Reducing Life Cycle Environmental Impacts of Waste Electrical and Electronic Equipment Recycling

Case Study on Dishwashers

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material hygiene
shredding

Summary

Collection and treatment of waste from electrical and electronic equipment (WEEE) is regulated in the European Union by the WEEE Directive. Producers are responsible for take-back and recycling of discarded equipment. Valuable materials are, however, at risk of "getting lost" in current processes. Thus, strategies to minimize losses are sought after.

The material hygiene (MH) concept was introduced to address this issue. Structural features, which are important for the outcome of reuse, recovery, and recycling, were investigated in an earlier field study of discarded dishwashers. It was proposed that a prestep, manual removal of copper prior to shredding could increase the purity of recovered material fractions.

This article builds on the field study and theoretical reasoning underlying the MH concept. Dishwashers are assumed to be designed for disassembly when the prestep is introduced. A limited life cycle assessment was performed to determine whether the proposed prestep may be environmentally beneficial in a life cycle perspective. Two alternatives were analyzed:

Case 1: the current shredding process.

Case 2: prestep removal of copper before shredding.

Targeted disassembly prior to shredding may reduce the abiotic depletion and global warming potential in a life cycle perspective. The prestep results in increased copper recovery, but, more important, copper contamination of the recovered steel fractions is reduced. The results also highlight the importance of minimizing energy consumption in all process stages.

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Introduction

Collection and treatment of waste from electrical and electronic equipment (WEEE) are regulated in the European Union (EU) by the WEEE Directive (European Union 2002). This directive puts the idea of extended producer responsibility (EPR) into practice, so that producers are made responsible for taking back and recycling discarded equipment. The ultimate aim of EPR is to establish economic incentives for improved product design (e.g., Mayers et al. 2005; Mayers 2007). The principles of EPR were developed and discussed at its very earliest stages in the context of industrial ecology by Lindhqvist and Lifset (1997), Lifset and Lindhqvist (2002), and Lindhqvist and Lifset (2003).

EU member countries are required by the directive to collect a minimum of 4 kilograms[1] (kg) WEEE per person each year. In Sweden, this figure was 14 kg in 2005 (SEPA 2006). Valuable materials are, however, at risk of getting "lost" in current processes (Hagelücken 2006). Increasing the efficiency of the treatment process is important for countries to recycle all materials. Thus, researchers are seeking new process strategies to minimize losses. Both product design and waste treatment processes must be adapted to meet increased recycling demands.

The material hygiene (MH) concept was suggested by Johansson and Luttropp (2009) as a mind-set targeted at increasing the outcome and quality of recycled materials. They defined it as follows: "in every step of the product life cycle to act towards larger amounts and increased purity of useful material from recycling, possible to use on the same quality level as before or degraded as little as possible"(29). MH consists of five target areas:

1. MH mix: targets the number and types of materials in a product.
2. MH identification: targets the identification of products and parts in products at end of life.
3. MH resources: targets the housekeeping of materials used in products during the life cycle.
4. MH weight: targets weight issues tied to recyclability.
5. MH map: targets the structure of the product.

The total MH of a product is then a balanced set of MH targets. Contradictions in targets are, however, the rule rather than the exception (Johansson and Luttropp 2009).

This study targets a specific WEEE product—the dishwasher. Dishwashers were selected as the demonstration product group because, regardless of brand, they have largely the same types and number of parts. The difference lies in how these parts are assembled. In an earlier field study, Johansson and Luttropp (2006) disassembled and analyzed 14 dishwashers to test part of the MH concept. The main focus in the field study was on design features, MH map, which would facilitate reuse, recovery, and recycling of product parts. On the basis of this field study, the authors formulated a waste process suggestion, the prestep (Johansson and Luttropp 2006).

Currently, waste treatment of dishwashers (see figure 1) may include removal of the start capacitor, because old types of capacitors contain oil. This is not needed for newer dishwashers. No further disassembly, on the basis of material issues, is performed. The dishwashers are then transported to the shredder, where they are fragmented. After shredding, automatic and manual separation of the different fractions is performed.

Copper was selected as the target material in this study. It is in itself a valuable resource but is also a contaminant in steel production (Ekerot 2003). Current practice in Sweden is to use manual labor after the shredder to remove copper from the ferrous waste stream. Copper windings from electric motors usually follow the magnetic steel waste stream, because they are entangled with other motor parts.

