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Reutilisation-extended material flows and circular economy in China

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ABSTRACT

Circular economy (CE), with its basic principle of Reduce, Reuse, and Recycle, has been determined as the key strategy for the national development plan by the Chinese government. Given the economy-wide material flow analysis (EW-MFA) that leaves the inner flow of resource reutilisation unidentified, the reutilisation-extended EW-MFA is first introduced to evaluate and analyse the material input, solid waste generation, and reutilisation simultaneously. The total amount of comprehensive reutilisation (CR) is divided into three sub-flows, namely, reutilisation, recycle, and reuse. Thus, this model is used to investigate the resource CR in China from 2000 to 2010. China's total amount of CR and its sub-flows, as well as the CR rate, remain to have a general upward trend. By the year 2010, about 60% of the overall solid waste generation had already been reutilised, and more than 20% of the total resource requirement was reutilised resource. Moreover, the growth patterns of the CR sub flows show different characteristics.

Interpretations of resource reutilisation-related laws and regulations of CE and the corresponding policy suggestions are proposed based on the results.

1. Introduction

Circular economy (CE), with its basic principle of Reduce, Reuse, and Recycle, was first introduced in 1990 (Pearce and Turner, 1990). However, only Germany and Japan completed the legislation on CE, whereas other countries shared similar policies and regulations of industrial ecology and cleaner production (Li and Qi, 2004). China, with an annual average gross domestic product (GDP) growth rate of 11% since the turning of the new century, is regarded as the fastest-growing country in terms of resource consumption (Schandl and West, 2012; Xu et al., 2008). Therefore, CE has been determined as the key strategy for its national development plan by the Chinese government (Geng et al., 2012; Li, 2009).

CE involves both raw resources input and resources cycling. However, tools to quantify and analyse input and cycle flows at the same time at the national level have not been well developed (Lu, 2009). For non-renewable resources input analysis, material flow analysis (MFA) is the first choice. Most existing national MFA studies follow Eurostat's economy-wide material flow analysis (EW-MFA) (Aoki-Suzuki et al., 2012; Hass and Popescu, 2011; Steinberger and Krausmann, 2011; Steinberger et al., 2010). As a powerful tool for evaluating the material link between the economy and the environment, EW-MFA was first introduced by the statistical office of the European Union (i.e., Eurostat) in 2001 (Eurostat, 2001). Several material flow analysis frameworks similarly originated from industrial metabolism (Ayres, 1989) and society's metabolism (Fischer-Kowalski and Hüttler, 1998). For instance, the MFA framework of the World Resources Institute is more tailored for the United States, Japan, Germany, and the Netherlands, whereas EW-MFA was designed to be more universal for international comparison. However, EW-MFA treats the economic system as a black box, leaving the material reutilisation unidentified, as reutilisation is the cycle flow without passing through the economic system boundaries. Consequently, although resource reutilisation is crucial to the economy's overall material metabolism, material reutilisation is not considered in most EW-MFA studies and reports, and the resource reutilisation analysis is isolated from EW-MFA.

Therefore, we expanded the conventional EW-MFA into reutilisation-extended EW-MFA to evaluate and analyse the Chinese direct material input, solid waste generation, and reutilisation simultaneously. The corresponding recommendations for the CE development of China are discussed based on the analysis of existing laws and regulations.

2. Survey of the cycle flow research efforts

A large number of studies have been conducted on cycle flows. However, most of which only discuss certain groups of cycle flows such as municipal waste (Chen et al., 2010; Tai et al., 2011; Zhang et al., 2010), industrial waste (Casares et al., 2005; Huang and Lin, 2008; Wei and Huang, 2001), agriculture waste (Bi, 2010; Liang et al., 2012b; Lu and Zhang, 2010; Wang et al., 2010b), and construction waste (Jia, 2008; Zhao et al., 2010), among others. At

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the same time, several studies focused on cycle flows by substance, especially metals (Fröhling et al., 2012; Spatari et al., 2002, 2005; UNEP, 2011). Studies on the corresponding environmental impacts of certain groups have gained significant interest (Moriguchi, 2007; Spatari et al., 2002; Zhao et al., 2011). However, only a few studies exist on cycle flows at the national level (Lu, 2009) because the most commonly used national material flows analysis tool, EW-MFA, does not include cycle flows. Japan is the only country that officially introduced cycle flows (cyclical use flows in Japanese definition) into EW-MFA based on the concept of a 'Sound Material-Cycle Society'. The cyclical use rate is set as one of the Japanese national target indicators derived from EW-MFA (Yoshida et al., 2007).

In summary, although several material cycle flow studies exist, the total economy-wide material cycle flow research is still in its infancy. Therefore, cycle flow studies should be combined with EW-MFA to support macroscopic decisions, such as the CE development in China, and to provide an outlook of the material metabolism of an economic system.

