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A conceptual chemical process for the recycling of Ce, Eu, and Y from LED flat panel displays

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ABSTRACT

The popularity and rapid obsolescence of electronic devices and products leads to many of these items eventually ending up in various waste streams. Understanding the tradeoffs in processing end-of-life E-waste materials for reuse is an important part of informing decision-makers who are considering recovery and recycle of these materials. An example study presented here is the recovery and recycle of rare earth metals in the light emitting diodes (LED) found in the backlighting unit for liquid crystal displays (LCD) of flat panel televisions. A conceptual and defined commercial-scale process for recycling E-waste is described, including the recycle of rare earth elements from the LED module. Synthesis of a full process, from display dismantling to rare earth separation, is proposed based on engineering principles and fragmented literature. The synthesis defines a process flow diagram, complete with mass and energy transfer modeling. Such a detailed commercial scale process model for recycling rare earth elements provides an advance to the science. Rare earth elements are critically important, but are low-quantity materials in many electronic items. Providing a process model for their recycle is an essential first step towards a sustainability analysis, with social, economic, and environmental implications.

1. Introduction

The popularity and potential environmental impacts due to electronic products have led to strong interest in product design (Electronic Product Environmental Assessment Tool (EPEAT), 2016), the disposition of used electronic products (U.S. International Trade Commission, 2013), the management of electronic waste (U.S. Environmental Protection Agency, 2017, 2013), and improving reuse and recycling (U.S. Department of Energy, 2017). Used electronic products also represent an opportunity, either for reuse or the value of their component materials, especially their rare earth elements (REEs). Additional factors are also of importance, for example, drivers dictating whether to have supplies originate from virgin or reclaimed feedstocks, the availability of REEs in nature, accessibility to these source locations in the global arena, the likelihood of obtaining those materials, complex mining and recovery processes, the value and supply of pure REEs and rare earth oxides (REOs), end-of-life scenarios for waste electrical and electronic equipment (WEEE) collection and recycling (Ardente et al., 2014), the availability of REE recovery processes, the economic feasibility of these processes (Chancerel et al., 2015), and the price and demand for these reclaimed REEs and REOs in the market. As evidenced by Binnemans et al. (2013) and the (DOE) Department of Energy's Critical Materials Strategy report (U.S. Department of Energy, 2010), these identified factors are complex and directly interconnected.

Coupling the above with the introduction of Sustainable Material Management (SMM) approaches which reduce environmental impacts, resource use, and costs, calls for an analysis of the supply chain of an electronic product and for increasing the sustainability of activities within the supply chain. Within the context of a life cycle perspective for studying the recovery and recycling processes for used electronic products, an in-depth examination of end-of-life (EOL) process options can provide important insights. These EOL processes can have significant resource use and environmental releases, as well as significant economic costs. However, in the case of recycling, these processes may also prevent the use of resources, environmental releases, and other costs. Understanding the tradeoffs in processing used electronic materials for reuse is an important part of informing decision-makers who are considering the recovery and recycle of these materials. An example study presented here is the recovery and recycle of rare earth metals found in the light emitting diode (LED) backlight unit (BLU) for liquid crystal displays (LCD) of flat panel televisions (TVs).

Of particular interest is how to recycle the BLUs and their valuable rare earth components. This conceptual recycling process does not consider the use phase, which can be important for the overall performance of lighting (U.S. Department of Energy, 2012). A further detailed analysis of a flat panel display is presented by Meyer et al. (2017),

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where the authors conduct a life cycle assessment (LCA) to consider the overall mining, manufacturing, use, recycling, and disposal for the REEs used within an LED BLU present in a LCD flat panel display. A recycling process for a LED backlighting unit, never before described in detail, is defined and evaluated here. Background information on conceptual process designs for recycling LEDs are described in the Appendix. In this contribution, a detailed process flow diagram, including mass and energy balances, for recycling a LED backlight unit is presented.

1.1. Sustainability

As one considers the three pillars of sustainability: environment, economic, and social, the recycling of WEEEs will touch upon all three. There are social aspects that are important in the discussion as to whether processes can be put in place for extracting virgin materials and for recycling existing ones. Communities, from small neighborhoods to nationwide, need to decide that extraction or recycling are desirable processes. One could also argue a social need for independent production of some REE materials. Also in the social sphere are health impacts that need to be considered.

Environmental issues can be analyzed through overall evaluations like LCA, and also for the process associated with the production or recycling of a WEEE with a tool like GREENSCOPE (Ruiz-Mercado et al., 2017). Many environmental indicators are available through these methods, and studying the results and acting to improve areas of unsustainability will result in better and more sustainable processes. The results of environmental analyses may have to be compared on a relative basis, as there may not be a solution without undesirable releases.