The implementation of a prestep targeting copper would consist of a manual (or automatic) disassembly operation to remove copper-containing parts prior to shredding in a waste treatment plant. It is then hypothesized that the resulting fractions would be less contaminated by copper.

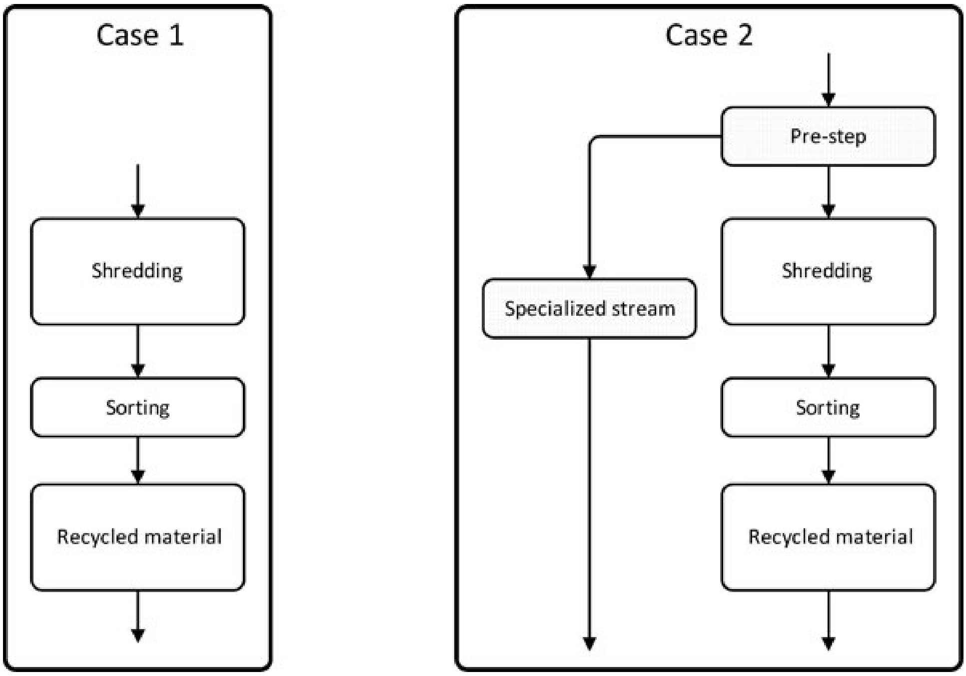

Figure 1 Shredding and sorting in Case 1 and Case 2.

Aim

The aim of this article is to explore the potential of the proposed prestep, in the form of a targeted manual disassembly operation, to improve the effectiveness of material recovery and to be environmentally preferable from a life cycle perspective. The importance of applying a life cycle perspective in the assessment of new waste treatment and recycling operations is emphasized in the WEEE Directive (2002/96/EC) as well as in the proposed revisions of the EU Waste Framework Directive (2006/12/EC). Two different process alternatives were analyzed:

- Case 1: current practice of dishwasher waste processing in Sweden by a typical shredding company.
- Case 2: manual disassembly prestep included before shredding; this represents a hypothetical case if dishwashers were designed to facilitate disassembly.

The analysis was based on life cycle assessment (LCA) methodology. Two environmental impact categories were prioritized in this exploratory study—abiotic depletion and global warming potential (GWP). The main rationale behind the MH concept is to act, in every life cycle phase of the product, toward the highest possible efficiency in recycling. The outcome of useful material is in focus. Higher output of high-quality material from recycling is expected to reduce overall consumption of resources. Hence, depletion of abiotic resources was considered a relevant impact category. Apart from improvements in the process system's material efficiency, changes in energy use may be expected as a result of the introduction of the prestep—hence the focus on global warming potential to target carbon dioxide (CO_2) emissions from energy production.

Methods

LCA methodology was used to assess the potential of the proposed prestep to reduce abiotic depletion and global warming potential. We used databases found within the software tool SimaPro® 7.1 (PRé Consultants 2008) in addition to primary data collected for this specific study.

System Description

The functional unit in this study is an average dishwasher, weighing 35 kg, processed in a shredder facility. That is, the same dishwasher is processed, but by different means, in the two modeled cases.

Only those stages of the dishwasher life cycle that would be affected by the proposed prestep in Case 2 are included in the analysis. Figure 1 presents the particular waste flows of interest in this study, covering treatment of dishwashers at the waste facility. Case 1 represents the current flow of materials, whereas Case 2 includes the proposed prestep prior to shredding, in which materials are separated, which creates a separate, specialized (in this study, copper) stream.

