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Is Economic Value an Effective Proxy for Embodied Energy and Environmental Impact in Material Systems?

Jeremy Gregory, Susan Fredholm, and Randolph Kirchain

Abstract— This paper uses economic value metrics to evaluate the retention of value of secondary materials and provides a framework for characterizing value throughout a material and product life-cycle. These economic value metrics are compared with analogous life cycle assessment metrics in order to determine the conditions under which economic value effectively represents environmental impact for EoL material recovery decision-makers. A comparison of these metrics using several different material types indicates that there is a strong correlation between LCA metrics and economic value metrics for most of the materials studied. However, there were a few cases in which the economic value metrics were poor indicators of the LCA metrics.

Index Terms—Life cycle assessment, metrics, economic value, recycling

I. INTRODUCTION

LIFE-CYCLE assessment (LCA) has proven to be a valuable tool for evaluating embodied energy and environmental impact in products, processes, and material systems [1]. However, conducting an LCA has been widely cited as complex, time-consuming, and, therefore, expensive [2]. These factors make LCA inaccessible to many stakeholders, and more broadly for many decision contexts, even where some LCA exists. This inaccessibility is currently true for the stakeholders and context that serve as the focus of this document: operational and tactical decisions made by stakeholders within material recovery systems. Unlike product design cycles, which can last several years and afford time to do detailed LCA studies, decision-makers in material recovery systems must deal with constant variation in incoming end-of-life (EoL) products and market demand for secondary materials and products. They have few practical methods available to evaluate the expected performance of the

Jeremy Gregory is with the Materials Systems Laboratory and the MIT Energy Initiative, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (phone: 617-324-5639; email: jgregory@mit.edu).

Susan Fredholm is an alumna of the Materials Systems Laboratory and the Engineering Systems Division at the Massachusetts Institute of Technology. She is now with PE Americas, Boston, MA (email: s.fredholm@pe-international.com).

Randolph Kirchain is with the Materials Systems Laboratory and the Department of Materials Science and Engineering and the Engineering Systems Division, Massachusetts Institute of Technology (email: kirchain@mit.edu).

many different strategies to materials recovery (e.g., should recyclers focus on high volume materials like plastics or scarce materials like platinum group metals).

In light of this need, two key research questions emerge: Is there information that is accessible to these stakeholders that could serve as a proxy for LCA to better inform their decisions, and when would it be appropriate to apply this proxy?

Economic value is clearly information that is readily available for materials recovery stakeholders. Furthermore, economic value of materials reflects, at least in part, the quality¹ of the material, the cost of production or use (including energy consumption), and scarcity rents for current use of that resource [3]. Indeed, many life cycle impact assessment methods, such as Eco-indicator 99 [4], consider some of these same issues. Thus, EoL material recovery metrics that include changes in value may provide significant information about the effectiveness with which resources are reclaimed and returned to productive use, providing an indicator of both retained quality and environmental impact.

This paper explores this connection between economic value and environmental impact by describing a framework for characterizing value change throughout a material and product life-cycle and then using economic value metrics to evaluate the retention of value for selected material recovery systems. These economic value metrics are compared with analogous LCA metrics in order to determine the conditions under which economic value effectively represents environmental impact for EoL material recovery decision-makers.

The broader research agenda is to explore whether readily available information can direct environmental decisions and whether market behaviors lead to lower environmental impact. The specific research question addressed here is: Can the use of economic value metrics lead to environmentally informed decisions?

II. LCA AND ECONOMIC VALUE METRICS COMPARISON

LCA metrics in this study were predominantly calculated using SimaPro software [5] and the ecoinvent [6] and Franklin USA 1998 [7] databases; the evaluation methods were

¹ Quality is used broadly to mean the state of the bundle of all physical properties associated with a material or semi-finished good from which intermediate processors or end-consumers derive utility.

Cumulative Energy Demand (CED) [8] and Eco-indicator 99 (E) [4]. Additional energy data was also obtained from published literature. The products chosen for this analysis are primarily composed of a single material. They were also chosen because LCA data for both their primary and secondary production was readily available. The primary production of a product refers to a product's manufacture from predominantly virgin raw materials. When available, the authors selected data that represented production from 100% virgin resources. For some materials systems this is rare (e.g., steel) and so more typical processes, relying predominantly on virgin resources were used as a proxy. The secondary production of a product refers to the ideal case in which 100% of the product's material is obtained from old scrap, or recycled products.

