annex E for Korean household appliances. It will be necessary to construct and maintain a database of such information that could be fed into the reusability/recyclability models.

5.3.3 Reuse, either via repair or refurbishment

Calculating reuse was not the intention of IEC TR 62635. However, given the increasing integration of reuse with recycling for ITC products, it will be necessary to do so. Revenues from recycling, with increasing product miniaturization and lower precious metal content, are increasingly unable to cover the costs of proper recycling. But with worldwide markets available for reuse of products cast off in the developed world, an increasing number of recyclers are including reuse in their services. The pathways of recycling and reuse are no longer as distinct as they once were. Thus, it will be necessary to include reuse in any calculation that adequately accounts for product performance at end-of-life.

No standard reviewed in this study provided reuse calculation metrics. The best we saw was through the iFixit Scorecard, which graded the ease of disassembly and reparability of a product — but it does not provide a way to calculate a percentage of how much of the product is actually reusable, nor does it provide a completely non-subjective way of conducting the grading. Rather, it is based on the experience of the repair technician performing the teardown activity.

There are fewer standards available that cover reuse, repair, and refurbishment than cover recycling.

TASK 6: CONDUCT ECONOMIC ANALYSIS OF 4R

6.1 Introduction

One of the goals of the project group was to evaluate whether the existing standards under review consider the economics of a product's recyclability. While it's important to understand the physical recyclability of the materials that comprise a product, the project scoping group believed it was equally important to evaluate how the product design and material choices result in favorable or unfavorable economics in an economic system where recyclers are for-profit private companies. A product may be technically recyclable — but if the process of material liberation and recycling does not yield positive economic value, then the materials in the product are unlikely to actually be recycled.[5] Therefore, in calculating their products' recyclability, designers also need to understand end of (first) life costs/value from the perspective of a recycler, reuser, or repairer.

A simple rule of thumb is that by descending the waste hierarchy, the value of the product as scrap decreases. In other words: in general, the highest value is gained by reusing a product, component or materials, a lower value is gained by recycling the materials, and the lowest value or even costs arise through heat recovery or landfilling. Therefore, the designer has a high influence on the sustainability of the end-of-life value chain.

6.2 What do we mean by economic analysis?

In the assessments by this project, by "economics" we mean whether the standard we are examining evaluates the potential income generation from selling the commodities, as offset by the potential costs for disassembly, processing, and transportation. One large electronics recycler who presented to the work group framed the math in a simple way: Cost of acquisition, separation and preparation of commodity materials less the value of commodity materials determines the profit or loss

6.3 Review of Existing Standards

In our matrix for reviewing the various standards, we included several very basic questions that are related to recycling and/or reuse economics. A true economic analysis would need to go beyond these basics (discussed below), but these were used to identify standards that addressed the topic at all:

1) Does the standard address the economics of recycling?
2) Does the standard include methodology for translating product Bill of Materials (BOM) and design into the likely recycling fractions once the product is at the end-of-life (recycling) phase? [This is a first step towards assessing recyclable commodities valuation.]
3) Does the standard include a measure of recyclability for material classes and/or components?
4) Does the standard measure and score for the time it takes for the disassembly of the product — that is, the liberation of materials? [This is a key part of evaluating costs for labor and other factors in disassembling the product into its recyclable commodities].

Does the standard address the practicality and economics of recycling, including:

- Does the standard include a methodology for translating the BOM and design into the likely recycling fractions?
- Does the standard include a measure of recyclability for different material classes and components?
- Does the standard call out factors affecting material liberation and separation, including:
    - Characteristics of connectors, joints, coatings
    - Ability to separate plastic resins into high-value streams
    - Ability to separate metals into streams which have compatible metallurgical processing possibilities

[5] Exceptions are products which fall under waste regulations, i.e. are legally required to be recycled. Here a (consumer or producer based) financing system covers usually collection and recycling costs. However, even in this case mainly bulk and valuable material are recycled

    - Ability to recover high-value and/or critical metals
- Since recycling is about reclaiming resource values, it is important to consider if recovered materials can be used in high-value applications (i.e. this is how we define a closed loop), or only downcycled.
    - Does the standard measure materials that are able to be closed-loop recycled versus downcycled?
    - Does the standard include a material hierarchy based on value recovery?
    - Does the standard reward materials that have the ability to be recycled many times without degradation of desired properties?
- Does the standard include a methodology to translate these relevant factors into economic terms?

6.4 What we found

Does the standard address the economics of recycling?
The only standard that addressed recycling economics in any way was VDI 2343, but without providing metrics on how to estimate the economics of recycling. See discussion of VDI in section 6.5.2.

Does standard include methodology for translating product Bill of Materials (BOM) and design into the likely recycling fractions once it is at the End-of-Life (recycling) phase?
None of the standards reviewed provided a methodology for this. But the IEC Technical Report 62635 does generalize recycling rates by part and material types. And the Cradle to Cradle Certification™ Standard calculates a material reutilization score. See discussion in section 6.5.