Expanded System Boundaries and Avoided Burdens

In the LCA model, resources are recovered in both cases from the processed dishwasher. Hence, in addition to the functional unit (processing the dishwasher), there is valuable output of recycled metals as well as heat and electricity from incineration of shredder residue (multioutput systems). To make the two compared cases equivalent, we need to take into account the benefits of the recovered resources. In accordance with the recommendations of the ISO standard (ISO 2006), we used system expansion to avoid allocation (partitioning of burdens between outputs). In this case, the avoided burdens of producing corresponding amounts of the recovered resources, but by alternative means, are subtracted from the total system impact. For instance, we assume that as a result of the prestep, more copper will be recovered and recycled in Case 2 than in Case 1, the reasons for which are explained below in the *Data* section. Subtracting the avoided burdens for copper from both cases allows us to compare them on equal grounds.

Because the focus of this study is on exploring the life cycle implications of the MH concept, the quality of recovered metals is important. As a consequence of more copper being recovered in Case 2 than in Case 1, the steel and stainless steel fractions will be less contaminated by copper. That is, Case 2 results in a higher quality of recovered steel and stainless steel. If there is a difference in quality between the two cases, they do not represent equivalent scenarios. We dealt with the problem in this study by modeling the required dilution of recovered metals with virgin metal to achieve comparable metal quality in both cases. This procedure is described in further detail in the *Data* section.

Data

This study is based on current Swedish waste management practices and conditions. Data were collected for the foreground system—that is, the shredder facility—to reflect this. The background system was modeled with process data from the Ecoinvent database (Ecoinvent Centre 2006) available in SimaPro® 7.1.

The dishwasher material fractions—that is, stainless steel, steel, copper, and other materials—have been assigned average weight values according to measurements made on site during the previous disassembly study (Johansson and Luttropp 2006). A typical dishwasher contains approximately 1 kg of copper distributed in four subassemblies, as listed in table 1.

Figure 2 depicts the material flows in a shredding operation according to current practice in Sweden (Case 1). The shredded dishwasher is divided into four separate streams.

In Case 1, copper is distributed to some extent in all material streams after shredding. The estimated removal rates in Case 1 are based

Table 1 Distribution of copper in different subassemblies of a typical dishwasher

Copper content in parts of an average dishwasher	*Weight in grams (g)*
Circulation pump motor	700
Drain pump motor	100
Wiring	100
Electronic components	100

Source: Johansson and Luttropp (2009).

