Resources, Conservation & Recycling xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Revealing the life cycle greenhouse gas emissions of materials: The Japanese case

Sébastien M.R. Dente[a,*], Chika Aoki-Suzuki[a,b], Daisuke Tanaka[a], Seiji Hashimoto[a]

[a] *Deparment of Environmental System Engineering, Ritsumeikan University, Japan*
[b] *Insitute for Global Environmental Studies, Japan*

A R T I C L E I N F O

Keywords:
Decoupling policies
GHG emissions
Life cycle materials
Environmentally weighted material consumption (EMC)

A B S T R A C T

Double decoupling of economic growth with resource use amounts and resource use with generated environmental effects has been recognized as a policy objective towards sustainability by the European commission. To achieve such a policy, indicators are needed to establish the specific environmental of materials from a life cycle perspective. To date, only environmentally weighted material consumption (EMC) indicators have been created to meet this objective. However, current developments of EMC restrain its application mainly to finished materials because of the risk of double counting occurring when considering resources and semi-finished materials supply chains. Furthermore, statistics availability is often cited as an obstacle to develop EMC analysis further. The present work presents strong improvements of the EMC concept and provides calculation methods to avoid double counting issues and to determine the life cycle environmental effects of materials of all types distinguishing between upstream effects linked to the production of materials and downstream effects linked to the use of these materials. The new methodology has been applied to the Japanese case considering 64 target resource materials among the 393 sectors available in the 2011 Japanese IO table and domestically emitted GHG emissions. Ten materials (crude steel, petroleum refinery product, cement, paper, rice, marine fishery, dairy cattle farming, aliphatic intermediated, vegetables and rice) were identified as accounting for more than three quarters of the total greenhouse gas emissions and should therefore constitute the priority of emission management and decoupling policies.

1. Introduction

Every socioeconomic system extracts materials and energy from the environment to produce materials, products, and services which are either consumed within the system or which are exported to other socioeconomic systems. Current management of socioeconomic systems is nonetheless unsustainable because the associated rapid depletion of natural resources and increases in waste and emissions negatively affect natural ecosystems. Indicators are necessary to assess how well socioeconomic systems decouple from environmental effects providing more wealth to citizens while diminishing the negative burden on natural ecosystems. Historically, an important first step to establish decoupling indicators has been the creation of material flow accounting systems. At the national level, such a system is known as the economy-wide material flow accounting system (Matthews et al., 2000; EC, 2001; OECD, 2008; Eurostat, 2013). In this system, material flows entering an economy are domestic extraction (DE). Two indicators, domestic material input (DMI = DE + IM) and domestic material consumption (DMC = DMI-E) are derived. Using GDP as a common indicator of wealth, decoupling indicators are either GDP/DMI or GDP/DME. GDP/DMI is, for example, used by Japan to measure its resource productivity, whereas the European Union uses GDP/DMC to measure material productivity of a domestic economy (Hotta and Visvanathan, 2014). Nevertheless, several criticisms have nevertheless been raised against such resource efficiency indicators. A first criticism is related to hidden flows i.e. materials that are extracted or moved but which do not enter the economy. Nevertheless, they affect the environment. Total material requirement (TMR) and total material output (TMO) are indicators developed to incorporated consideration of these hidden flows (Hotta and Visvanathan, 2014). A second criticism is the absence of material circularity in DMI or DMC indicators as assessed by Valero et al. (2015), who proposed a domestic material dispersion (DMD) indicator including recycling activities and expressed in exergy cost terms to resolve this issue. A third criticism is linked to the description of foreign material inputs in DMI or DMC. Indeed, these indicators only account for direct physical imports, though an imported product might have more materials embodied in its production than an imported raw material. Relying on the recent development of multi-regional input-

---

* Corresponding author.
E-mail address: 15v01062@gst.ritsumei.ac.jp (S.M.R. Dente).

https://doi.org/10.1016/j.resconrec.2017.12.011
Received 15 May 2017; Received in revised form 20 September 2017; Accepted 6 December 2017

Please cite this article as: Dente, S.M.R., Resources, Conservation & Recycling (2017), https://doi.org/10.1016/j.resconrec.2017.12.011

output databases (MRIO) and a life cycle assessment database for assessing flows in physical units, raw material equivalents (RME) and material footprints (MF) have been developed and used extensively in the literature. For example, Weinzettel and Kovanda (2009) used RME to calculate the raw material inputs (RMI) at the sectoral level and to propose strategies for decreasing the material inputs of the sector. Wiedmann et al. (2015) determined the material footprints of nations and demonstrated that large resource exporters such as Australia, Russia and South Africa had a DMC/capita much larger than their MF/capita because of trade effects. The importance of international trade for material flows was elucidated further by Bruckner et al. (2012) who formulated a raw material trade balance indicator (RTB). Nevertheless, IO based LCA studies are not limited to a material perspective because energy use can also be accounted for in this way, as demonstrated by Wu and Chen (2017).