Does the standard include a measure of recyclability for material classes and/or components?
The IEC Technical Report 62635 does include some guidance for assigning recyclability percentages to certain material classes or components. The Cradle to Cradle Certified™ Product Standard does something similar.

Does the standard measure and score for the time it takes for manual disassembly of the product?
None of the standards measured disassembly time.

6.5 Discussion of findings in Cradle to Cradle Certified™ Product Standard, VDI 2343 and IEC TR 62635

Because we found language in only three standards that in any way addresses the economics of recycling, we thought it would be most useful to summarize how each of these three standards treats these issues.

6.5.1 *Cradle to Cradle Certified™ Product Standard* (C2C)

First, we should point out that the C2C is not currently being used to evaluate electronics. In our discussions with the Cradle to Cradle Products Innovation Institute, they indicated that they modify their standard as needed when they decide to apply it to a new product category. They don't have immediate plans to use it for electronics, and believe that it would need to be amended to adequately address products as materially complex as electronics. But still, we think it's useful to describe what Cradle to Cradle Certified™ does now.

Section 4 of the C2C evaluates a product's Material Reutilization. The cradle to cradle design concept seeks to reach an optimized materials economy that eliminates the concept of "waste." To do that, all materials should be either "recyclable" (it can be recycled at least once after its initial use phase) or "compostable" (capable of undergoing biological decomposition in a compost site as part of an available program, such that the material is not visually distinguishable and breaks down into carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with known compostable materials).

The standard calculates a Material Reutilization Score for a product that uses this formula:

$$\frac{\left(\text{\% of the product considered recyclable or compostable} \times 2\right) + \text{\% of recycled or rapidly renewable content in the product}}{3} \times 100$$

This doesn't get at economics, but it does partly address our metric of providing a methodology for translating product BOM into the likely recycling fractions. There are elements of product design reflected in the material reutilization score since the percent recyclable is not only based on the inherent material properties but also on whether materials are separable. C2C also offers useful guidance for assigning an industry-wide average of recycled content

6.5.2 VDI 2343 Recycling of electrical and electronic products

VDI 2343 is a German guidance document from 2001, and is more of a discussion paper that addresses some general information and guidance around recycling and reuse in electrical and electronic products. It also provides some details as to what should be considered in planning recycling systems and treatment plans. It does provide some comments on the economics of recyclability, including delineating what elements need to be included in costing out disassembly, recycling and reuse of electrical and electronic products. However, it does not provide much guidance on how to calculate those costs. It does include the following features:

<u>Disassembly and recycling</u>

- Disassembly depth and disassembly time (Added value of work costs decreases with increasing disassembly time, up to the point where the first saleable part/material has been disassembled)
- Working steps
- Working time
- Transport costs/Logistics costs
- Storage costs
- Investment costs
- Energy costs
- Process costs
- Disposal costs
- Usability and marketability of the recovery products

<u>Re-use</u>

- Access to information (product, markets),
- Product type (consumer/investment goods, market cycle)
  - turnover rate, time and regularity
  - innovation cycles and technical advances
  - product design: modular, disassembly friendly, upgradeable, highly integrated, etc.
  - scarcity of the raw materials: security of supply
  - proportion of material value in the total product
  - wear and tear through use
- Access to the products (acquisition)
  - Buy-back price
  - Logistics (transport, storage, consolidation, commissioning, handling)
  - Personnel costs
- Revenue through service
  - Collection
  - Product dismantling
  - Transport services for customers
- Scope and requirements of the technical reconditioning

- Processes
  - Personnel
  - Operating supplies (plant, machines, tools for identification/sorting)
  - Other costs (including expertise build-up/alignment)
  - Sale of re-used products
  - Sale of replacement parts
  - Hire/Leasing of re-use products
- Extent of manual work required (labor costs)
- Sale options (remarketing).

6.5.3 IEC/TR 62635

IEC/TR 62635 is a technical report that provides a methodology for information exchange involving electronics manufacturers and recyclers, and for calculating the recyclability and recoverability rates. Of all the standards reviewed by this project, it comes the closest to providing a measure of a product's recyclability (discussed in Task 5). It provides a methodology that assists with some of the steps that would be needed for calculating the economics of recycling a product.

However, IEC/TR 62635 does not directly address the economic realities of recycling as determined by product design and material selection. Some economics may be assumed in materials to which it assigns low or zero recyclability rates. But none of that is documented for the user, so a designer/manufacturer can't determine if that assumption is correct for the specific part or material in a product.

