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Measuring material efficiency: A review of the historical evolution of indicators, methodologies and findings

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ABSTRACT

Increasing material efficiency, or material productivity, is essential for decoupling resource depletion and associated environmental pressures from economic development. This paper reviews the historical evolution of indicators monitoring material efficiency, their underpinning methodologies and major findings in the past three decades. Early studies investigated the material-economy relationship through intensity of use (IU) of some selected single materials. Economy-wide material flow accounting (EW-MFA) established a standardized framework for aggregating overall material inputs into an economy. Consumption-based material footprint (MF) analysis extended the system boundary to cover global resource extraction along supply chains to satisfy final consumption. Studies on material cycles (MC), especially metal cycles, further helped trace all major life cycle stages of anthropogenic material use, with the capability to account for in-use stocks of materials and products. Impact-based indicators investigate the opportunities to reduce negative environmental, social and economic impacts of material use, which is the ultimate purpose of improving material efficiency. Monitoring material efficiency with different indicators might lead to very different conclusions regarding a society's dependence on material and its dematerialization trend. We present a generalized framework for constructing all kinds of material efficiency/productivity indicators and make the case that election of indicators should be problem-oriented and policy-relevant.

1. Introduction

The 20th century has witnessed remarkable socio-economic changes, especially in its second half after World War II, referred to as "the Great Acceleration" (Hibbard et al., 2006; Steffen et al., 2011), when world population increased from 2.5 billion at the middle of the 20th century to 7 billion by the end of the first decade of the new millennium. Meanwhile, global real gross national product (GNP) expanded roughly eightfold. On average, humans have been enjoying improved medical conditions, prolonged expected lifespans, rising living standards, and more diverse services provided by numerous technology innovations and modern infrastructures. Ever-accelerating exploitation of natural resources has accompanied many of these achievements (Krausmann et al., 2009; Sverdrup et al., 2013).

Concerns about resources depletion are not new. Early in the 1860s, the British economist William S. Jevons expressed the worry that Britain could not sustain its economic development when its coal resources are being exhausted (Polimeni et al., 2008). He pointed out that efficiency improvements would not be able to alleviate the problem because economic growth and increased consumption occurred at higher rates than efficiency gains, a phenomenon known as "rebound effect". Although Jevons's original worry did not come true thanks to fuel substitution from coal to oil, debates regarding resource scarcity continued to evolve. The "*Oil peak*" curve proposed by M. King Hubbert in the 1950s (Bardi, 2009), the sobering prospect modeled in *The Limits to Growth* by experts from the Club of Rome in the 1970s (Meadows et al., 1972), and a 1980s bet on the future prices of five basic metals between Julian Simon, a resource optimist, and Paul Ehrlich, an ecologist concerned about environmental degradation (Sabin, 2013) were among the most famous events, all igniting long-lasting discussions and arguments.

Optimists express their faith in human ingenuity, and argue that natural resource depletion could be overcome by growth in productivity, technology innovations and the power of market in adjusting human behavior (Nordhaus, 1992). It is true that technology advancement, especially radical innovations, can turn potential resources

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into new applicable reserves and utilize new minerals and energy sources to substitute for traditional ones. Nevertheless, it was often the case that new resource and environmental problems were caused by innovations on which society counted to solve existing ones.

The focal point of the resource scarcity debate has also shifted from questions whether natural resources are abundant enough for human use to issues surrounding the disutility that comes from adverse environmental and social impacts of accelerating resource extraction and mass production. Facilitated by improved data collection and deeper understanding of the functioning and resilience of the earth system, the notion of planetary boundaries was established as a metaphor for the safe operating space for human societies to thrive (Rockström et al., 2009; Steffen et al., 2015). Empirical evidence has existed since at least the 1990s that humans have by then begun to dominate almost all major biogeochemical cycles (Vitousek et al., 1997). More recent research shows that at least six out of the nine planetary boundaries have already been approached or overshot by human interventions, including climate stability, biosphere integrity, land-system change, biogeochemical flows, ocean acidification and freshwater use (Jaramillo and Destouni, 2015). These emerging crises are to a large extent caused by the expansion of material throughput to meet human needs. Based on the mass balance principle, all materials entering a socio-economy system will ultimately exit as wastes into the natural environment. Larger gross material throughput leads to a larger potential of environmental pressures (Mayer et al., 2017).

Two relevant concepts namely “dematerialization” and “decoupling” were proposed as core strategies to solve resource scarcity and the associated environmental problems. **Dematerialization** refers to the absolute or relative reduction in the quantity of materials used and/or the quantity of waste generated in the production of a unit of economic output (Cleveland and Ruth, 1998). **Decoupling** emphasizes a break in the link between an environmental pressure and its economic driving force (OECD, 2006; von Weizsäcker et al., 2014), for example when economic output is able to grow faster than its carbon emissions. Both dematerialization and decoupling can be realized through **material efficiency** measurements, which include all changes that result in decreasing the amount of materials used to produce one unit of economic output or to fulfill human needs (Allwood et al., 2011; Söderholm and Tilton, 2012).

