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The role of in-use stocks in the social metabolism and in climate change mitigation

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ABSTRACT

Human well-being includes the use of physical services from buildings, infrastructure, and consumer products. These in-use stocks link the services enjoyed by humans to energy and material consumption. Climate change mitigation requires us to transform current in-use stocks to decouple energy and material throughput from service provision. Assessing the potential environmental benefits of emissions mitigation and other sustainable development strategies requires a solid understanding of in-use stocks and their dynamics.

We identified the different roles of in-use stocks in the social metabolism and showed to what extent they are included in current impact assessment models. We extended state-of-the-art dynamic stock models by including direct and indirect energy demand and greenhouse gas emissions. We applied the new modeling framework to three case studies in the major sectors transportation, buildings, and industry. We assessed the emissions reduction potential of the decoupling strategies energy efficiency, material efficiency, and moderate lifestyle changes.

For the global steel industry and for residential buildings the emissions reduction potential of the above-mentioned strategies was so large that the benchmarks corresponding to the 2 °C climate target could be reached. Decoupling alone might be sufficient to reach the 2 °C benchmarks in some sectors. Considering decoupling next to supply side measures such as new energy technologies may make it easier to consider other objectives than emissions reduction. Decoupling may therefore revitalize the debate about sustainable development because it allows us to loosen the focus on climate change mitigation and put more weight on the economic, social, cultural, and other environmental aspects of sustainability.

1. Introduction

1.1. The transition to a new metabolic regime

Man dominates Earth, human activities reach the physical boundaries set by our planet, and human impacts started transforming the global environment (Barnosky et al., 2012; IPCC, 2007a; Rockström et al., 2009). The examples reported in the above-cited papers include species extinction; desertification; land transformation; human interference with the nitrogen cycle; and climate change. Global physical constraints require a new paradigm for resource use and emissions; the transition from the 'cowboy economy' to the 'spaceman economy' is a prominent example (Boulding, 1966). Other stakeholders call for an 'energy technology revolution', which aims at incorporating a new paradigm into energy supply but not the rest of the economy (OECD/IEA, 2008), or 'sustainable development' (World Commission on Environment and Development, 1987).

To anticipate future challenges related to global physical boundaries and to design mitigation and adaptation strategies, one requires a model framework to study the interactions between human activities, the associated energy and material requirements, and the planetary boundary layer from a systems perspective. This framework is called the *anthropogenic, socio-economic*, or *social metabolism*, and based on previous work (Ayres and Simonis, 1994; Baccini and Brunner, 1991; Fischer-Kowalski and Huttler, 1999; Fischer-Kowalski et al., 2011; Fischer-Kowalski, 2011; Fischer-Kowalski, 1997), it can be defined as *the set of all anthropogenic flows, stocks, and transformations of physical resources and their respective dynamics assembled in a systems context.* Climate change mitigation and other global environmental challenges may require modern societies to transform their social metabolism as radically as during the shift from agrarian to fossil-fuel based industrialized societies. Such transformation is called

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socio-metabolic transition or *shift between socio-metabolic regimes* (Fischer-Kowalski et al., 2011; Fischer-Kowalski, 2011; Haberl et al., 2011; Krausmann, 2011; Krausmann et al., 2008).

1.2. The role of in-use stocks in the social metabolism

Increasing human well-being by alleviating global poverty is a central pillar of development policy (UN, 2013). Human well-being includes the use of physical services such as food, shelter, and transport, whose provision relies on *in-use stocks* in form of products, buildings, factories, or infrastructure. These stocks are actively used by households, governments, the public, or industries, over a certain time span to satisfy service demand and to facilitate industrial production (Baccini and Brunner, 1991; Boulding, 1966). In-use stocks as we conceive them are a subset of fixed assets as defined in the European Standard Accounts (OECD, 2003). They comprise the "built environment (infrastructure and buildings) and artifacts (machinery and durable consumer goods)" (Fischer-Kowalski et al., 2011; Fischer-Kowalski, 2011). Together with humans, livestock, and other domestic animals, in-use stocks form the totality of stocks in the social metabolism (Fischer-Kowalski and Weisz, 1999; Fischer-Kowalski et al., 2011; Fischer-Kowalski, 2011). In-use stocks can be split by product type (cars, buildings, roads, furnaces, etc.) or by end-use sector (private, governmental, public, and industrial). In-use stocks in industrial sectors are usually termed fixed capital (monetary units) or fixed assets (physical units) (European Commission, 2008). The role of in-use stocks in the social metabolism is manifold, and the following list provides a first overview, which is neither comprehensive nor definitive.