6.6 Additional Guidance from Lifecycle Costing (LCC) Approaches

We also looked for guidance on costing from entities that compiled lifecycle costing approaches. VDMA 34160[6], IEC 56/1549/CD[7] and VDI 2884[8] offer guidance on how to calculate lifecycle costs for investment goods, such as machinery, PV systems or buildings. The main difference between traditional investment calculus and LCC is that the LCC approach has an expanded lifecycle perspective, and thus considers not only investment costs, but also operating costs during the product's estimated lifetime and costs/revenues at the end of its life. For example, the LCC approach takes into account the cost of:

- dismantling and decommissioning
- logistics and transport
- final disposal
- renovation
- re-sale
- recycling
- re-use
- recycling of spare parts
- storage

Environmental lifecycle costing approaches adjust some variables in the equation of investment LCC approaches in order to include environmental impacts as additional costs, e.g. recycling costs or environmental taxes (Gluch 2004)[9]. Schmidt (2003), for example, included savings, on-costs respectively, for recycling/disposal due to design for environment actions in order to compare

[6] VDMA 34160 (2006) Forecasting model for lifecycle costs of machines and plants
[7] IEC 56/1549/CD (2014) „Dependability management – Part 3-3: Application guide – Lifecycle costing“
[8] VDI (2005) "Purchase, operating and maintenance of production equipment using Lifecycle Costing (LCC)"
[9] Gluch, Pernilla; Baumann, Henrikke (2004): The lifecycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. In *Building and Environment* 39 (5), pp. 571–580. DOI: 10.1016/j.buildenv.2003.10.008.

design decisions.[10] However, environmental lifecycle costing approaches are in reality seldom used for several reasons: they are too laborious and there are uncertainties about (future) costs and monetization of multi-dimensional environmental impacts in a one-dimensional monetary unit is insufficient. To conclude, lifecycle costing approaches give an overview of which costs accrue at the end-of-life of goods, but a lot of information is required to actually calculate those costs.

6.7 Summary: Parameters required to assess the 4Rs economically (metrics)

The following tables summarize cost-influencing factors. Here factors are listed that the team found in our review of the standards, mentioned by the educational section speakers and mentioned in a personal interview with a recycler.[11]

6.7.1. Recycling

Parameter/Metric	Description
Logistics	
Acquisition cost	Did the recycler incur costs (collection costs, trade in costs, etc.) to acquire the used products from the customers? Include marketing costs for recycling/trade in programs. Comment: Due to the collection system in Europe, part of the e-waste is delivered “for free”
Transportation cost (inbound)	Cost to move product from collection to recycler’s (disassembler’s) facility.
Transportation cost moving commodities to processors	Shipping cost recycler incurs to ship various streams to the downstream processor.
Disassembly	
Disassembly time/steps	How long does it take/how many steps are needed to disassemble the product into the various recyclable commodities or fractions? May be a combination of manual disassembly plus mechanical (shredding).
Disassembly labor cost	What’s the labor cost for disassembling above? This will vary depending on geography - where the recycler is located. This will also vary depending on the level of “responsibility” of the recycler. Formal, high road recyclers will pay more for protective equipment and practices, training, workers comp, etc. to be sure workers are not harmed. Low road or informal recyclers have lower or none of these costs. Some of these costs are mandated by government regulations.
Identification of plastics	Can the recycler identify the type of plastics being used that are large enough to go into a recycling stream?

[10] Schmidt, Wulf-Peter (2003): Lifecycle costing as part of design for environment environmental business cases. In *Int J Lifecycle Assess* 8 (3), pp. 167-174. DOI: 10.1007/BF02978464.
[11] Maik Bergamos, ELPRO GmbH interviewed by Max Marwede on 2015/02/17

Parameter/Metric	Description
Material selection	
Type of plastic used	Certain plastics have higher value as recyclable commodities
Size of plastic used	Larger plastic parts can be baled together for resale.
Plastic additives	Pigment, flame retardants, and other additives may reduce the value of the plastic as a sellable commodity
Metal alloys	Alloy choices will determine recoverability of metals. Only alloys that can be recovered at base metal smelter will be reclaimed.
Commodity sales	
Resale prices of commodities	This is the price the recycler receives for selling the various commodity streams to processors. - Manual disassembly often results in higher recovery rates of metals (than does shredding). - Commodity market fluctuates constantly. Need assumptions based on price trends. Gold, steel, plastics are most volatile.
Determine saleable material fractions	Mainly metals and PCB boards; plastics, glass
Disposal costs of non-sellable commodities	Wood, glass, low value plastics, hazardous materials, mixed material fractions, oil
Plant and overhead	
Machinery costs	Depreciation and operational costs (energy, consumables)
Personal costs	Personnel for manual disassembly (batteries take out, CCFL removal of flat screens) and for operation of mechanical treatment; administration staff
Wear materials	Manual tools, machinery tools
Logistics (internal)	Forklift, equipment, etc.
Occupational health and safety	Costs associated with processes that are more protective of workers and environment

6.7.2. Reuse, Repair and Refurbishment

Parameter/Metric	Description
Availability of manuals	Does the manufacturer include a link to publicly available service and repair manual?
Standard formats	Is the service manual in an open format (oManual or XML)?
Battery removability	Are rechargeable batteries able to be removed and replaced by the end-user using, at most, a Philips or flat-head screwdriver?

