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Material use for electricity generation with carbon dioxide capture and storage: Extending life cycle analysis indices for material accounting

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ABSTRACT

Understanding of life cycle material use from novel technologies can assist informed decision making on technology and material selection consistent with natural physical boundaries. Though an intermediate process in conventional life cycle assessment (LCA), the information on material use is only translated into environmental impact potentials. In this study, we present a procedure to extract the intermediate information on material evaluation and perform a systematic life cycle material use analysis. The approach is then used to analyze electricity systems including electricity generation and transmission, with and without post-combustion carbon capture and storage (CCS) technology. Scenario analysis is then performed to understand the relations to the respective annual material production volumes.

Results from the analysis of life cycle material use in the studied systems show that the implementation of CCS in a hard coal power plant results in the increased use of about 35% coal and limestone, 20% copper, 60% steel and 400% of the selected chemicals, as compared to the without CCS system. In addition to the complementary increase in specific resource use, the CCS technology uses over 35% and 70% increase in land and water requirement respectively. CCS scenario with coal power plant using CO_2 capture (scenario S4) provides 83% reductions in the life cycle CO_2 emissions and significant increase in the life cycle material use varying from 13% for coal to 168% for ammonia, as compared to the scenario with no CCS and with global average coal power plant efficiency (scenario S1).

1. Introduction

Life Cycle Assessment (LCA) as a tool has been widely applied to evaluate environmental impacts associated with a product or process with a holistic approach, i.e. impacts from main production process as well as from the upstream and downstream extended value chains. Such evaluation primarily focuses on estimation of emissions from different processes in the life cycle value chain, characterizing these emissions to various potential impact categories and obtaining results as life cycle environmental impacts. LCA literature so far largely discusses impacts like global warming, acidification, eutrophication, cumulative energy demand, and toxicity. One important aspect of such environmental analysis pertains to material use in the system. Evaluation of requirements of various materials by product or process is an inherent step of the life cycle inventory (LCI) modeling. Characterization factors for natural resource use aggregate different material requirements to fossil and metal or mineral depletion, while the life cycle results for specific material or resource use are seldom reported. This limitation of conventional LCA practice bears relevance for various low-carbon energy technologies which often depend on large infrastructure settings with sizeable material requirements. While characterization to midpoint or endpoint impact categories is useful from an environmental perspective, it is of limited use to uncover vulnerabilities related to material use in the value chain. Such an additional perspective can be useful from an economic point of view. Many LCAs are performed in relation to prospective technologies. Additional knowledge resulting from a material use analysis, for example a relatively high copper intensity in the technology under investigation or upstream in the value chain, could provide valuable information that is not reflected in the (midpoint) metal depletion potential. By nature, the inclusive perspective of LCA can uncover vulnerabilities that might not be apparent in

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conventional supply chain analysis, as (similar to environmental impacts) hotspots might occur in the production tiers that lie beyond what is normally investigated. As some material intensive technologies require significant upfront investments, an overview of material use in the supply chain could therefore influence investment decisions. In addition, material efficiency (defined as delivering same required services with less primary production) represents the biggest opportunity for combating climate change in building and infrastructure sector (Allwood and Cullen, 2012). Similar to the usability of life cycle environmental impacts, the knowledge of the material requirements will help understand the implications of a product or process on our physical natural resources and assist in making informed decisions in material selection depending on material intensity, availability, scarcity etc.

In this article we present a procedural approach to use LCI analysis as part of LCA method for evaluating material use. In the context of this article, we reserve the term resource for flows that are considered an environmental extension and consequently not represented as inter-process flows. We reserve the term material for inter-process material flows, even though these materials are sometimes considered resources themselves. Thus, in the context of this study, iron ore is a resource, and iron and steel are considered materials. We then use this approach to assess the material use in coal based power generation with CO_2 capture and storage (CCS) technology. For contextual overview of the scope of environmental analysis of CCS in the available literature, several LCA studies (Zapp et al., 2012; Schreiber et al., 2012; Corsten et al., 2013) have presented global warming benefits and different conventional environmental impacts associated with the technology. Due to the energy penalty and additional infrastructural requirements from capture, transport and storage chain, the technology also has higher material intensity (material requirement per unit product). Kleijn et al. and Hertwich et al. are the early proponents to explore the issue of material use in CCS technology. Kleijn et al. (2011) evaluate metal requirement of various low-carbon power generation technologies including CCS, and present results for requirements of iron, aluminum, copper, zinc, nickel, tin, molybdenum, silver and uranium, and CO_2 emissions associated for different technologies and scenarios. Hertwich et al. (2014) present results for requirements of iron, cement, aluminum, copper and cumulative energy along with the scores on global warming, eutrophication, eco-toxicity, particulate matter and land use impacts for low-carbon electricity systems and supply scenarios. Both of these works use LCA method in their analysis.