Service suppliers: In-use stocks provide service to end-users and industries: Major human activities such as residing, working, transportation, and communication require in-use stocks such as buildings, cars, factories, and machines for their function. In-use stocks can serve as measure of physical service (e.g., car ownership and living space per person), and the stock levels in industrialized countries can serve as *benchmark* for future development in other regions (Müller et al., 2011).

Capital containers and resource repositories: In-use stocks represent large monetary investments and material stocks. Between 10% and 40% of economic output are devoted to building up and maintaining in-use stocks (World Bank, 2013). Stocks link services such as shelter or mobility to economic activity.

Dynamics determiners: In-use stocks determine the long-term dynamics of the social metabolism: Stocks have a slow turnover in many sectors. For example, blast furnaces in the steel industry can reach a lifetime of up to 100 years (Riden and Owen, 1995). This poses constraints to how quick new technologies can replace old ones. The availability of post-consumer scrap for recycling is to a large extent determined by the retirement rate of in-use stocks (Van der Voet et al., 2002).

Wealth watchers: The size of in-use stocks represents a different perspective on human wealth that may complement flow-based affluence measures such as gross domestic product (GDP). The suitability of economic throughput indicators such as gross domestic product as measure of human well-being was criticized by several authors (Goossens et al., 2007; Jackson, 2009; UNDP, 2010). In a physically constrained economy, throughput is precious and should be minimized rather than maximized, and maintenance of stocks becomes the central purpose of economic activity (Boulding, 1966). The stock level measures how much physical capital a society has built up; information that is complementary to throughput measures such as GDP.

Consumption couplers: The physical properties of in-use stocks link the provision of service to energy and material throughput. In the example of a passenger vehicle, the product parameters engine efficiency, mass, area cross-section, and drag coefficient determine the coupling between kilometers travelled and fuel consumption.

City shapers: The spatial arrangement of built environment stocks in human settlements has strong influence on urban density, accessibility, transport distance, and choice of transport mode. Urban stocks as constituents of the urban fabric have been an object of research for some time (Brunner et al., 2004; Kennedy et al., 2007) and determining the location and function of stocks is an integral part of urban design.

1.3. How in-use stocks are reflected in current models of the social metabolism

Material and substance flow analysis (MFA and SFA) as well as material flow accounting recognize in-use stocks as important element of the social metabolism. Additions to in-use stocks enter the mass balance of a process and therefore they have to be considered in mass-balanced systems. Static material flow analyses, typically with a sampling period of one year, have been published for more than 20 years (e.g., Baccini and Brunner, 1991; Baccini and Bader, 1996; Graedel et al., 2004; Rechberger and Graedel, 2002). Some studies contain more than one layer, e.g., the material and the economic layer (Kytzia et al., 2004; Nathani, 2009). Dynamic stock models (Baccini and Bader, 1996; Müller, 2006; Van der Voet et al., 2002) are central in dynamic material flow analysis, and models that calculate entire material cycles from exogenous assumptions on population, the size of in-use stocks, and lifetime were applied to the building sector (Bergsdal et al., 2007; Müller, 2006; Pauliuk et al., 2013b), passenger vehicles (Pauliuk et al., 2012), and the steel sector (Hatayama et al., 2010; Pauliuk et al., 2013a). There has been no systematic discussion about how to assess indirect impacts and emissions caused by the processes and stocks in the system studied.

In process-based life cycle assessment (LCA) the reference flow includes the products required to realize a given functional unit, and physical process inventories are used to determine the inputs and outputs required to build up, operate, maintain, and dispose of the products contained in the reference flow (EU JRC, 2010). A life cycle assessment provides a detailed and specific assessment of individual products, which are part of the in-use stock while being used. Due to their small-scale scope, life cycle assessments provide no information about total resource use and emerging system-wide properties such as the potential for material recycling and the total service level required.

Static input–output modeling does not consider in-use stocks with the end-users as drivers of energy and material demand, the dynamics and requirements of stocks are reflected only indirectly in the final demand vector (Miller and Blair, 2009). The addition to capital stock, the so-called gross fixed capital formation, comprises investment flows to industrial assets and residential buildings and is part of the final demand (European Commission, 2008). Only the technical coefficients of industrial in-use stocks are modeled in form of the A-matrix, but not their dynamics and material content. Both static and dynamic input-output models can be closed for capital demand and service (Duchin and Szyld, 1985; Lenzen and Treloar, 2005), which allows for feeding back the product demand from capacity expansion into the model. These models only consider additions to capital stocks as part of in-use stocks, but not the stocks or their properties and dynamics themselves.

Integrated assessment modeling (IAM) and general equilibrium modeling (GCE) both contain detailed models of productive capital stocks (Burfisher, 2011; Loulou et al., 2005). This is necessary as these models endogenously determine supply curves using a detailed list of different types and in some cases consider vintages of production facilities within each economic sector. Especially technology-rich integrated assessment models such as the 'TIMES'