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System Dynamics Modeling of Indium Material Flows under Wide Deployment of Clean Energy Technologies

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ABSTRACT

Clean energy technologies represent a promising solution to the global warming challenge. Many clean energy technologies, however, depend on some rare materials and concerns have been raised recently. Indium is one of these materials as it is critical for two emerging energy applications, that is, Copper indium gallium selenide (CIGS) photovoltaics (PV) and light-emitting diode (LED) lighting. This study analyzes the supply and demand of indium under different energy and technology development scenarios using a dynamic material flow analysis approach. A system dynamics model is developed to capture the time-changing stocks and flows related to supply and demand of indium over a 50-year time period, while considering carrier metal (i.e. zinc) production, price elasticity of demand, and indium usage in other applications (mainly liquid crystal display). Simulation results indicate that a shortage on indium is likely to occur in a short time period even under favorite case of indium supply. The rapid expansion of CIGS technology dominates indium demand in about 14 years, which outruns the growth of zinc mine production (thus indium supply). Sensitivity analysis suggests that model parameters related to solar PV market penetration, CIGS technology advancement, and price elasticity of indium demand have large effects on the total indium demand over simulation period. Eight scenarios combining projections on solar PV market growth, technology advancement, and zinc mine production are explored. It is observed that only under conservative estimates of solar PV market growth there is relatively enough indium supply to support the deployment. Even in these scenarios a shortage may occur toward the end of simulation.

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1. Introduction

Energy is one of the most important utilities for modern society, with demand continuously increasing as the world becomes more industrialized (EIA, 2015). A majority (87%) of global energy consumption relies on fossil fuels (BP (British Petroleum), 2013). The dependency on fossil fuels has raised serious concerns on global warming and climate changes. Clean energy technologies have emerged as a promising solution, which aims at utilizing renewable energy sources and improving energy efficiency. The Critical Materials Strategy Report by U.S. Department of Energy (DOE), however, pointed out that many clean energy technologies rely on rare materials (US DOE (U.S. Department of Energy), 2011). 16 materials (Li, Mn, Co, Ni, Ga, Y, In, Te, La, Ce, Pr, Nd, Sm, Eu, Tb, Dy) were analyzed in the report for their "criticality", which is determined in two dimensions, that is, importance to clean energy and supply risk.

One of the critical materials studied in the DOE report is indium. Indium is a post-transition metallic element that has an atomic number of 49. It is primarily used for producing indium tin oxide (ITO), a key material for manufacturing liquid crystal display (LCD) panels (USGS (U. S. Geological Survey), 2009c). Because ITO had been responsible for a majority of indium consumption and the demand from clean energy technologies has been minimal in the past, indium was reported as a near critical material in the DOE report (all the critical materials identified are rare earth elements) (US DOE (U.S. Department of Energy), 2011). Given indium, however, is needed in several fast growing clean energy applications, in particular thin-film photovoltaic (PV) and light emitting diode (LED) lighting (USGS (U. S. Geological Survey), 2012b), the material sustainability and criticality of indium should be closely examined.

In addition to the potential demands from clean energy technologies, the fact that indium is mainly produced as a byproduct of zinc mining and refining makes the indium supply-demand scenarios more interesting. One tool that could be used to analyze these complex scenarios is material flow analysis (MFA), which is an

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analytical methodology that quantifies the flow of a material of interest in a defined system. MFA has found applications in a wide range of applications, ranging from resource conservation, environmental management to regional material management (Brunner and Rechberger, 2004; Huang et al., 2012). Many studies in materials management, especially for metals, used MFA as a tool in various temporal and spatial boundaries. (Buchner et al., 2014; Bicanová et al., 2015; Leal-Ayala et al., 2015; Wang et al., 2015). MFA of indium has also been conducted in several researches. For example, USGS performed an analysis on indium material flows within the United States for year 2008 (Goonan, 2012). There are also MFA studies on indium with focus on flat panel display (Nakajima et al., 2007; Yoshimura et al., 2013). Traditional MFA analyses are largely "static", that is, they only show a snapshot of material flows within a determined boundary for a specified time period in the past. To study the future supply and demand of indium and how the material flows are affected by the wide deployment of clean energy technologies, a "dynamic" MFA is needed.

According to a review done by Müller et al. (2014), the methodology of dynamic MFAs was first developed by Baccini and Bader in 1996, with the first studies on metals published in 1999 for copper in the United States (Zeltner et al.,1999) and for aluminum in Germany (Melo, 1999). To date, there are more than 60 dynamic MFA studies on metals published (Müller et al., 2014). No standard methodology or protocol for dynamic MFA of metals, however, has been established: modeling approach, spatial/temporal scale, and system boundary vary from study to study. In general, stock and flow models are used for dynamic MFA and system dynamics (SD) simulation seems to be a powerful tool for this purpose.