Fig. 1 shows the numbers of publications with the keywords ‘resource efficiency’, ‘material efficiency’ and ‘dematerialization’ since 1990 retrieved from the Scopus database. (Only studies at the macro level are included here, i.e., those focusing on global, national, regional or sectoral resource and material efficiency issues. Micro-level studies on specific technologies and processes in the fields of chemical engineering, civil engineering, and material science, for example, are not considered in this study). Since ‘resource’ has broader meanings than ‘material’, which can also include energy, water and land resources, it is not surprising that ‘resource efficiency’ returns the largest number of

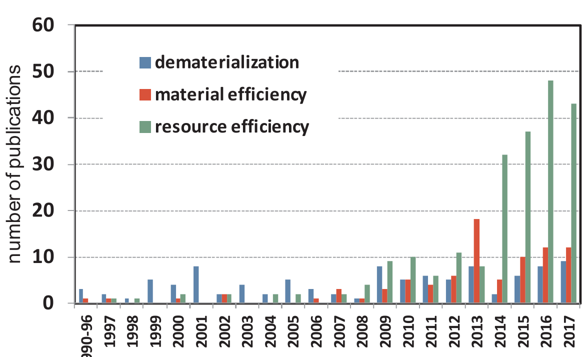

Fig. 1. Number of publications with keywords ‘resource efficiency’, ‘material efficiency’ and ‘dematerialization’ retrieved from the Scopus database since 1990.

studies, especially after 2014. Numbers of ‘material efficiency’ and ‘dematerialization’ publications are around a hundred. While ‘dematerialization’ occurs more often in earlier studies before 2010, ‘material efficiency’ is used more frequently in recent years. Top source journals of the three keywords are different. ‘Resource efficiency’ appeared in a wider range of journals; with the Journal of Cleaner Production (JCP) as the largest source. Resources, Conservation and Recycling (RCR) and Journal of Industrial Ecology (JIE) are the top source journals for ‘material efficiency’ and ‘dematerialization’, respectively (see Fig. 2).

Monitoring and measuring material efficiency relies on rigorous quantitative analysis of the social metabolism of materials, which emerged as a new research tradition in late 1960s (Fischer-Kowalski, 1998). Given the complexity and dynamics of resource utilization and material transformation in a society, the measurement is not as straightforward as one may expect. Early studies used material intensity of use (MIU) to reflect material efficiency, i.e., the ratio of the mass of a material over an economic output indicator (for example, paper production per unit GDP). Such simple metrics can only provide a limited and sometimes misleading picture of the material-economy relation, for example because weight of materials may not be the appropriate unit of measurement that relates to environmental degradation. A lack of clear system boundaries on which the selected indicators were defined and little consideration to the role of the studied material in society and its interactions with economic development further cast doubt on the general usefulness of early studies.

The past three decades have seen increased understanding of society-environment interactions due to methodology improvements and better data acquisition. The purpose of this paper is to provide a review of the intellectual history of measuring material efficiency at the macro level, with focus on the evolution of indicators and methods as well as major research findings. We first present a general schematic diagram of anthropogenic cycle of materials in Section 2, which is an established concept in the field of industrial ecology. We identify that different material efficiency indicators can be constructed based on quantification of material flows, in-use stocks or corresponding environmental impacts at different stages or from different accounting perspectives (e.g., production-based or consumption-based) embedded in the anthropogenic material cycles. Alongside material intensity of use (Section 3), we identify four branches of studies representing landmark progresses on this topic. These include standardized economy-wide material flow accounting (EW-MFA) to quantify aggregate material throughput (Section 4); material footprint (MF) indicators to trace consumption-based upstream raw material use (Section 5); indicators of material flows and in-use stocks in the anthropogenic material cycles, especially metal cycles (Section 6); and impact-oriented indicators to extend mass-based accounting to environmental impact evaluation (Section 7). The pros and cons of different metrics and representative findings from empirical applications are elaborated in Sections 3, 4, 5, 6, 7.

Different interpretations of material efficiency are not merely a result of quantitative data accumulation but also stem from differences in understanding of the relation between social metabolism and development. Section 8 establishes a framework for classifying diverse indicators measuring material efficiency. That framework serves as an organizing device for researchers and decision makers interested in conducting case studies or setting goals on material efficiency.

2. Mapping material efficiency indicators in anthropogenic cycles of materials

Anthropogenic cycles of materials have been widely studied in the field of industrial ecology (Chen and Graedel, 2012a; Müller et al., 2014). They refer to the flows and stock changes of materials into, within and from the technosphere that are dominated by human activities. An anthropogenic material cycle is generally represented by a series of processes that transform materials from one stage into another