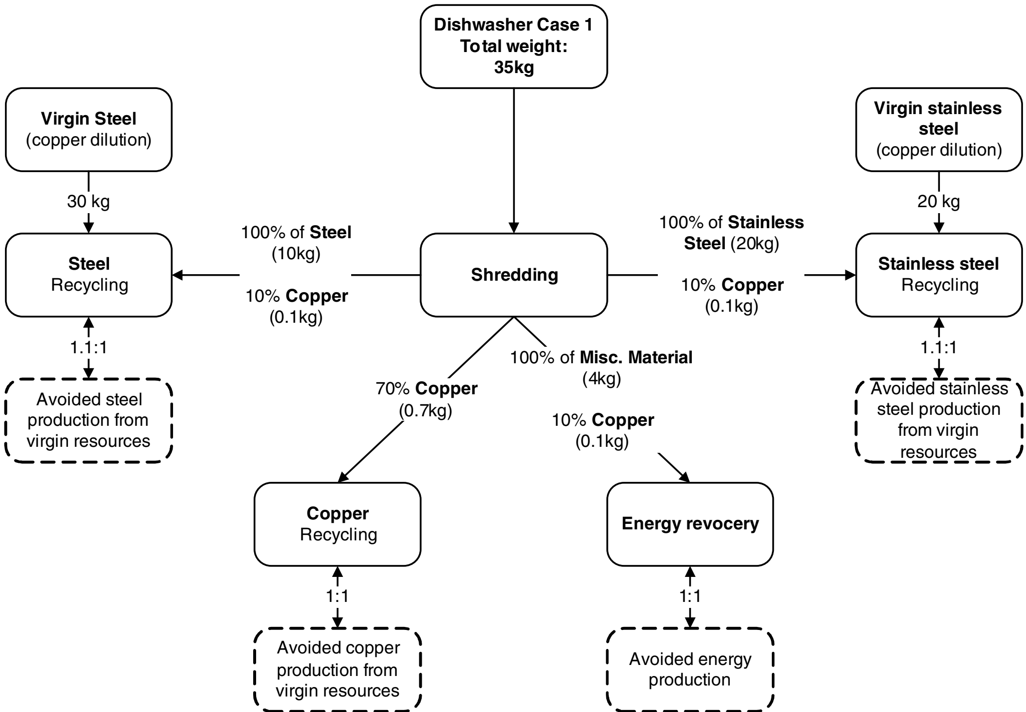

Figure 2 Flow chart of Case 1, current practice of dishwasher processing.

on field studies on dishwasher composition and practical experience of disassembly (Johansson and Luttropp 2009) combined with technical reasoning. The largest sources of copper in dishwashers are the motors, which represent 80% (0.8 kg) of the copper. It is primarily motors that are hand-picked from the conveyor belt to recover copper. For instance, copper in wiring (10%) becomes part of a "fluff" fraction after shredding, from which it is difficult to separate. Given that hand-picking after shredding is dependent on workforce motivation (Johansson 2008) and that workers cannot always remove all motors from the conveyor belt, only 70% (0.7 kg) of the total amount of copper is assumed to be separated. Motors that are not hand-picked are sorted as magnetic steel, including 10% (0.1 kg) of the copper. The remaining flows of copper in figure 2 are likewise the result of discussion and technical reasoning. The miscellaneous material stream contains mostly polymers but could also include pieces of copper that contain wiring and pieces from printed circuit boards.

High-performance steel production requires almost copper-free raw material (Ekerot 2003). When recycled scrap steel is used as a raw material, dilution with virgin, copper-free steel is required to reach acceptable levels of copper contamination. This is done in practice in Sweden today, as was documented in work by Johansson (2008). Case 1 results in copper-contaminated recovered steel and stainless steel fractions. For Case 1 and Case 2 to represent equivalent scenarios with regard to recycled steel and stainless steel quality, these metal streams are modeled as being diluted with virgin steel feedstock from converter-based producers to reduce the copper level to 0.25%. This is the maximum acceptable copper contamination level for fragmented scrap from household appliances and the like, according to an agreement between recyclers and steel mills in Sweden (Erasteel et al. 2005).

If we use the specified distribution of copper in figure 2, the 10 kg of recovered steel will contain 1% copper. To reach the target of 0.25% copper contamination in steel, we model this fraction as being diluted with 30 kg copper-free virgin steel. The same reasoning applied to the stainless steel fraction results in the addition of 20 kg of virgin material to that waste stream. Data on steel and stainless steel production from scrap were modeled with the Ecoinvent database available in SimaPro, with adjustments made for the input of virgin steel and stainless steel feedstock for dilution. It was assumed that the virgin stainless steel added for dilution purposes does not need addition of alloys, as does the recycled scrap. Electricity use was also adjusted to represent the marginal production technology in Sweden.

The virgin materials added for dilution purposes add to the total amount of recycled steel and stainless steel. Because this also increases the amount of offset avoided production of virgin materials in Case 1, indicated by the dashed boxes in figure 2, the net modeled effect of dilution with virgin steel and stainless steel is only that of the extra handling of these materials in the recycling process. It is also important to note that although more steel and stainless steel are handled in Case 1 than in Case 2, the two cases still represent equivalent scenarios.

In Case 2 (see figure 3), the product is initially divided by the manual disassembly prestep into two material streams, one copper fraction representing 95% (0.95 kg) removal of the copper-containing parts of the dishwasher, and a further fraction that is shredded. Johansson and Luttropp (2009) found 95% to be the maximum practical removal rate of copper, representing a case in which the dishwasher was designed to facilitate disassembly ("design for disassembly"). This implies that Case 2 is a hypothetical scenario representing what could be achieved if dishwashers were designed for optimal ease of disassembly. The shredding process is the same as in Case 1, except that the shredder now fragments a basically copper-free fraction. There is no need for dilution of recycled steel with virgin steel in Case 2.

The miscellaneous material stream after shredding in figures 2 and 3 contains mainly plastic material, which is assumed to be incinerated with recovery of both heat and electricity in a combined heat and power plant. The total energy efficiency is 90%, with 34.8 megajoules[2] (MJ) being recovered as 29.5 MJ heat and 5.3 MJ electricity. The avoided marginal heat production is assumed to be heat from biofuels, and the avoided marginal electricity production is assumed to be electricity from coal-condensing power plants.