SD can model complex dynamic systems for better understanding of non-linear behavior over time in a defined system (Matsuno et al., 2012; Morf et al., 2008; Hatayama et al., 2007; Kleijn et al., 2000). A handful of efforts have been made to adapt SD in dynamic MFA. Glöser et al. (2013) studied global copper flow using SD methodology. Pruyt an Delft (2010) developed a SD model for generic scarce minerals and performed sensitivity analysis to explore system behavior over time. Recently, Houari et al. (2014) developed SD model to predict tellurium availability for CdTe PV. It should be pointed out that this study did not consider the effects of market price on the supply and demand.

Dynamic MFA studies on indium have been rare. Zuser and Rechberger (2011) and Zimmermann (2013) analyzed the material demand and resource availability for metals (including indium) critical for PV industries, while considering PV market growth, material intensity, and material efficiency in production. Although being discussed, the issues of indium as a by-product from zinc mining and the competitive usage from electronics industry and other emerging technologies are not modeled. The most advanced (and most recent) study is the one by Stamp et el., in which indium demands related to the implementation of different energy system transition scenarios were simulated using SD (Stamp et al., 2014). The study considered the indium demands from flat panel display and other applications, as well as the possible responses from the supply system to the increasing demands, including improving extraction efficiency, increasing production of carrier metal zinc, mining indium with other carrier metals, and accessing historic residues. As noted by the authors, however, the SD model developed is a much simplified one. That is, the model does not internally generate dynamics via feedback loops. Instead, the dynamics is externally driven by the PV market penetration scenarios and the factors affecting the supply and demand are simulated separately. In this research, a more integrated SD model will be developed to include market/price mediated supply and demand responses of both zinc and indium, and other emerging clean energy technology (i.e. LED) that contributes to increased indium demand.

2. Model description

2.1. Purpose and implementation

Main purpose of this model is to explore the dynamic balance between global supply and demand of indium under different clean energy technology adoption and economic growth scenarios over next 50 years. The time period encompasses market saturation of both LED and solar PV as well as the phase-out of LCD. Analysis of results from these scenarios could provide insights on whether indium supply will be a limiting factor for wide deployment of clean energy technologies and the possible root causes. For this purpose, standard SD modeling approach is followed. System boundary is first defined, followed by constructing causal loop diagram which visualizes how variables (stocks and flows) in the model are influencing each other. The stock and flow diagrams are then constructed for simulation, using commercial software Powersim Studio 10. Model validation is performed before implementing different scenarios.

2.2. System boundary of the model

For SD simulation, including all factors that play a role in the system being studied could be very challenging (and costly), although the accuracy or reliability of the results could be increased by including more entities in the model. Therefore, a common practice is to define a reasonable system boundary and analysis is conducted within that boundary. Fig. 1 shows the system boundary considered in this research. Because indium is a by-product of zinc mining and refining, demand and supply of zinc have to be included. Zinc supply relies on both primary production (i.e. mining from the earth) and secondary production (i.e. recycling from end of life products). Zinc demand is mainly influenced by economic growth since the major demand for zinc is steel galvanization in construction and automobile industry (USGS (U. S. Geological Survey), 2012c). As with other commodity, market price also affects its demand.

On the demand side, ITO manufacturing accounts for 80% of indium consumption, followed by alloys and solders (USGS (U. S. Geological Survey), 2009c). Here the demands of indium for alloys and solders are grouped with all other minor demands and are assumed to be constant over time. Thin-film PV and LED (in flat panel display and lighting) each account for less than 2% of global indium consumptions (USGS (U. S. Geological Survey), 2008), but they represent potential major demand sources of indium in the future.

It should be noted that there are three major thin film PV technologies under development, that is, Cadmium Telluride (CdTe), amorphous silicon (a-Si), and Copper Indium Gallium Selenide (CIGS), with CdTe dominating the thin film market now (Fraunhofer Institute, 2012). Compared to the other two types of thin-film technologies, CIGS has higher conversion efficiency along with lower manufacturing cost and also does not require toxic material such as cadmium (Dimmler, 2012). A-Si technology and CdTe system are excluded from system boundary of this research because of their lack of mandatory indium requirement during module manufacturing.

2.3. Causal loop diagram (CLD)

The CLD for indium material flow along with zinc supply and demand in this research is shown in Fig. 2. Zinc demand is positively influenced by economic growth. High demand reduces zinc slab stock in the world, resulting in price increases of the mineral commodity, which in turn decrease the demand. This relationship is called negative (balancing) feedback in system dynamics, which represents a closed causal loop that has odd number of negative

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