Earlier indicators, although constituting important improvement of the economy- wide MFA, include an important shortcoming when addressing the question of decoupling. They all specifically examine mass rather than environmental effects. Implicitly, the hypothesis is therefore made that environmental effects are linked closely to the amount of materials extracted from the environment and their subsequent transformations into semi-finished products and finished products within society. Although some correlation between resource use quantities and the overall impacts might exist at the country level (Giljum et al., 2011), that correlation does not hold at the level of single materials because of the high variation of per-kilogram environmental effect (Van der Voet et al., 2005). Particularly, Van der Voet et al. (2004) have emphasized that MFA in considering only mass engenders overestimation of the environmental effects of intensively consumed materials with low environmental effect such as sand and gravel and an underestimation of those with low consumption but high environmental effect such as chemicals. Decoupling economic growth from environmental effects therefore demands a double decoupling framework: a decoupling between economic growth and material use and a decoupling between material use and environmental effects. Such a double objective has been acknowledged by the European Union, which states as a new policy objective the double decoupling of GDP from resource-use amounts and resource use amounts from the environmental effects that are generated (EC, 2005). In Japan, such objective is encompassed into the fundamental plan for establishing a sound material cycle-society (MOE, 2013). This double framework was theorized further into a systemized framework of resource-use indicators from micro-scale to macro-scale indicators (Huysman et al., 2015). Those efforts notwithstanding, the main challenge remains mainly unaddressed by the literature: ascertaining the specific effects of materials.

An important attempt at addressing this issue was undertaken with the creation of the environmental weighted material consumption (EMC) indicator. Developed by Van der Voet et al., 2009, this indicator is the result of a combination of a material balance at the material level using production and consumption statistics and of life cycle inventory databases, such as the Ecoinvent database, to assess environmental effects. Applied to European countries, results demonstrated that building materials, although representing a high share of domestic material consumption (DMC), represent only a small share of environmental effects. The opposite trend was found for food chains especially animal ones (Van der Voet et al., 2009). Although the whole life cycle of materials was considered, no distinction between effects within and outside EU was possible because of limitations in the statistics and LCA database. Extension of EMC to incorporate consideration of the trade effects was nevertheless realized by the European commission (EC-JRC, 2012) but at the expense of the level of details because few materials could have been studied as a result of the lack of availability of statistics. Aside from issues of statistics availability and uncertainties of LCA inventories, a main shortcoming of the current development of EMC is the absence of harmonized and recognized calculation methodology and the limitations of current indicators to finished materials and consumption. A reason behind the latter limitation is the risk of double counting. Indeed, when considering final consumption and finished materials, unitary life cycle effects of the material can be derived directly from a lifecycle database and using statistics and apparent consumption to multiply the unitary life cycle effects derived accordingly. This derivation does not stand anymore for basic resources or semi-finished materials. For example, based on analysis of the 2011 Japanese IO table, crude petroleum is an intermediate product as no crude petroleum is directly required by final demand. Based on the current EMC calculation, the environmental effects associated with the production of crude petroleum would be allocated to the finished material category “petrol, gasoline and other final products” but the life cycle impacts (production, use and waste) of “crude petroleum” itself remain unknown.

The main objective of this report is to overcome issues raised earlier by proposing a calculation methodology that explicitly manages double counting, which allows calculation of time series EMC indicators, and which clearly distinguishes between upstream and downstream environmental effects of materials. For the crude petroleum example described before, our new framework considers the EMC of crude petroleum as constituted of an upstream phase made of the supply chain impacts related to the production of crude petroleum and a downstream phase related to its use either to produce other material, products and services or by households for their energy needs.

The *Material and Methods* section presents the matrix development associated with the distinction of upstream and downstream impacts and solving of the double counting issue. The *Results* section presents a description of the Japanese case and the application of our new methodology to the determination of life cycle greenhouse gases emissions (GHG) of fossil fuel, biomass, metallic and non-metallic resource materials produced in Japan in 2011. The *Discussion* section then presents details underscoring the importance of obtained results for shaping Japanese decoupling policies illustrating the benefits of our renewed EMC or life-cycle indicator.

2. Material and methods

2.1. Upstream and downstream production allocation

Bringing into the light the life cycle of a material presumes a capability of distinguishing among the materials, products and services used to produce this material (upstream) and the materials, products and services using the material (downstream). This distinction is highly dependent on the choice of the target material. For example, pig iron is used mainly to produce crude steel. Selecting crude steel as a target material has for consequence to allocate almost all the pig iron produced to crude steel production (upstream). By contrast, selecting pig iron as a target material makes crude steel production a process using pig iron (downstream). For strongly intertwined materials, a choice has been made, e.g. crude steel was preferred over pig iron as a target material. Overall, 64 materials were selected as presented in Table 1. These materials are labelled as target sectors of the studied input-output table (TS). Other materials, products and service available in the studied input-output table are labelled as non-target sectors (NTS). By definition, the downstream phase of target sectors only relates to non-target sectors. Indeed, if TS_1 is used by TS_2 then TS_1 is allocated to the production of TS_2 (upstream). Similarly, the total amount of TS and NTS necessary to produce one unit of TS as described by the Leontief framework is an important characteristic of TS supply chains and should not be modified. The issue is therefore to find a production amount of TS ($\boldsymbol{X_t^{wdc}}$) for which the production amount obtained once applying the Leontief framework (L) describing TS supply chains equals the total production of TS ($\boldsymbol{X_t}$). This condition is expressed by Eq. (1).

$$X_t = L_{tt} * X_t^{wdc} \tag{1}$$