Parameter/Metric	Description
Required tools	List all the different tools that are needed to allow for safe disassembly and reassembly of the product in a like-new working condition? Are tools common/standard, or are they proprietary to the manufacturer?
Circuit diagrams	Link to publicly available circuit diagrams.
Diagnostics	Does the product have a built-in self-diagnostic tool that indicates where failures in the product are occurring?
Modification of Software	Is embedded software (Firmware, Bootloaders etc) able to be modified by third-parties without voiding product warranties?
	The OEM must allow individual serialized assets to be under hardware maintenance contracts without any linkages to any software, services, or other contracts.
Availability of diagnostics software	External diagnostic software, hardware, or equipment shall be available to the owner in the same format and effectiveness as those provided to the OEM-badged employee
	All licenses, including those with no charge, must be separately, specifically, and optionally contracted. Many OEMs have taken to adding "catch all" terms and conditions for code that is not specifically identified, such as IBM's "License for Machine Code". The terms of these licenses impact the future use of the hardware, but are neither separable from the hardware nor optional.
Availability of information, tools necessary to effect repairs	1. Service parts (cost, regional availability, independent access) 2. Training (manuals, schools, certifications, independent access) 3. Tools (how many proprietary / non-standard tools are used, cost) 4. Time required to repair vs. labor cost (varies by region but is relative to device / part cost) 5. Diagnostic software / firmware availability / standard debug interfaces 6. Board-level schematics and BOMs

6.8 Gaps and Recommendations

While we found some useful elements for consideration, none of the standards provided a clear methodology for determining the simple math that gets to a recycler's bottom line for any given product: Cost of acquisition, separation and preparation of commodity materials or reusable parts. Less value of commodity materials or reusable parts determines profit or loss, and therefore, whether the recycling will take place within a free-market system, that is, without subsidization.

Indeed, to do our recycler's "simple" math requires one to determine a significant list of assumptions about where and how the recycling is done. The actual economics, in dollars and cents, or in the currency of the applicable country, will be highly variable over time. This would be variable for individual recyclers, operating in economic conditions of their time and place, to determine based on their technologies and markets. Also the recycler's business model will impact final costs, as well as income from commodities: some recyclers have large (expensive) shredding equipment for disassembly and separation, but others do this manually. Recyclers that have processes that are more protective of workers and the environment have higher costs. Also legal requirements from region to region influence the cost structure (e.g. reporting or decontamination requirements). But also the revenues vary in time and region. Whereas for some material global market prices exist, other materials are dealt with on local markets. Furthermore, the design of the product (separation, liberation) influences the recycling costs.

For those reasons, it's impractical for a manufacturer to determine the cost factors at the time of product design. Therefore, this team recommends two complementary approaches to determine the recycling costs. Each of these will require the development of tools that would be necessary for implementation. These tools would be databases, assessment checklists of factors for products, and systems for assigning scores.

1) **Calculation of the net cost to recycle materials (revenues minus costs) and, therefore, the ability to assess whether a material is recyclable based on positive economics.**

   Development of a Lifecycle Assessment-type database of assumptions and related costs/pricing, as well as a methodology for how to calculate economic recyclability of a given product. While this project would develop the full list of data attributes that need to be determined, we thought it would be helpful for us to suggest a preliminary set of key cost factors as shown in 6.7.1 and 6.7.2 to be considered.

   The need to be able to choose assumptions and determine related costs and prices is the same challenge faced by anyone performing a Lifecycle Assessment (LCA) on a product. There are tools and databases already populated with information that makes it easier for LCA practitioners to choose their assumptions and gather starting data. One approach is the development of a similar tool for determining the economics of recycling, available to product designers, to help them understand how changes in their design and material selection might impact the economic viability of recycling their product when it reaches end-of-life. IEC TR 62635, in presenting recyclability rates for different materials, in fact projects the availability of markets. A similar exercise could be conducted for components and products for reuse. These factors would, of course, be variable over time and place, and would require regional data and periodic updating.

2) **Calculation of the most critical variables that determine cost, especially those determined by product design.**

   Development of a product design related semi-quantitative scoring system, which takes cost-influencing factors—such as difficulty to disassemble, type of interconnection, use of hazardous substances (depollution), etc.—into account. Here, factors which are easy to determine by the manufacturer and have an influence on the recyclability of a product should be identified.

   For the purposes of assessing a product's recyclability, it may therefore not be necessary to present an actual cost to prepare for reuse or recycling. Cost is, of course, a function of time, plus other overhead items, and the time factor can be measured by a factor-based scoring system. These factors would essentially seek to quantify the ease or difficulty of liberating materials based on the product's design features. The scoring system could be used, in a structured standard, to assess the product's relative feasibility to be recycled. That is, thresholds of difficulty to liberate materials could be defined, and scores above those thresholds would result in an assessment of lesser recyclability.