The relative levels of primary and secondary environmental impacts were compared using the metric:

$$E_{\text{Avoided}} = \frac{E_{\text{primary}} - E_{\text{secondary}}}{E_{\text{primary}}} \quad (1)$$

where E is some metric of environmental impact or energy consumption. Calculated values of E for a selected set of five single-material products are shown in Figure 1. Cumulative Energy Demand and Eco-indicator 99 (EI99) values are nearly identical for all of the products studied except copper wire. This indicates that energy consumption is the dominating factor in environmental impact for the primary and secondary materials evaluated, with the exception of copper. The discrepancy between the CED and EI99 E_{Avoided} copper values is due to the fact that the EI99 considers copper to be a scarce material and places a high importance on scarcity, which drives up the E_{primary} values.

Three points in each product's lifecycle are used in the calculation of the economic value metrics [9]. Figure 2 shows

the general trend of how a material's value changes at various stages in its life. The first value used in the metric calculation, V_3 , is that of the primary material in ingot, or equivalent pre-manufacturing form. The second value, V_6 , refers to the product at its end-of-life, the point at which a consumer is no longer willing to use the product in the manner in which it was originally intended. Finally, V_7 is a value after a separation or other recycling recovery step. In comparing this final value to the two previous values, both the value the recovery added to the product, as well as the percentage of the original material value the product has retained, can be calculated. The value added and value retained are mathematically defined as:

$$\text{Value Added} = \frac{V_7 - V_6}{V_3 - V_6} \quad (2)$$

$$\text{Value Retained} = \frac{V_7}{V_3} \quad (3)$$

These equations represent the ideal scenario for single material products. Each term in the equations can be mass-weighted to account for changes in the available mass of a material over the course of its lifecycle and also to account for multiple materials used in the same product [9]. The ideal, single material scenario is used here to test the correlation between value metrics and traditional environmental metrics.

The value metrics calculated for the same selected set of single material products analyzed using LCA are shown in Figure 3. Value Retained metrics are slightly higher than Value Added metrics for all materials, which is consistent with the definition of the metrics: the numbers in the Value Added metric are the same as those in the Value Retained metric, but are reduced by the end-of-life value, V_6 . The relative values for the five materials are similar to the LCA metrics in Figure 1.

The LCA metrics are plotted against the economic value

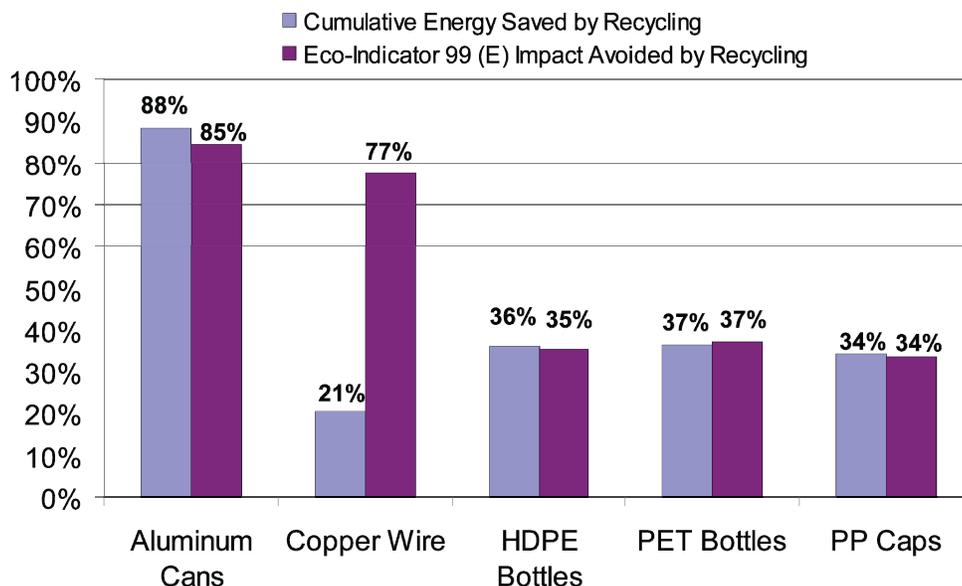


Figure 1. Example LCA metrics of energy or environmental impact avoided by secondary materials recovery.

metrics for all materials analyzed in Figure 4, including those plotted in Figure 1 and Figure 3. Multiple data points for the same material in the upper-two Energy Saved plots indicate that multiple data sources were available for the material and listed different energy consumption data; the same economic value data are used for the material. Several materials are absent from the Eco-indicator 99 plots because of a lack of complete LCA datasets for those materials.