Electricity is used by the shredder and by electric hand tool operations in the prestep. The shredding operation is assumed to require 30 kilowatt hours per tonne[3] (kWh/tonne) when shredding mixed material (Ribbenhed 2006). Manouchehri (2005) is in agreement and states that a shredder of hammer mill type requires 28–36 kWh/tonne. Shredding a dishwasher weighing 35 kg would demand 1.05 kWh/dishwasher. This figure is used for both Case 1 and Case 2 shredding operations.

The proposed prestep is estimated to take 10 min per dishwasher. This is a conservative estimate based on practical experience we gained when performing the case study described by Johansson and Luttropp (2009). We determined the hand tool electricity consumption assuming a maximum power usage of 500 W for 10 min, which gives a total of 0.083 kWh/dishwasher.

As this is a change-oriented study (see, e.g., Tillman 2000), electricity use is modeled as marginal electricity. Under current Swedish conditions, marginal electricity is assumed to be produced in coal-condensing power generation plants.

Emissions produced by the shredding process itself are assumed to be negligible and have not been included. They could consist of air emissions, such as fine dust from the shredder itself, and liquid emissions in the form of leakage from various sources in the plant. Leakage is closely monitored in such plants, as required by environmental authorities. The WEEE Directive contains strict specifications for the operation of such plants; for example, hardened surfaces and oil separation wells for waste water are required in processing plants. The directive also states that minimizing the environmental load of shredder facilities is desirable.

The required data of the foreground system in this study (operations at the shredder facility) are sensitive from a corporate perspective. Therefore, it has not been possible to collect process-specific data for all steps of the waste management process. This leads to limitations in data quality and specificity. As this is a comparative study, to some