   By first specifying the preferred method of reuse or recycling, whether via manual disassembly or mechanical, and then identifying the steps and the key factors, as identified in Appendix B, the time, and cost, can be accounted for. Then the product could be rated by means of an accumulated score according to a rating system for each factor. Such a system could be developed by applying the system to a number of products, measuring the mean, and then assigning points for exceeding or falling short of the mean.

   It is important to note that this projected system does not produce a time to process or a financial cost. Rather it would produce a score that would be used in relation to a comparative database to project the practicality of reuse or recycling.

6.9 What is needed?

These two alternative approaches to developing a comprehensive methodology for calculating a products reusability, reparability and recyclability suggest further project activities to make progress toward development of such a methodology.

The first step would be to decide whether to develop the tools for one or both of the approaches identified in the section above. And then, of course, to develop those tools. This will address the issue of product recyclability. These same steps could be conducted for the measurement of a product's reusability/reparability, with many overlaps. An example of such an overlap is that the factors for assessing ease or cost of materials liberation could be used, with appropriate modification, to assess the ease or cost of product disassembly for repair or refurbishment.

For material recycling, the system should recognize that the downcycling of a material (e.g. into a lesser value usage, such as a bulking agent) is not equivalent to upcycling or recycling (e.g. into a value at least as great as its initial use). For example if a plastic material in a product is in a mixed resin form, it may not be reusable as a valuable resin. Such a metric, which would measure the potential for use of the individual recyclates as a high-value material, could be incorporated into a mass-based metric system.

A further area of work will be the development of regional databases on recyclability and reusability, based on available technologies and markets with the region itself. Some of this was begun in the IEC TR 62635, and it needs to be continued for other regions.

An additional, and quite complex, step is to incorporate factors that measure the environmental benefits of recycling different materials into a more cohesive recyclability metric. As it is now, strictly based on mass, recycling plastic counts for much more than recycling gold, because its mass is greater in the product. However, the precious metals and some of the critical metals are far more important to recycle than the bulk materials from the perspective of the core purpose of recycling: resource conservation. This suggests an additional phase in developing the metric system: to incorporate an environmental metric.

Another important factor is the availability of information from the manufacturer that is needed by the recycler or reuse organization to efficiently carry out its functions. This is addressed well in IEC TR 62635, and it will need to be expanded to address the other issues raised in this report.

Repair manuals, circuit diagrams, bill of materials, and diagnostics for testing of a product's functionality should be made available to all who request and/or need them to extend the life of a product. The necessary information should not be restricted only to OEM-authorized users, but be available to all. Spare parts necessary to complete repairs also need to be made available to all for a certain number of years after a product is no longer being produced.

To encourage repairable product designs, better design for disassembly guidelines are needed. The iFixit Scorecard and similar propriety tools are an indication that the market needs a disassemble-ability scoring system to assist in the development of product designs and environmental scoring systems. Educational material for product designers such as Autodesk's Sustainability Workshop provide a framework those future standards could build upon.

TASK 7: DEVELOP GAPS AND RECOMMENDATIONS/NEXT STEPS

Based on the results presented in this report we conclude there is a critical need for a *better* metric for product recyclability and more information to be available in order to properly calculate a recycling rate at the product level. Additionally we found NO "standards" much less metrics for repair, reuse and refurbishment of products. As mentioned earlier, the industry has only one type of metric – mass based in its most simplistic form and that measure alone is inadequate.

Using the mass based metric as a starting point, the best mass based metric system for calculating only the recyclability of an electronic product was developed in the IEC TR 62635 (which was built upon the ISO 22628 standard for automobiles). The accomplishments of IEC TR 62635 are:

- Defined a methodology for the calculation through a stakeholder process
- Developed detailed formulas for calculating electronic product recyclability rates based on material content by mass
- Incorporated important factors, such as regional variability of recycling systems, into the methodology — though it did not finish that work
- Identified different recyclability rates for different materials based upon real-world recycling factors
- Provided a tool that the industry is familiar with and some companies are using

However, IEC TR 62635 falls short of the goal of a fully inclusive recyclability calculation methodology for the following reasons:

- IEC TR 62635 does not take into account the practical realities of the liberation of material and components
- IEC TR 62635 fails to take into account metrics for reparability, reuse or refurbishment. Increasingly these are part of the overall recycling process, whereby whole products or certain components are often recovered for reuse, either in a recycling facility or in facilities dedicated to repair or refurbishment. Such factors should be included in the metric system.
    - Does not incorporate the environmental benefit/burden for the recovery of the materials selected for recovery. All materials, based on mass, are treated equally.
- IEC TR 62635 does not incorporate any consideration of the quality of recycled materials — specifically whether they are upcycled, downcycled, or recycled into the same quality as virgin material

Some of the important work that IEC TR 62635 began has not been completed. A case in point is that the IEC TR 62635 recognizes the difference of the availability of recycling technologies and materials markets in different regions and addresses the regional recyclability of different materials. However, the IEC TR 62635 stopped short of developing these metrics beyond a single sample case.