Generally, there appears to be a strong correlation between the value change and both of the two types of environmental impact metrics as most data points fall near the line of equality. This suggests that market behavior is moving in parallel with environmental impact for these materials decisions. As energy requirements are naturally reflected in prices, the apparent correlation between the energy saved metric and the value metrics is unsurprising. However, the correlation appears to be even stronger between the environmental impact LCA metrics and the value metrics. This suggests that the resource scarcity included in the environmental impact LCA metrics, but not the energy metric, also plays a significant role in influencing material pricing.

The position of a material in the lower right half of the graph suggests that the material has a relatively high secondary value and may even be overpriced (e.g., copper). Despite lower energy and environmental savings, these materials are being recycled due to the economic gains available. Secondary materials which have a relatively high avoided environmental impact yet retain little economic value fall in the upper left portion of the graph. Given their low economic position, materials which fall in this region are unlikely to be recycled without policy intervention. Even products which did not fall into this region before recycling

policies were implemented could move to the left of the graph and into this area, if they result in the creation of a supply of secondary materials which exceeds demand, thus lowering the price of the secondary material. The majority of lead produced each year is used in the production of lead-acid batteries, a product for which recycling is often mandated. This intervention leads to a relatively high availability of secondary copper and, therefore, a relatively depressed price for secondary copper. In light of this, it is unsurprising that lead falls in this upper left region given the policies surrounding its end of life treatment. Newspaper is another example of a material that lies in the upper half of the graph. The low end-of-life economic value is partially driven by a supply from municipal collection programs that exceeds demand.