3. Methods

3.1. Model

The reutilisation-extended EW-MFA model is shown in Fig. 1, where material flows are divided into two main categories: direct flows and indirect flows. The indirect flows of international trade-related raw material equivalents (RMEs) and unused extraction (UE), as well as the domestic extraction (DE)-related UE, are not included in the latest EU EW-MFA guide because of the lack of supporting data and undeveloped calculation methods (Eurostat, 2009). Direct flows can be classified into three groups:

Input: 1 DE, 2 Imports (IM).
Output: 3 Exports (EX), 4 Domestic Processed Output (DPO).
Cycle: 5 Reutilisation (RU), 6 Recycle (RC), 7 Reuse (RE).

The definitions of flows 1, 2, 3, and 4 are consistent with that of the EU EW-MFA (Eurostat, 2001, 2009), whereas flows 5, 6, and 7 are the newly extended definitions. The derived indicator of direct material input (DMI) is equal to DE plus IM (Eq. (1)), measuring the total direct input of materials into the economy (Fig. 1). In other words, all resources that a nation needs are from either domestic extraction or imports. Theoretically, more cycle flows lead to less DMI because renewable resources may replace some of the raw materials. The only adjustment is that the used crop residues, with code A.1.2.1 of the EU EW-MFA questionnaire 2009 (Eurostat, 2009), is excluded from DE because it is reassigned to RU. Further explanations can be found in Table 1.

$$\mathrm{DMI} = \mathrm{DE} + \mathrm{IM}. \quad (1)$$

The extended flow of RU indicates the material reutilised in productive activities that consists of two flows: agricultural reutilisation (ARU) and industrial reutilisation (IRU) (Eq. 2).

$$\mathrm{RU} = \mathrm{ARU} + \mathrm{IRU}. \quad (2)$$

ARU represents the collected and reprocessed agricultural plastic films, livestock and poultry manure, and crop straw (excluding those directly returning to the field) that are mainly used for fuels, fertilisers, industrial or constructional raw materials, culture medium of edible fungi, and so on. IRU is the amount of reused solid waste extracted or converted from the solid waste generated in the production process through reclamation, processing, recycling, and exchange. IRU is mainly used as fertilisers, building and road materials, and so on.

RC is the amount of recycled and recovered materials after the final use (recycled consumption wastes). The four primary sources are construction, municipal solid waste, scrapped vehicles, and waste electrical and electronic equipment (WEEE). Scrapped iron and steel, non-ferrous metal, organics, plastic, paper, rubber, and construction materials constitute the major substance categories of construction and municipal solid waste in RC. RE consists of second-hand WEEE, second-hand vehicles, and reused packages, only referring to direct reused products without any physical or chemical process. Comprehensive reutilisation (CR) is the sum of RU, RC, and RE, referring to the total amount of the reutilised resources in the economic system (Eq. 3):

$$\mathrm{CR} = \mathrm{RU} + \mathrm{RC} + \mathrm{RE} \quad (3)$$

The comprehensive reutilisation rate (CRR) has many definitions based on different perspectives, two of which share more common consensus than others. The first CRR is defined as CR divided by the sum of DMI and CR (Eq. 4):

$$\mathrm{CRR}(1) = \frac{\mathrm{CR}}{\mathrm{DMI} + \mathrm{CR}} = \frac{\mathrm{RU} + \mathrm{RC} + \mathrm{RE}}{\mathrm{DMI} + \mathrm{RU} + \mathrm{RC} + \mathrm{RE}} \quad (4)$$

The first CRR is defined as CR/(DMI + CR), whose subtext is that more use of reutilised material may lead to less non-renewable resource input. Japan defines the reutilisation rate as the total amount

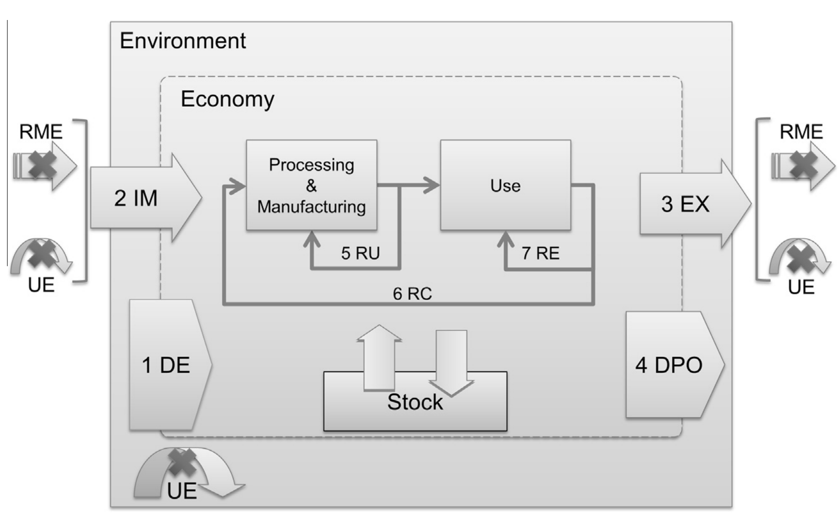

Fig. 1. Schematic of the reutilisation-extended EW-MFA model.