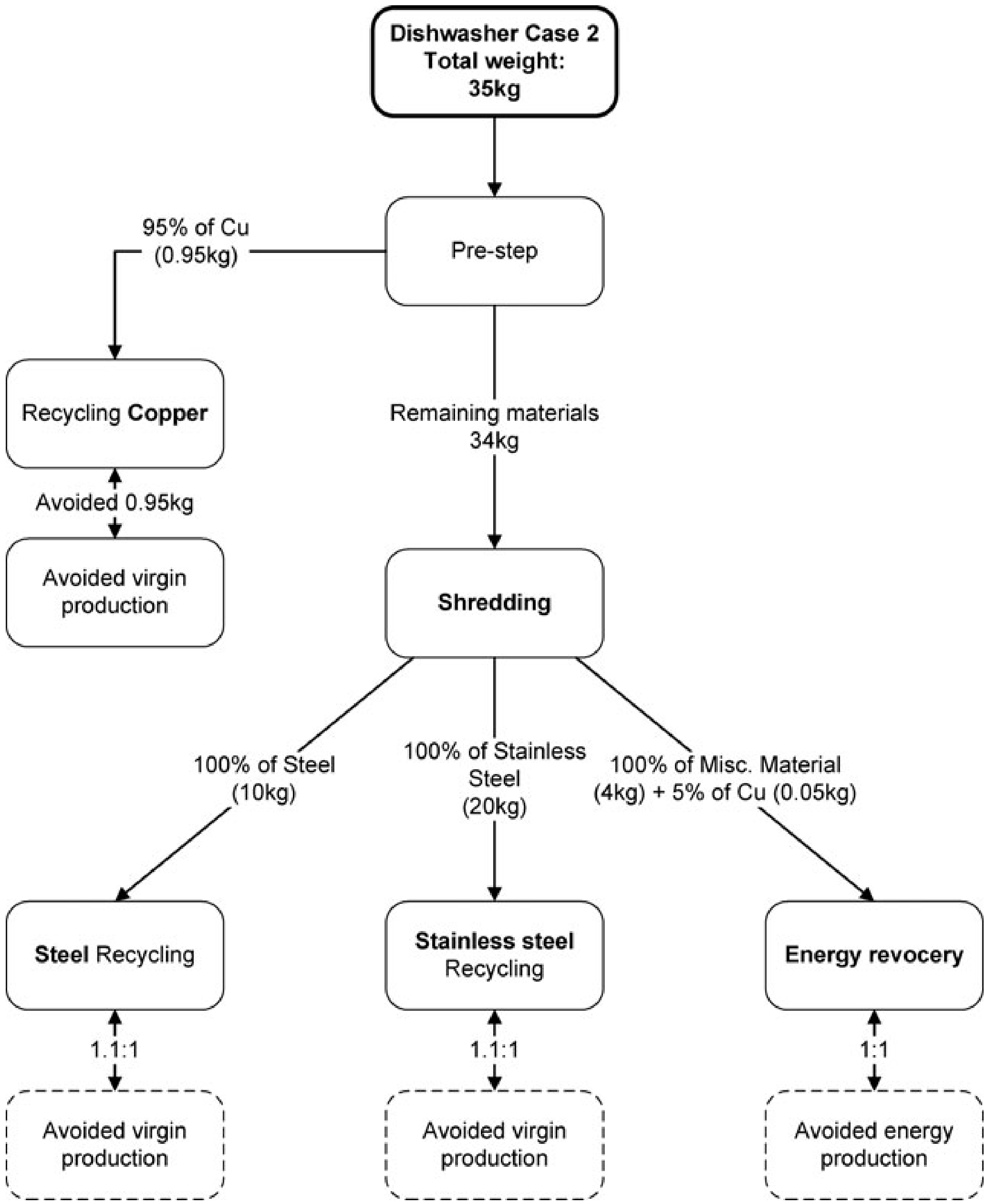

Figure 3 Life cycle assessment flowchart of Case 2, including a prestep targeting copper (Cu) removal.

extent the same inaccuracies appear in both cases and should partly cancel each other out. A key issue in both cases is, however, the modeled rate of copper removal, which has not been fully substantiated. Because many shredding companies manually separate copper, the loss rate is dependent on workforce motivation, and results likely differ considerably from day to day. A sensitivity analysis of the importance of this figure was performed and is presented in the Results section. The aim is not to achieve pinpoint accuracy in the results but rather to reach some conclusions

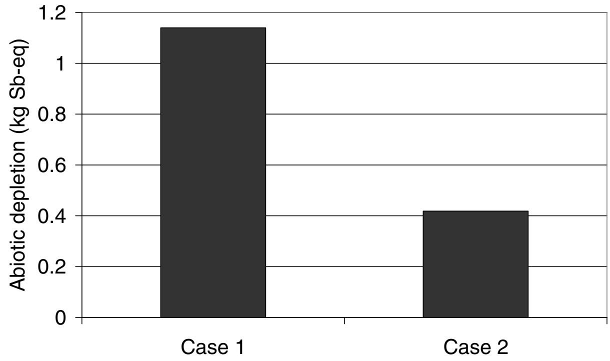

Figure 4 Life cycle abiotic depletion potential of processing one dishwasher in Case 1 and Case 2.

regarding how the selected environmental impacts of the processes would differ.

Sensitivity Analysis

To a great extent, the difference in the rate of copper removal determines the outcome of the comparison between the two cases. The copper removal rate in Case 2 is hypothetical in the sense that this case has not yet been implemented in practice, and the assumed 95% removal rate depends on "design for recycling" measures being taken. Hence, 70% removal of copper in Case 1 is a key parameter. Although this removal rate is fairly well experimentally and technically supported, we have not fully substantiated what the actual level is in current practice. It may be argued that better practices for removal after shredding could achieve higher levels of copper removal. Because manual separation of copper after shredding is dependent on workforce motivation and results likely differ considerably from day to day, a sensitivity analysis was performed. The sensitivity analysis was designed to analyze the effects of a higher (90%) or lower (50%) copper removal rate in Case 1.

Results

The environmental assessment in this study was limited to two impact categories, abiotic depletion and global warming potential. Characterization was performed with the CML2 baseline 2000 v2.03, as implemented in SimaPro® v 7.1.

The results presented in figures 4 and 5 indicate that with the assumed copper removal rates, the process including the prestep in Case 2 could reduce the net impact on both abiotic depletion and global warming potential during end-of-life treatment compared to current practice (Case 1). This difference can be tied primarily to the remelting of virgin steel and stainless steel, which is needed to dilute recovered steel and stainless

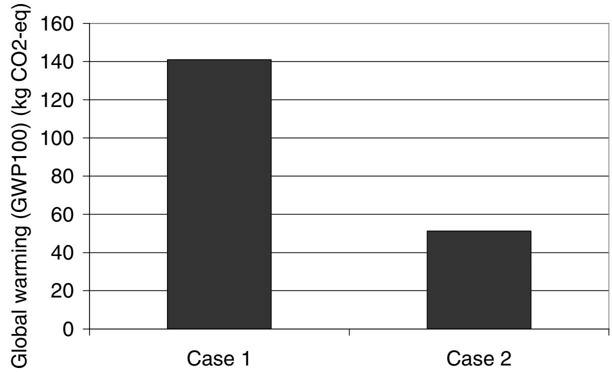

Figure 5 Life cycle global warming potential of processing one dishwasher in Case 1 and Case 2.

