Where Has All the Copper Gone: The Stocks and Flows Project, Part 1

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“The quantitative assessment of stocks and flows of materials throughout the technological cycle, from resource extraction to final disposal, can inform resource policy, environmental science, and waste management. This paper describes the technological cycle of copper based on work by the Stocks and Flows Project of the Yale Center for Industrial Ecology. Of copper produced in the 20th century, as much as 85% remains in use today. The recycling rate, while high, leaves nearly as much in waste destined for disposal (e.g., over 40% in the United States). The copper in production wastes currently approaches the quantity in post-consumer wastes, but the latter will dwarf the former over time as large in-use stocks reach end of life.

INTRODUCTION

Discussions of resource availability have been dominated by debates between cornucopians, optimistic about the prospects of meeting the need for materials and energy, and Malthusians, anxious about the specter of scarcity. The former look to the incentives provided by the market to locate new reserves, increase the efficiency of extraction processes, and identify feasible substitutes. The latter worry that, in spite of a historical record of expanding resource availability, growing economies and rising populations will nonetheless overwhelm the resource base. This debate can be resolved only by Malthusian catastrophe, an unlikely event in the near term.

More can be understood about resource availability, however, by looking beyond the question of the size of virgin deposits to questions of how resources are used and where they end up when society is done with them, a more nuanced picture can be drawn. A comprehensive analysis of the entire materials cycle from extraction to discard, to reuse or disposal (termed materials flows analysis or MFA) is key. An MFA can identify novel repositories of resources, provide the foundation for more accurate forecasting of waste management challenges—and opportunities—and complement narrower, more detailed analysis in environmental science.

This article describes the work and some of the findings of the Stocks and Flows (STAF) Project at the Center for Industrial Ecology of the Yale University School of Forestry & Environmental Studies. This project, funded primarily by the U.S. National Science Foundation, was originally motivated by the question, “Should we mine the landfills?” That question remains, but is now supplemented by others such as “Does materials flow analysis generate important or novel insights?” and “Is resource policy overlooking some key considerations?”

The STAF project is using this approach to investigate copper, zinc, and other metals. Plans are underway to examine construction timber and a plastic resin. The technological cycle for copper, that is, the flows from mine to mill to smelter to product manufacturers to users to end-of-life disposal, are described in this article. (When an MFA is focused, as in the STAF project, on individual substances or materials, rather than groups of materials, it is sometimes also called a substance flow analysis or SFA.) The cycles are characterized on a global basis, using data from all seven continents.

Unless the system is in steady state—which never occurs—stocks
accumulate or are drawn down at each stage of the life cycle. Some metal recycles one or more times before final disposal. If we knew how fast copper flows between each stage of this cycle, and how much has accumulated in each reservoir, we would know:

- Where to look in the future for more metal (should new metal become costly). This is the “should we mine the landfills” question.
- Where to look for “leakages” into the environment. This provides contextual, quantitative information to complement much more precise, but more narrowly focused studies of fate and exposure in environmental science.
- How much metal could enter future flows, such as the recycling and waste streams, due to changes in the contents of the reservoirs. This, in turn, could provide the basis for forecasting models for waste management.

For non-metals that contain carbon, an MFA as outlined in this article can inform investigations of anthropogenic carbon use and storage in discussions of climate change.

Analysis of the stocks and flows of anthropogenically important materials can indicate not only how much and for what purpose a material has been used, but also where the reservoirs of materials might be located. This spatial dimension of an MFA is also described in this article.

**HISTORICAL USE OF COPPER**

A major motivation for addressing these questions is humanity’s burgeoning rate of use of materials. An example, typical of almost any industrial material, is the use of copper in the last three centuries, shown in Figure 1. Integrating the rate of copper use over time quickly demonstrates that the 20th century accounted for about 90% of all copper mined and put into service throughout five millennia of human history, 70% of it in only the last 50 years, and 50% in only the last 25 years. This increase in use occurred in spite of the transfer of many services originally performed by copper to other metals such as aluminum. Where is the copper now?

**CHARACTERIZING THE COPPER CYCLE**

The research method necessarily draws on data of variable quality and quantity obtained from diverse sources, such as government agencies, trade associations, market research firms, and the research literature. These data must be assembled into a complete technological cycle. The best flow data are for metal production; the sparsest are for end-of-life disposal. There are no data on in-use stocks in most applications; these stocks are determined by integrating the flows over time, that is, by estimating production rates and product life spans, and calculating the resulting accumulation of copper-containing products at various stages of the product life cycle. (Alternatively, one can approach this determination by making direct measurement of concentrations of copper in typical repositories such as residences and automobiles.) Sometimes proxy indicators based on knowledge of particular processes or products have to be used.

The underlying challenge in this