In this work we elaborate on the challenges in analysis of the extensive life cycle inventory datasets and present a procedural approach to deduce the direct and life cycle requirements of any specific material. We then use the developed approach to evaluate the use of selected material and resources for producing electricity with CCS technology; and discuss their relevance to impacts, technical parameters and production volumes. The article is structured into four sections including this introduction. In Section 2 we discuss the LCA approach for the evaluation of material use and provide system description of the case study. Section 3 presents the results of the analysis for selected materials. In addition, this section also presents the sensitivity analysis pertaining to relevant technical parameters, and comparison with the global production volumes of the materials in different scenarios. Section 4 presents the main conclusions.

2. Method

2.1. LCA approach

The standard framework for LCA has four consecutive stages: goal and scope definition, inventory analysis, impact assessment and interpretation (Baumann and Tillman, 2004). Based on the defined functional unit and system boundaries in goal and scope definition (step 1), a comprehensive inventory is compiled for inputs (materials, energy) and outputs (air/water/soil emissions, solid waste, product/byproduct) in relation to the functional unit (step 2). This information is then translated to relevant environmental impact scores using pre-defined characterization factors for each stressor (step 3), and the findings are used to reach conclusions and recommendations in conjunction with the defined goal and scope (step 4). In the conventional LCA practice, the information on material use in an inventory is deconstructed to specific raw material use, emissions to air, water and soil, which applied to appropriate characterization factors, are aggregated to different environmental impact categories. Therefore though every LCA evaluates the material use in intermediate steps, it is often not reported or analyzed within the conventional LCA steps.

The process of performing an LCA is standardized in the ISO14044:2006 international standard. With respect to carbon dioxide capture and storage LCAs, additional specification can be found in the Product Category Rules (PCR) for carbon capture and storage services (PCR, 2014), and the PCR related to electricity generation and distribution (PCR, 2015). A PCR is a set of specific rules, requirements and guidelines for developing environmental declarations in the framework of the Environmental Product Declaration (EPD) system. The PCR on CCS presents rules on LCA-related topics such as general system boundaries, the specification of the functional unit, and general data sources for inventory compiling (Strazza et al., 2013).

In compiling the life cycle inventory, we distinguish a foreground, in which the life cycle under investigation is modeled, and a background, which consists of a life cycle inventory database with a high process resolution such as ecoinvent (Frischknecht et al., 2005). Processes in the foreground generally contain what is referred to in the PCRs as the core and downstream module, whereas all connections with the background contain the upstream process requirements.

In principle, a material balance can be evaluated from the inventory data of the individual processes. However, these processes are usually inventoried with respect to a reference flow logical for the unit process, e.g. kg of copper produced or km of pipeline built. Though the material balance per unit process is satisfied, it is not immediately clear what the material contribution is for the functional unit employed for the LCA. Tracking down the material contribution for the thousands of upstream processes is, though theoretically possible very time consuming, which is why in this study we take a matrix based approach and present a procedure to extract the intermediate information on material evaluation and perform a systematic material use analysis.

In essence, material accounting by making use of the LCI is an aggregation problem. For the purpose of this study, the unit processes in the background database are on a level that is more detailed than required, i.e. we would like to group the output of many different unit processes, while preventing double counting. Additionally, when investigating material use, it is possible that some processes in the background refer to each other, i.e. a feedback loop between material flows is present, for example due to export of material in one region to another region. When interested in (primary) material use these feedback loops could cause potential double counting. For example, in ecoinvent, copper from electrowinning is used as an input to produce primary copper (Classen et al., 2007). Ecoinvent contains more than 10 different unit processes for copper in some form and thoughtlessly adding individual outputs per final demand of these copper processes leads to double counting, as summing up both the primary copper output and copper from electrowinning introduces an overestimation