7.1 Critical Next Steps for the development of effective and complete recycling and repair metrics:

In order to further advance progress toward a meaningful set of metrics AND the *accurate* data needed to support the calculations, the team recommends the next critical steps:

1. Develop a product recyclability metric that incorporates a scoring factor which assigns a reasonable impact value based on the design –for-disassembly and recycling features (like ease of removal, ease of sorting to clean material streams) and a weighted recovery rate which brings the reality of actual recycle results around the world into the traditional mass-based metrics. Incorporating the real world impact and the economics of recycling into the product design lifecycle is essential. To do so, the team recommends the following actions:

    a. Complete the IEC TR 62635 research on mass-based recycling, which includes regional based recyclability rate of individual materials for all major product types and regions.

b. Develop a relative scoring or cost factoring system that product designers can use as a guide for their designs. Examples include: penalties or reduction of score for inclusion of hazardous materials in the product design, reward or improvement of score for designs that provide easy, tool-free separation into clean material streams. With that, we need to develop and understand the practicality of liberation of parts and components that includes economic (time, effort, regional) and technical factors and method of scoring the relative impact of the design decisions. The cost/liberation factor(s) for recycling must be used in conjunction with the mass-based metric, such as that developed by IEC TR 62635. Cost-effective liberation is a primary driver in practical recovery of material. The team has identified some, but not all, cost/liberation factors to be developed, which include a material liberation factor for recycling (destructive and/or non-destructive), material choice factor, and hazardous material factor.

c. Develop a worldwide, regional recovery rate database, which shows the actual recovery rate of materials including regional treatment options and materials markets.

2. Develop an assessment tool to objectively determine the disassembleability of a product for repair and parts recovery. This could include product-specific design metrics by using a relative scoring system similar to what is recommended for building a recycling metric (1 above) that focuses on non-destructive disassembly.

This would provide designers, manufacturers, and stakeholders a standardized method for determining the reparability of a product. One potential method is to estimate the difficulty to remove specific items for parts recovery, repair, or maintenance. Another is to analyze disassembly times and complexity. A widely adopted tool would allow manufacturers to incorporate innovations into new products as new design ideas emerge or as new information is learned about the reparability of products.

Appendix A: Common Vocabulary Adopted and Developed by the Team

Reuse – Includes repair and refurbishment – operation by which a product, or a part thereof, having reached the end of one use-phase is used again for the same purpose for which it was conceived. [IEC 62635 modified]

Repair - restoring function of the part/component to working condition (does not include cosmetic fixes)

Refurbishment **-** bring a whole product from a used condition up to a like new condition (includes cosmetic fixes and upgrades)

Refurbishing - rebuilding of a product to specifications of the original manufactured product using a combination of reused, repaired and new parts. It requires the repair or replacement of worn out or obsolete components and modules.

Recycling – Processing of waste material for the original purpose or for other purposes, excluding energy recovery [ISO 15270:2008 modified]

Recovery – Process in which a waste product and its constituent material(s) is subjected to part re-use, recycling (material recovery) or energy recovery [IEC 62635]

Closed Loop Recycling - Recycling materials back into the highest and best use of the material (may mean into same kinds of products, or other products maintaining the material at the same value). Not "downcycling" the material into lower quality uses.

Infinite recyclability - Refers to the properties of materials that allow them to be recycled an unlimited number of times for the same level of material use (not "down-cycled" into a lower value material), without degradation of desired properties, without losing significant mass of material and without requiring the addition of significant amounts of new, virgin material in order to do so.

Technology Metals – Includes the following types of metals: Base Metals such as ferrous and aluminum, Specialty Metals such as cobalt, and Critical Metals such as rare earth elements.

APPENDIX B: DETAILS OF EVALUATION SPREADSHEET CRITERIA

Administrative metrics The survey examined the degree to which the standard addressed the core goals of this project:

- Are ICT products in the scope of the standard?
- Does the standard define in measurable ways key terms such as repair, refurbishment, reuse, recycling, recovery and disposal?
    - Does the standard include metrics for repair, refurbishment, material recycling, energy recovery, disposal?
- Is the intention of the standard to provide guidance to manufacturers in the calculation of reusability and/or recyclability?
    - Does the standard recognize that the manufacturer does not control the recycling system?
- Does the standard incorporate real-world reuse/recycling methodologies?
    - Does the standard account for different methods of recycling in different geographies?
- Does the content of the standard address the important factors affecting reusability/recyclability, including:
    - Product design
    - Information provide by the manufacturer
    - Triage and pre-processing
    - Methods of recycling
    - Final processing
- Does the standard require public disclosure?
- Certain aspects of the standard itself affect its applicability:
    - Is it a formally adopted standard?
- Was it developed through a voluntary consensus process?
    - Is the standard available? Is there a cost?
    - Are claims of conformance verified?

