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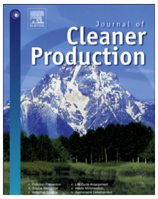

Assessing carbon dioxide emission reduction potentials of improved manufacturing processes using multiregional input output frameworks

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ABSTRACT

Evaluating innovative process technologies has become highly important within the last decades. As standard tools different Life Cycle Assessment methods have been established, which are continuously improved. While those are designed for evaluating single processes they run into difficulties when it comes to assessing environmental impacts of process innovations at macroeconomic level. In this paper we develop a multi-step evaluation framework building on multi regional input–output data that allows estimating macroeconomic impacts of new process technologies, considering the network characteristics of the global economy.

Our procedure is as follows: i) we measure differences in material usage of process alternatives, ii) we identify where the standard processes are located within economic networks and virtually replace those by innovative process technologies, iii) we account for changes within economic systems and evaluate impacts on emissions.

Within this paper we exemplarily apply the methodology to two recently developed innovative technologies: longitudinal large diameter steel pipe welding and turning of high-temperature resistant materials. While we find the macroeconomic impacts of very specific process innovations to be small, its conclusions can significantly differ from traditional process based approaches. Furthermore, information gained from the methodology provides relevant additional insights for decision makers extending the picture gained from traditional process life cycle assessment.

1. Introduction

The recent 5th Assessment Report by the Intergovernmental Panel on Climate Change (IPCC, 2014a) highlights the urgency to act on climate change mitigation if agreed global warming stabilization targets were to be met. Assessing historical developments as well as model based scenarios of possible transition pathways, the IPCC underlines the importance of technological progress in order to achieve ambitious goals.

Even though industrial sectors currently emit more than 30% of global GHG emissions (IPCC, 2014b), their cumulated impacts are estimated to be by far larger due to their influence on emissions caused by related pre- and post-processes such as infrastructure, transportation, material usage or electricity generation (IPCC, 2014b). A relevant share of technological innovations, is located and implemented in industrial sectors (Saygin et al., 2011). In practice those innovations take place at the micro level, where single processes are improved.

Assessing potential macro-economic impacts of technological innovations at process level occurs to be highly non-trivial due to

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complex interactions within production chains and markets forces. In practice, conclusions are drawn at the micro level by applying Life Cycle Assessment (LCA) methodologies that have become standard for assessing single processes (innovations). Most prominently Process LCA (PLCA), Input–Output LCA (IOLCA) and combinations of both, Hybrid LCA (HLCA) are applied (Guinée, 2011; Suh and Huppes, 2005). While using LCA approaches allows to assess single processes, an overall macroeconomic estimation of possible impacts is hardly possible, a research need commonly identified in the literature (Egilmez et al., 2013).

Frequently used PLCA represents a standardized bottom-up approach, where starting with the investigated process, upstream and downstream stages are traced until a predefined system boundary is reached (ISO 14044, 2006; Suh and Huppes, 2005). Considered flows are used to quantify impacts on various indicators including environmental impacts, human health or global warming (Finkbeiner, 2012; Finkbeiner et al., 2006; Klöpffer and Grahl, 2014). PLCA modeling shows to have a high level of detail and many available impact indicators as detailed process databases are available (Finnveden et al., 2009), which enables the calculation of Use- and End-of-Life phase, but suffers from system incompleteness (Suh et al., 2004). The resulting underestimation of impacts related to the production of goods results in so called truncation errors. Estimates on truncation errors vary (Junnila, 2006; Lenzen, 2000; Norris, 2002; Rowley et al., 2009), but suggest significant influence. Furthermore, specific sectors are not (sufficiently) considered (Junnila, 2006; Majeau-Bettez, 2011). It has been further highlighted that PLCA has specific shortcomings when decomposing supply chains at the macroeconomic level distinguishing contributions of drivers, providing relevant information for politicians (Feng et al., 2011; Kucukvar and Samadi, 2015; Kucukvar et al., 2015; Wiedmann et al., 2010).

IOLCA utilizing input output data has been developed as an alternative. Even though IOLCA is “system complete”, as an infinite number of upstream production stages can be traced via a power series, it has been criticized for aggregating economic sectors and assuming homogeneity therein (Finnveden et al., 2009; Majeau-Bettez, 2011; Suh et al., 2004), which can cause under- or overestimates of consumption based impacts associated to production (Rowley et al., 2009). Furthermore, when using IOLCA it is hardly possible to account adequately for the End-of-Life- and Use phase (Suh and Huppes, 2005). However, IO databases consider sectors that are neglected in PLCA databases (Majeau-Bettez, 2011).

