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Resource efficiency in the German copper cycle: Analysis of stock and flow dynamics resulting from different efficiency measures

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ABSTRACT

In the context of the increasing depletion of finite natural resources and associated environmental and social problems, it is vital for societies to understand the drivers of resource demand and develop strategies to reduce its negative impacts. One such strategy is the move towards a circular economy, in which linear industrial systems are turned into circular systems where former waste streams from one part of the system can act as inputs in other parts. This includes the substitution of primary with secondary materials, thus reducing some of the negative impacts of primary production. The extent to which this is possible depends on the amount of retired material stocks that are made available for re-use. This article develops a methodology for analyzing material flows in relation to the wider economic system for the special case of copper. For this, a macroeconomic simulation model and a substance flow model are coupled to determine sectoral copper demand on the one hand, and the availability of secondary copper on the other hand. A number of scenarios aimed at reducing primary copper demand or increasing the supply of secondary copper are modeled. The results vary considerably between scenarios, depending on which material efficiency measure is analyzed. Due to delays in the retirement of copper stocks, trade-offs can be observed between reductions of original material demand and the availability of secondary material.

1. Introduction

Raw materials are essential inputs for the world's economies. Along with continuing economic growth, many world regions have shown a growing demand for raw materials. However, resource extraction is often accompanied by a number of economic, ecological and social issues. Some countries, including Germany, have therefore developed material efficiency strategies, which among other things aim at reducing the primary material input of the economy (BMWi, 2010; Bundesregierung, 2016; European Commission, 2011, 2015). Next to absolute reductions in input requirements, e.g. in the form of lightweighting, or substitution of materials with high environmental footprints, the increased use of secondary material is a widely discussed technical option.

Particularly for metals, a higher efficiency in recycling is relevant from both an economic and an ecological point of view. Regarding the former, Germany as well as most other western economies strongly depend on imported primary materials, making their industries vulnerable to both high material prices and potential supply disruptions (Bach et al., 2017; Erdmann and Graedel, 2011; Glöser-Chahoud et al., 2016). Furthermore, the substitution of imported primary materials with domestic recycling materials holds opportunities for additional value added (Mitchell and James, 2015). Regarding the latter, mining activities are accompanied by high ecological impacts and energy consumption (Ayres, 1997; Norgate and Haque, 2010; Nuss and Eckelman, 2014). This effect is reinforced by decreasing ore grades and, as a result, increasing specific energy demand and environmental exposure (Frenzel et al., 2017; Springer, 2017; van der Voet et al., 2018).

Even though recycling also has ecological limits as energy demand increases with decreasing scrap quality and material contents in obsolete products, there still is significant potential for improvement in

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the circularity of industrial metals (Reuter et al., 2013; Reuter and van Schaik, 2012). In the case of copper, energy demand for recycling depends on scrap quality and is estimated to be up to seven times lower than primary[1] material production (Rankin, 2012). Next to energy consumption, further ecological impacts of conventional copper recycling are far below those of primary production (Nuss and Eckelman, 2014).

The potential to use secondary material in production processes depends, however, crucially on its availability. Material Flow Analysis (MFA)[2] is a suitable approach for assessing the availability of secondary material since it tracks materials from the point of entry into economies, their processing, use and storage over product lifespans, and eventually their recycling or disposal (Chen and Graedel, 2012; Müller et al., 2014). Within MFA, material flows are, however, mostly not recorded in relation to the wider economic system. One reason for this is a lack of data sets using suitable product or sector classifications, while theoretically suitable data sets, such as the European PRODCOM[3] database, often contain sizeable gaps (Tukker et al., 2006). Another reason is the divergence between material flow and economic accounting principles. In sum, as Gravgård Pedersen and de Haan (2006, p. 28) note, “in economy-wide material flow accounting, the economic system itself remains basically a black box.”

However, the physical system and the economic system are not independent of each other; the use of materials is driven by economic activity while the economy depends on material inputs (Duchin, 1992; Kytzia et al., 2004). In other words, there is a “coupling between the physical and the monetary layer of industrial systems” (Pauliuk et al., 2015). Therefore, a detailed understanding of the interplay between material flows and economic dynamics is necessary in order to be able to inform policies related to raw material use. This is particularly true on the level of individual economic sectors, which have differing material requirements but are interconnected and thus exchange materials along their respective supply chains.

A suitable way of portraying economic dynamics at the sectoral level and the interconnectedness of sectors within an economy are macroeconomic models based on input-output tables, such as E3ME (e.g. Barker et al., 2015), GEM-E3 (e.g. Fragkos et al., 2017), ENGAGE (e.g. Winning et al., 2017) or GINFORS (e.g. Distelkamp and Meyer, 2017). They allow for the calculation not only of direct but also of indirect deliveries between sectors, and corresponding material requirements. However, the commonly available input-output tables are generally highly aggregated and therefore by themselves unsuitable for a detailed analysis of material or substance flows (Weisz and Duchin, 2006).