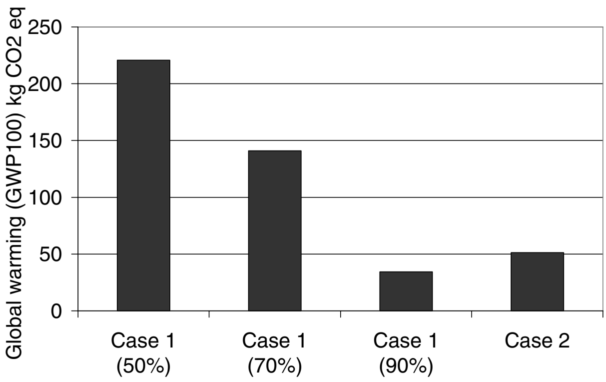

Figure 6 Sensitivity analysis of the variation in global warming impact with lower (50%) and higher (90%) copper removal rate in Case 1.

steel in Case 1 but which can be avoided in Case 2 due to the higher purity of these recovered metal fractions. It is important to note that the virgin metal added to dilute the recovered metal to an acceptable level of copper contamination adds to the total output of steel and stainless steel in Case 1. Because the avoided burdens of this output are subtracted from the total impact, the net effect of adding the virgin material as such is, however, zero. Only the additional impacts of the remelting of virgin steel to dilute recycled steel remains.

We can gain a better understanding of the underlying reasons for this improvement in Case 2 by examining the contribution of individual processes to the total impact of the system. As one might expect, energy generation dominates the contributing processes for both abiotic depletion and global warming, and energy use is reduced in Case 2, in which no energy is needed to remelt virgin steel in the recycling processes.

The results show that the increased recovery of copper is not important in itself, but the reduced copper contamination in steel and stainless steel is. The results imply that optimizing the recovery of secondary material through improved MH is beneficial not only in a "housekeeping" sense but also from an energy perspective. Minimizing energy consumption in all processes would accomplish the most in terms of mitigating the environmental impacts of the waste processing.

Sensitivity Analysis

To analyze the importance of the assumed copper removal rate without the prestep in Case 1, we modeled the rate as 50% and 90%, as compared to 70% in the base case (see figure 6).

The result of this sensitivity analysis illustrates the great importance of this key parameter. A 20% lower copper removal rate in Case 1 gives more than a 50% increase in global warming potential, whereas a 20% higher removal rate results in more than a 70% decrease in global warming impact. The impacts of Case 1 and Case 2 would be about the same if the removal rate in Case 1 could reach nearly 90%. Similar results were achieved for abiotic depletion potential.

Discussion and Conclusions

The aim of this study was to explore the potential of the proposed prestep, in the form of a targeted disassembly operation, to improve material recycling efficiency and to be environmentally beneficial in a life cycle perspective. The results lead to the conclusion that copper removal before shredding would be beneficial in a life cycle environmental perspective. This conclusion is based on the results of a limited LCA study that looks at two prioritized impact categories—global warming potential and abiotic depletion potential. The proposed prestep is generic and not geographically limited; it could be applied in many product groups to increase the amount of useful materials obtained after shredding. Because the entire dishwasher life cycle was not analyzed, no conclusions can be drawn regarding the net environmental impact of the take-back system for household appliances induced by the WEEE Directive.

Contributions

The main contribution of this study is to illustrate the clear benefits when the prestep results in less copper mixed with the recovered steel and stainless fractions. This results not only in higher yields in terms of displaced new copper production but also in less contaminated steel and stainless steel. As a matter of fact, this leads to the most significant environmental improvement of the system. A study performed in Switzerland by Hischier and colleagues (2005) showed that recycling of products mentioned in the WEEE Directive is environmentally beneficial in a life cycle perspective. The authors did, however, argue that sorting and dismantling are of minor interest because the major environmental impacts occur further downstream in material recycling. We want to emphasize, on the contrary, the importance of sorting and dismantling operations. When a targeted disassembly operation, such as the proposed prestep analyzed in this article, is introduced, operations further downstream may be optimized to achieve reduced environmental impact.