Mainly single region IO systems are chosen for IOLCA application as, depending on the underlying country, they have higher sectoral resolution and more impact indicators (Finnveden et al., 2009; Lenzen et al., 2013) than multi regional input–output (MRIO) databases. Exemplary the single region U.S. Bureau of Economic Analysis IO table has been used for different IOLCA purposes (Egilmez et al., 2014; Junnila, 2006; Majeau-Bettez, 2011). However, in contrast to MRIOs (e.g. Tukker and Dietzenbacher (2013)) single region IOs do not account for differences in sectoral production characteristics across countries (Voigt et al., 2014), nor is trade data accounted for, which holds relevant information for e.g. embodied emissions calculations (Cristea et al., 2012; Davis and Caldeira, 2010). In case of MRIO data, recently, new databases have been published (Tukker and Dietzenbacher (2013)) and new concepts aiming for highest possible detail and regular updates (Lenzen et al., 2013) have been installed. There have been promising approaches to consider further indicators (Ewing et al., 2012; Wiedmann et al., 2013).

Reducing possible weaknesses of IOLCA and PLCA, different HLCA methodologies have been developed (Egilmez et al., 2014; Finnveden et al., 2009; Lenzen and Crawford, 2009; Suh and Huppes, 2005). They combine both alternatives, using the high level of detail of PLCA, its End-of-Life- and Use phases impacts and the system completeness of IOLCA. Generally, it is assumed that HLCA causes smaller relative errors because errors related to aggregation, homogeneity, neglecting of sectors, End-of-Life phase, availability of impact categories or regional and sectoral resolution are reduced (Egilmez et al., 2014; Guinée, 2011; Majeau-Bettez, 2011; Rowley et al., 2009).

In this paper we develop a framework based on MRIO data, allowing to estimate overall environmental impacts related to production when adapting technological innovations considering the global economic network. Our analysis builds on the comparison of a conventional (reference) process i.e. one that is currently used in practice, with innovative alternatives. All processes are evaluated based on their requirements for direct inputs, enabling (P)LCA as well as evaluation within the developed MRIO-framework. After identifying conventional processes within the MRIO network, the impact of technological adaptation is assessed by replacing those by innovative alternatives and adjusting flow structures using third party data on related processes. The resulting changes – under the assumption of fixed final demands within the economic network – are then translated to specific assessment criteria, e.g. CO_2-emissions.

We exemplarily apply this methodology for two innovative manufacturing processes: longitudinal welding of large diameter steel pipes and turning of high-temperature resistant materials with an internally-cooled turning tool. For each process, three scenarios are conducted, in which reference processes are hypothetically replaced by innovative processes in Germany, Europe and across the globe, respectively. For demonstration purposes the application of this paper solely investigates changes in CO_2-emissions.

Results show that our framework allows for conclusions on overall emissions considering changes within the economic network. We find that for longitudinal welding and internally cooled turning processes innovative alternatives could contribute to overall emissions reduction.

We contrast our analysis by established PLCA (performed with GaBi process database (PE International, 2015)), IOLCA and HLCA, hence allowing for a comparison of the micro (process) with the macro (economy wide) perspective. We find that all methodologies identify the innovative welding technology to be environmentally beneficial, while in case of turning alternatives conclusions differ.

The paper is structured as follows: Section two describes the methodological foundations and gives an overview of recent MRIO databases. Section three introduces the considered process alternatives. In section four and five we give results for MRIO-based assessment methodology and LCAs, respectively. Section six concludes.

2. Process assessment using multi-regional-input–output data

This section describes the integration of process innovations into MRIO data as an approach to assess their macroeconomic impacts holistically.

2.1. Multi-regional-input–output data

MRIO data approximates structures of the global production networks. Depending on the dataset it considers a characteristic set of r regions $R = \{r_1, \ldots, r_r\}$ and s sectors $S = \{s_1, \ldots, s_s\}$, that reflect all interactions throughout production allowing for an arbitrary trace back of production steps (Miller and Blair, 2009). As each dataset has individual R and S, as well as specific satellite data it serves for specific application. The current most prominent MRIO

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