Quantification of recycling and repair Claims of recyclability must be accompanied by evidence that recyclability is practical. The survey identified several relevant factors:

- Does the standard require identification of important factors that are vital to effective reuse/recycling, including identification of:
    - The location of hazardous components
    - Parts that require selective treatment
    - Parts that should be further disassembled
    - Methods to remove the housing
    - Methods of processing that provide the most effective recovery
- Does the standard recognize the importance of non-destructive disassembly for claims of reusability to be made? Does the standard define "easy to remove and replace" in measurable terms?
- For non-destructive manual disassembly, does the standard measure the ease of removing:
    - Casing with no damage
    - All batteries
        - By service technician
        - By consumer
    - Hazards including mercury containing lamps
    - Other parts frequently replaced
- For destructive disassembly, appropriate for recycling but not reuse, does the standard define "easy to remove"?
- For destructive disassembly, does the standard measure, for manual processing, the ease of removing:

    - All hazards, including batteries, mercury lamps, others
    - Parts that should be further disassembled
    - Parts that require selective treatment
    - Parts made of a single recyclable material,
    - Parts that are difficult to process
- For both destructive and non-destructive manual disassembly, does the standard measure or score time or ease to disassemble. Measures may include:
    - Number of steps
    - Presence of obstacles
    - Number and types of screws, clips or other fasteners
    - Number and standardization of mechanical and electrical interconnectors
    - Number of different tools required, including commonly available and non-proprietary or specialty tools
    - Adhesives used, including area and method of detachment
    - Accessibility, positioning and force required to liberate components
- For reuse and repair, does the standard address design for ease of reassembly, including the factors in the previous bullet.
- For reuse and repair, does the standard address the availability of spare or replacement parts
- For destructive disassembly via mechanical processing does the standard address design and material selection for optimal recovery of materials following shredding?
    - What percent of the product ends up as a mixed material stream?
- Does the standard address the practicality and economics of recycling, including:
    - Does the standard include a methodology for translating the BOM and design into the likely recycling fractions?
    - Does the standard include a measure of recyclability for different material classes and components?
    - Does the standard call out factors affecting material liberation and separation, including:
        - Characteristics of connectors, joints, coatings
        - Ability to separate plastic resins into high-value streams
        - Ability to separate metals into streams which have compatible metallurgical processing possibilities
        - Ability to recover high-value and/or critical metals
    - Since recycling is about reclaiming resource values, it is important to consider if recovered materials can be used in high-value applications (i.e. this is how we define a closed loop), or only downcycled.
        - Does the standard measure materials that are able to be closed loop recycled versus downcycled?
        - Does the standard include a material hierarchy based on value recovery?
        - Does the standard reward materials that have the ability to be recycled many times without degradation of desired properties?
    - Does the standard include a methodology to translate these relevant factors into economic terms?

Provision of information needed for effective recycling and reuse

Without information from the manufacturer, practical recovery of value can be seriously decreased. Does the standard address the providing of information regarding:

- For reuse and repair
    - The availability and level of detail of service manuals
    - That service manuals include circuit diagrams, step-by-step disassembly instructions, and a troubleshooting tree
    - The availability of a BOM

- Identification of hazardous components
- Software for diagnostics and reinstatement of functionality

Appendix C: MEErP EcoReport Tool

Table 1: Definition of recycled content and recyclability benefit rate in the MEErP EcoReport Tool

MEErP EcoReport Tool	
Recycled content	Recycled content can be defined as the “input” of materials with origin on waste (i.e. secondary material). This is limited here to some recycled plastics and recycled paper, as metals already integrate a share of secondary material which is not always known by the manufacturer. The aspect “recycled content” refers to additional data sets which were added to the tool, so that products with recycled material as input material can now be modelled with the EcoReport tool. (Comment: the choice of material defines the environmental impact → choice of material with recycled content means less environmental impact)
Recyclability benefit rate	The recyclability benefit rate shows the potential benefits of a recyclable product and was developed by DG JRC (see (Ardente & Mathieux, 2013)). Within the EcoReport tool 2013, the recyclability benefit rate (RBR) is calculated only for bulk and technical plastics. Row 269 (Figure 1) deals with recyclability, the potential of the new products to change the course of the materials flows , e.g. due to faster pre- disassembly or other ways to bring about less contamination of the mass to be recycled (see MEErP Methodology Report Part 2[12]) . Therefore it is economically likely that the recycled mass at EoL will displace more virgin material in other applications. The recyclability does not influence the mass balance but it does give a reduction or increase up to 10% on all impacts of the recycled mass. It is forward looking, e.g. values different from 'avg' (=base case) should only be filled in for design options. Row 269 contains dropdown-boxes allowing the analyst a choice between best, better than average (‘>avg), average (‘avg’, applies to basecase), worse than average (‘<avg’) and worst. The reasoning is that through an optimised pre-disassembly of larger metal, glass, etc. parts --before the rest of the product goes into a shredder-based recycling route-- the contamination of these materials is limited and therefore they are more likely to be recycled in applications where they displace virgin materials. The appropriate criteria for this classification need to be determined in the preparatory study for a specific product.
Recycling/Reuse/ Recovery	Rows 263-267 (Figure 1) give the destination of the EoL available mass over 5 fractions: re-use, recycling (material), recovery (heat), incineration and landfill/missing/fugitive.