To address the respective shortcomings of MFA and input-output analysis, and to be able to portray the interconnection between the physical and the economic layer, hybrid approaches have been developed (see Suh and Kagawa, 2005 for an introduction, and Duchin, 1992; Konijn et al., 1997 for early work in this area). Conceptual contributions in this area have been made by Bailey et al. (2004a,b), Joshi (2000), Lenzen (2002) and Suh (2004). A recent overview of hybrid approaches to calculate material footprints is provided by Lutter et al. (2016). Such hybrid approaches generally consist of a combination of (top-down) input-output analysis and bottom-up approaches capturing material flows, such as life cycle assessment (LCA), and often analyze the material use of specific processes or sectors (e.g. Acquaye et al., 2011; Joshi, 2000; Nakamura and Kondo, 2002; Nakamura and Nakajima, 2005; Onat et al., 2014; Rodríguez-Alloza et al., 2015; Suh, 2004; Suh et al., 2004; Takase et al., 2005; Treloar et al., 2000; Watanabe et al., 2016; Wiedmann et al., 2011). Fewer studies have been conducted at the economy-wide or regional level (e.g. Lindner and Guan, 2014; Liu et al., 2012; Schoer et al., 2012).

The majority of these approaches are static and thus only provide information on the physical and monetary *flows* within one accounting period, which is typically one year. The *stocks* which thereby accumulate and stock variations over time between and within individual product groups are thus not covered in these static analyses (Pauliuk et al., 2015). This makes the treatment of secondary material problematic since its use can only be based on *demand* (e.g. through fixed shares between primary and secondary material as production inputs) but not on actual *availability*. In dynamic models the latter can be determined through the calculation of recycled material from retired stocks (Glöser et al., 2013; Pauliuk et al., 2017, 2015; van der Voet et al., 2002). At the same time, future material demand can be informed by stock dynamics as retired stocks may (partially) need replacement. This would represent a ‘stock-driven’ approach, such as proposed by Müller (2006). The stock-driven approach assumes that stocks provide services to society and therefore have to be maintained or replaced through flows, thus reversing the logic of economic approaches where flows (e.g. investment) determine the development of stocks (e.g. fixed capital).

In this paper, we present a dynamic hybrid modeling approach for Germany, which couples a substance flow model for copper with a macroeconomic simulation model. Using the macroeconomic model as the driver of sectoral copper demand, the substance flow model calculates copper stocks for different applications and the corresponding amounts of recycled copper which become available as secondary material. This approach is similar to that of Pauliuk et al. (2017), who present a prospective simulation tool for steel flows and stocks, which they use to analyze different improvement scenarios. However, their focus is on the regional distribution and the losses of end-of-life steel throughout multiple product life cycles. In contrast, we primarily focus on the demand for primary copper in the German production system, which can be calculated as the difference between total copper demand and available secondary copper. We simulate a number of scenarios based on different assumptions regarding copper recycling rates, production efficiencies, product lifetimes etc. These scenarios also have an economic dimension in the form of investments, including operation and maintenance (O&M), and changes in the intermediate deliveries between sectors. This can be explicitly portrayed in the present model setup. It will be seen that different material efficiency measures can lead to considerably different trajectories of primary copper demand and secondary copper supply. Even though the implementation is data-intensive, the general approach can be applied to other materials.

The paper is structured as follows. Section 2 outlines the data and the respective methodologies used in constructing the substance flow and the macroeconomic simulation model. Section 3 first describes the analyzed efficiency scenarios and then discusses the effects on relevant variables. Section 4 concludes with a short summary and outlook.

2. Methods and material

2.1. The substance flow model for copper

We present a dynamic substance flow model for copper within Germany which captures annual material flows, including trade across system boundaries and stock accumulation in society. This model builds upon previous work on global and European copper flows with respect to the modeling approach (cf. Glöser et al., 2013; Soulier et al., 2018), and simulates the copper cycle beginning in 1950 in order to ensure a reliable accumulation of current stocks and development of waste

[1] We do not consider primary copper supply to be at risk since the static depletion time is within the time frame of the analysis (Tilton and Lagos, 2007). More information can be found in the supplementary material.

[2] Fischer-Kowalski et al. (2011, p. 870) use the acronym MFA for the related concept of Material Flow Accounting, which they call a more “descriptive” term than the “theoretically demanding” Material Flow Analysis, which as the name indicates, goes beyond accounting to also entail an analytical component. The authors point out that no well-defined distinction between the two uses exists.

[3] The PRODCOM (Production Communautaire) classification originates from a survey of manufactured goods at the European level (Eurostat, 2015).