The greater goal of this work is to develop a conceptual design for a commercial scale recycling process that meets the ability to recover valuable materials found in WEEEs and to do it in a sustainable manner. To begin this endeavor, this work first identifies the process system under evaluation and establishes the system boundaries under consideration. This is much more easily said than done. If a process does not exist, then one must be developed and detailed before it can be evaluated. But, the process must also be developed with an evaluation method in mind. For this conceptual process, the authors will utilize the GREENSCOPE methodology for establishing the process level detail needs, as well as system boundaries and constraints. Providing a process flow diagram and model for the recycle of REEs is an essential first step towards a sustainability analysis, with social, economic, and environmental implications. Utilizing developed process level information for this sustainability evaluation then follows.

GREENSCOPE is a methodology and on-line software tool for the evaluation and design of sustainable chemical processes, including recycling processes. GREENSCOPE incorporates nearly 140 indicators in four areas: environment, economics, efficiency, and energy, to evaluate existing or potential processes for the generation of various products (Ruiz-Mercado et al., 2012a). The results of GREENSCOPE provide indicator analyses which show the relative strengths and weaknesses of processes, including showing areas of high performance and where improvements could be made.

There are many GREENSCOPE indicators that can be relevant to a recycling process. For instance, the efficiency of mass and energy use is available in a number of indicators. Other indicators represent the releases of toxic pollutants, global warming gases, ozone precursors, etc. In addition, another set of indicators show the economic results, either as net present value, discounted cash flow rate of return, payback period, etc. While these indicators will be evaluated in future analyses, the data needs for the indicators (Ruiz-Mercado et al., 2012b) motivate establishing the mass and energy balances, equipment, inputs, and releases in this work.

2. Materials and methods

2.1. Flat panel display collection, dismantling, and separation

Existing consumer products contain the greatest supply of rare earths, thus having the largest recycling potential (Meyer and Bras, 2011). This indicates that a collection or recycling infrastructure and operations could be desirable (U.S. Environmental Protection Agency, 2012). The recycling process for post-consumer, end-of-life WEEE articles generally consists of four steps: collection, dismantling, separation (i.e., preprocessing), and processing.

2.2. Description and collection of flat panel displays

Given the complex nature of electronic articles, the multitude of designs and technologies used for each product, and the many options that can be chosen when recovering and recycling materials, a number of assumptions have to be made regarding the flat panel displays and their collection. For the analysis completed here, the following assumptions were made:

- All flat panel displays collected and recycled are based on LCD-LED technology
- Collection of the flat panel display occurs off-site and the displays are transported to the recovery and recycling facility and arrive as a whole entity
- A completely manual dismantling process of the display is performed
- All resulting material streams are manually separated and sorted
- The materials, compositions, and masses are based on an industrial average of 17 LED-LCD flat panel TVs (55″) from 6 manufacturers (Meyer et al., 2017)
- Only REE based materials are recycled within this conceptual process. All other materials, such as plastics, metal, glass, etc., are handled using other well-established recycling and reuse processes.

Establishing these assumptions is an important step in evaluating a REE recycling process (i.e., EOL stage), which is dependent on operating costs, product(s) revenue, and the implemented recovery/recycling process.

2.3. Dismantling and separation

Upon arrival of a flat panel display at the recovery and recycling facility, the panels begin the dismantling process. Although automatic, semi-automatic, and manual dismantling processes exist, in this study a completely manual process is assumed. While this type of method is more costly, involves more labor-hours and number of employees, the benefit of using this approach is the ability to recover more components from the display and produce more homogeneous feedstock streams (e.g. cables, printed circuit boards (PCB), plastics, etc.), as well as maintaining component integrity for potential reuse and preventing accidental destruction of a component. Fig. 1 provides an illustration of the parts and types of materials that can be obtained upon dismantling a LCD-LED flat panel display.

The average LCD-LED flat panel display unit (shown in Fig. 1) is comprised of a plastic housing, cables and wiring, metal chassis, power supply and circuit boards, and an LCD-LED module. Additional parts include speakers, screws and fasteners, and other mixed plastic parts. While the list of materials can be categorized into groups such as plastics, metals, and other materials, the structural and technological design of flat panel displays offer challenges in developing efficient recycling processes. Thus, it is imperative that Design for Recycle (DfR) and design for end-of-life approaches are considered during the product design phase (Elo and Sundin, 2014). Reusing parts is presented as a favorable approach for end-of-life use of materials in Fig. 1.