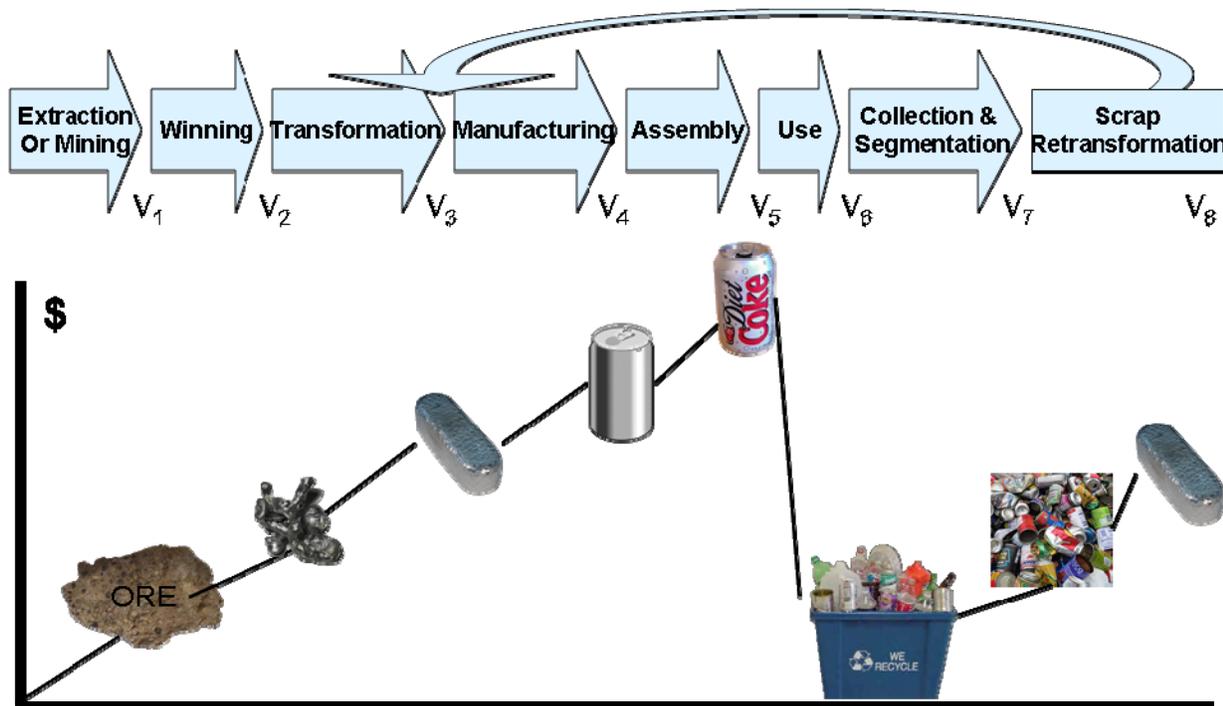


Figure 2. The economic value of a material changes throughout its lifecycle.

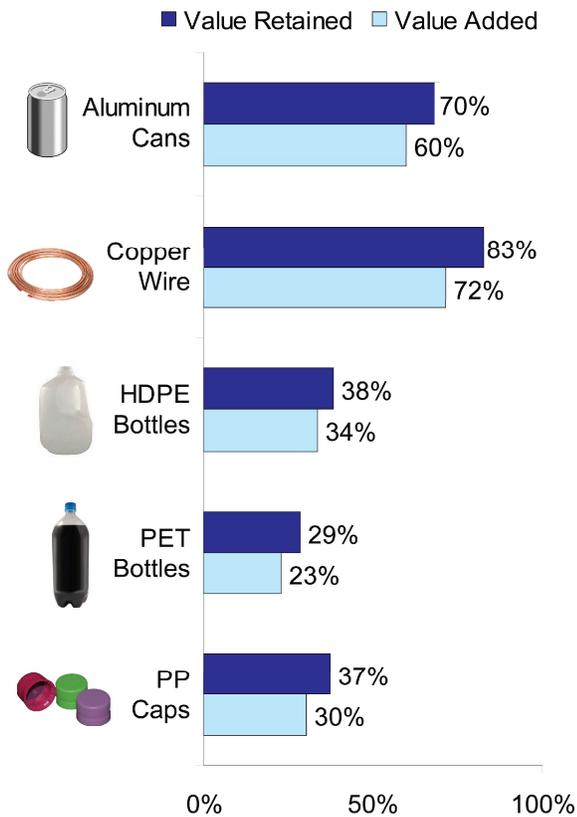


Figure 3. Examples of Value Added and Value Retained from material recovery.

III. CONCLUSIONS

This preliminary work has shown that there is a strong correlation between LCA metrics and economic value metrics for most of the materials studied. This suggests that market behavior is moving in parallel with environmental impact for materials decisions. However, there were cases in which the economic value metrics were poor indicators of the LCA metrics, particularly for materials where policies are in place to improve collection rates. In addition, variation in reported energy requirements data for certain materials contributed to uncertainty about the correlation with LCA metrics for those materials. Ultimately, the correlation for the LCA and economic value metrics was strong across several classes of materials, including plastics and metals. Interestingly, the correlation appeared to be even stronger between the environmental impact LCA metrics and the value metrics. This suggests that the resource scarcity included in the environmental impact LCA metrics, but not the energy metric, also plays a significant role in material pricing.

The results presented in this work are also promising for the use of economic value metrics as a mechanism for tracking the effectiveness of a material recovery system and for informing operational and tactical decisions in that industry. Nevertheless, the variation in these results suggests that there are some cases where this may be inappropriate and that more work needs to be done.

An outcome of this work is an evaluation of the relative

merits of the LCA and economic value metrics. The advantages and disadvantages of each set of metrics are listed in Table 1.

TABLE 1. ADVANTAGES AND DISADVANTAGES OF LCA AND ECONOMIC VALUE METRICS.

	LCA Metrics	Economic Value Metrics
Advantages	<ul style="list-style-type: none"> • Detailed and Flexible • Directly accounts for environmental impacts including scarcity and toxicity 	<ul style="list-style-type: none"> • Uses readily available data which is frequently updated • Easy to calculate • Easily comprehensible
Disadvantages	<ul style="list-style-type: none"> • Expensive • Requires value judgment on environmental priorities • Requires extensive detailed knowledge to conduct and interpret 	<ul style="list-style-type: none"> • Does not directly incorporate environmental data • Policies do not influence all material metrics evenly

Future research in this area will include the investigation of other materials, particularly those which would be expected to deviate from the trend of correlated LCA and economic value metrics (perhaps due to toxic content). In addition, complex products with commingled materials will also be evaluated using LCA metrics and mass-weighted economic value metrics. Finally, it will be important to evaluate the impact of the inherent volatility in materials prices on the use of metrics like those described herein.