Source: http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/methodology/index_en.htm

12 http://ec.europa.eu/DocsRoom/documents/106/attachments/1/translations/en/renditions/native

Pos nr	DISPOSAL & RECYCLING Description				
253	product (stock) life L, in years	0	Please edit values with red font		
		current	L years ago	period growth PG in %	CAGR in %/a
254	unit sales in million units/year	0,000	0,000	0,0%	0,0%
255	product & aux. mass over service life, in g/unit	0	0	0,0%	0,0%
256	total mass sold, in t (1000 kg)	0	0	0,0%	0,0%

Pos nr	Per fraction (post-consumer)	1	2	3	4	5	6	7a	7b	7c	8	9		
		Bulk Plastics	TecPlastics	Ferro	Non-ferro	Coating	Electronics	Misc., excluding refrigerant & Hg	refrigerant	Hg (mercury), in mg/unit	Extra	Auxiliaries	TOTAL (CAGR avg.)	
257	current fraction, in % of total mass (or mg/unit Hg	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0	0,0%	0,0%	0,0%	
258	fraction x years ago, in % of total mass	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0	0,0%	0,0%	0,0%	
259	CAGR per fraction r, in %	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%		
	current product mass in g	#	#	#	#	#	#	#	#	#	#	#	#	
260	stock-effect, total mass in g/unit	0	0	0	0	0	0	0	0	0,0	0	0	0	tc
261	EoL available, total mass ('arisings') in g/unit	0	0	0	0	0	0	0	0	0,0	0	0	0	tc
262	EoL available, subtotals in g		0		0		0	0	0	0,0	0	0	0	
													AVG	
263	EoL mass fraction to re-use, in %						1%					5%	0,0%	
264	EoL mass fraction to (materials) recycling, in %		29%		94%		50%	64%	50%	39%	60%	30%	0,0%	
265	EoL mass fraction to (heat) recovery, in %		15%		0%		0%	1%	0%	0%	0%	10%	0,0%	
266	EoL mass fraction to non-recov. incineration, in %		22%		0%		50%	5%	5%	5%	10%	10%	0,0%	
267	EoL mass fraction to landfill/missing/fugitive, in		35%		5%		19%	29%	64%	55%	29%	45%	0,0%	
268	TOTAL	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0,0%	
269	EoL recyclability****, (click& select: 'best', '>avg', 'avg' (basecase); '< avg' ; 'worst')	avg	avg	avg	avg	avg	avg	avg	avg	avg	avg	avg	avg	
		#c	#c	#c	#c	#c	#c	#c	#c	#c	#c	#c		

Figure 1: MEErP EcoReport Tool (clipping source: http://ec.europa.eu/DocsRoom/documents/5308/attachments/1/translations/en/renditions/native)

APPENDIX D: VDI 2343

Market and product lifecycle	Material product lifecycle		Costs	Revenue
Development phase		manufacturer	• R&D personnel • materials and personnel for prototype construction and tests • materials and personnel for series planning	• subsidies, grants, tax rebates • licence revenue
Market and aftercare phase	production	manufacturer	• personnel • material • operating supplies • miscellaneous	
	sale	manufacturer	• logistics • discounts	• sale of new products • hire/leasing of new products
	use	manufacturer	warranty	• replacement part sales • sale of consumables • special service • hire/leasing of new products
	manufacturer-independent third parties: take-back	manufacturer	• buy-back price • personnel downsizing • logistics	services: downsizing, logistics
	manufacturer-independent third parties: re-use	manufacturer	• personnel • material • operating supplies • miscellaneous	replacement parts/materials
	manufacturer-independent third parties: remarketing	manufacturer	logistics	• sale • hire/leasing
	second use	manufacturer	• warranty • guarantees	• replacement part sales • sale of consumables • special service • hire/leasing
	take-back	manufacturer	• buy-back price • personnel downsizing • logistics	services: downsizing, logistics
	disposal	manufacturer	disposal services	sale of secondary raw materials

Figure 2: Player specific cost and revenue categories over the product lifecycle (source: VDI 2343)