Studies by Mayers and colleagues (2005) and Barba-Gutiérrez and colleagues (2008) on the impacts of EPR legislation for waste electronics argued that the environmental impacts may in some cases in fact increase. Mass-based targets for collection and recycling were identified by Mayers and colleagues (2005) as a serious obstacle to optimal system solutions. Our results support this view. Despite the obvious benefits of targeted disassembly of the type exemplified by the prestep in this study, mass-based targets give little or no incentive to either designers or waste treatment companies to facilitate or perform such operations.

Besides, as scrap recycling currently works in practice, there is little incentive for companies working with WEEE to improve the MH by implementing additional operations, such as the prestep analyzed in this study. Practical obstacles are, for instance, the pricing of scrap. More differentiated pricing, which reflects better the quality of scrap, could give an incentive to implement better processes.

Uncertainties

The results of this study rely to a large extent on two important assumptions: dilution of recovered metal with virgin metal, and the copper removal rate in Case 1. We included dilution with virgin metal to take into account the difference between the two cases with regard to recovered steel and stainless steel quality. When too much copper is mixed in the recovered steel fractions, virgin steel is added to reach a required maximum level of copper contamination. This represents a case in which high-quality steel products are produced from scrap steel. This would not always be the case. If low-end steel products were produced, the quality requirements would not be so strict as to require dilution. Nevertheless, dilution of scrap metal with virgin steel is done in practice, as was described by Johansson (2009). Hence, the modeled case represents a realistic, but not the only possible, case.

The copper removal rate in Case 1 is important because it affects the need for dilution of recovered steel and stainless steel. This was analyzed in a sensitivity analysis, which showed the importance of this assumption for the total results but also that the impacts of Case 1 and Case 2 would be about the same if the removal rate in Case 1 could reach nearly 90%. If techniques are established that achieve this high removal rate without disassembly as a prestep before shredding, it would be preferable at least for practical reasons and possibly also for economical reasons. With current practices this is, however, not likely. In addition, the prestep would be a more "foolproof" solution. Considering the high sensitivity of the removal rate, under current conditions this would be the recommended solution from a life cycle environmental point of view.

Recommendations

In Sweden the financing of WEEE handling and treatment is based on producers' market shares. With this practice, virtually no feedback exists in this system. The outcome of recycling would benefit from the adaptation of new products to the recycling system and vice versa. The prestep operation presented in this article is part of the MH concept. To achieve increases in outcome, manufacturers must design products with disassembly operations, such as the analyzed prestep, in mind. Johansson and Luttropp (2009) presented practical design suggestions for dishwashers that would enable an effective prestep to take place. One suggestion is to keep electrical components, motors, and the like connected physically so that they can be removed in one operation. This design feature is already present in certain dishwashers in the current waste stream, although probably not to facilitate disassembly but rather for ease of assembly during production. This kind of mutually beneficial design solution is important for the successful implementation of a prestep.

The results highlight the fact that in the end-of-life phase of the dishwasher life cycle, energy generation is an important source of environmental impact. Thus, the benefits of material recovery are twofold; not only is less virgin material required, but also less energy is needed to make secondary material into new products. Hence, we stress the need to implement energy-conservation measures in waste processing and material recovery and recycling processes.

The economic feasibility, which was not explored in this study, would partly be determined by the work intensity of the manual disassembly prestep as compared to the current case. This step was estimated to take 10 min per dishwasher. This is a conservative estimate based on practical experience we gained when performing the case study described by Johansson and Luttropp (2009). With a prestep, no manual picking after the shredder would be required. Hence, it is not unrealistic to assume that roughly the same workforce would be needed.

The results presented in this article should be viewed as a contribution to the general discussion and policy making related to WEEE recycling. Our results indicate that the MH concept is a sound guiding principle and that better separation would be worthwhile from an environmental point of view.

Notes

1. One kilogram (SI) ≈ 2.2 pounds (lbs).
2. One megajoule (MJ) = 10^6 Joules (J, SI) ≈ 239 kilocalories ≈ 947 British Thermal Units.
3. The term *tonne* refers to metric ton. One tonne = 10^3 kilograms (SI) ≈ 1.1 short tons.

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