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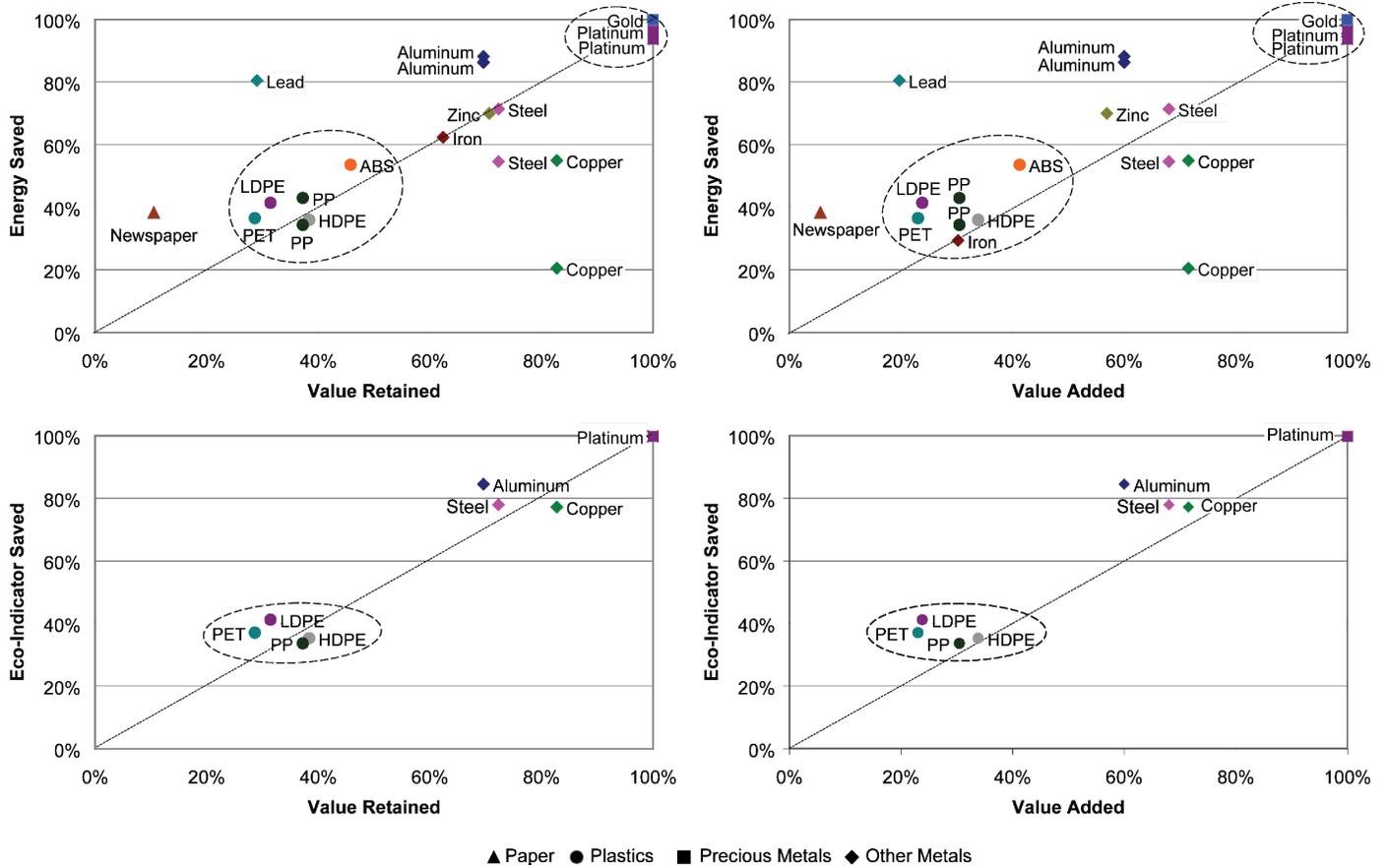


Figure 4. Environmental impact LCA metrics versus economic value metrics.