# The Role of In-Use Stocks in the Social Metabolism and in Climate Change Mitigation

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# The Role of In-Use Stocks in the Social Metabolism and in Climate Change Mitigation

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## Abstract

In-use stocks in form of buildings, infrastructure, and products play a central role in the social metabolism as they link service provision to energy and material throughput. The transition to a low-carbon energy future requires substantial transformation of existing in-use stocks over time. In-use stocks and their dynamics are not consistently considered in the major assessment tools life cycle assessment, input-output analysis, and integrated assessment modeling.

We included direct and indirect energy demand and greenhouse gas emissions into state-of-the-art dynamic stock models, and applied the new modeling framework to three case studies in the major sectors transportation (passenger cars in China), buildings (dwellings in Norway), and industry (the global steel cycle). We investigated how substantial greenhouse gas emissions reductions could be achieved by decoupling the service provided by in-use stocks from energy and material throughput. We considered energy efficiency, material efficiency, and moderate lifestyle changes.

In the case of steel and dwellings, the emissions reduction potential was so large that the sectoral and national benchmarks developed for the 2°C climate target could be reached by decoupling only. The combined emissions reduction potential of supply side measures and stock decoupling may be higher than what is needed to reach the 2°C target, which makes it easier to consider other objectives than mere 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.

**Keywords:** Climate change mitigation; Decoupling; In-use stocks; Social metabolism; Sufficiency; Material flow analysis;

# 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). 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, 1999; 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 *socio-metabolic transition* or *shift between socio-metabolic regimes* (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 use of physical services such as food, shelter, and transport, whose provision relies on products, industries, and infrastructure, which can be described in the framework of social metabolism. The latter allows us to understand the link between the provision of physical services and resource use and environmental impacts. Many physical services within society are provided by *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, 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, 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 level 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**. A substantial fraction of economic output is devoted to building up and maintaining in-use stocks. 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 GDP.** The suitability of economic throughput indicators such as GDP 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 and Rechberger, 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 MFA studies, 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 MFA, 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). A systematic discussion about how to assess indirect impacts and emissions of MFA systems with dynamic stocks is lacking, however.

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). An LCA 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, LCA studies yield no information on 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 IO 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 vintages of production facilities within each economic sector. Especially technology-rich IAMs such as the TIMES-model (Loulou et al., 2005) consider vintages and ageing of production assets and detailed process inventories. Material stocks, however, are covered only inconsistently, if at all. The relation between material and energy throughput, in-use stocks, and service provided to end-users is treated inconsistently and cursory. An example is the steel industry extension of the POLES model, where availability of post-consumer scrap is not limited by the dynamics of in-use stocks, but is taken for granted (Hidalgo et al., 2003).

There is a lack of understanding of how the different roles of in-use stocks influence the transition to a new metabolic regime. This is to a large extent a consequence of the cursory treatment of in-use stocks and their dynamics in the different assessment models. A more consistent and realistic treatment of in-use stocks in the different models of the social metabolism would enable us to better understand the coupling between different human activities, service provision, in-use stocks, and energy and material throughput. Ultimately, this understanding would allow us to quantify the connection between human well-being and resource use, recycling opportunities, waste generation and greenhouse gas emissions.

**Scope and research questions:**

To assess the long-term effect of specific emissions mitigation strategies related to in-use stocks, one needs detailed models of product and material supply chains, account for technological change on the process level, and track products through their useful life. We chose to extend the framework of cohort-lifetime-based dynamic material flow analysis (Baccini and Bader, 1996; Müller, 2006) to assess the direct and indirect resource demand and emissions associated with building up, maintaining, disposing of, and recycling in-use stocks (Pauliuk, 2013). Here the term ‘direct’ refers to emissions directly emitted by in-use stocks, such as direct emissions from passenger cars, and ‘indirect’ refers to emissions that occur elsewhere in the system. This modeling framework allows for much more detailed representation of the social metabolism than the standard system definition of material flow *accounting* (Fischer-Kowalski, 2011), and is in our opinion the natural choice for the questions we worked on. We applied the model in a set of case studies on climate change mitigation on the country- and sectoral level. We chose to focus on climate change mitigation because of the significance and the high level of scientific understanding of climate change (IPCC, 2007b; Rockström et al., 2009), that includes a quantitative correlation between greenhouse gas emissions and temperature stabilization levels (Fisher et al., 2007), and the sustained and unperturbed growth of anthropogenic greenhouse gas emissions further into the unsustainable regime (Peters et al., 2012).

To demonstrate the importance of understanding in-use stock dynamics we focused our assessment on strategies that reduce energy and material throughput while keeping the service provided by in-use stocks constant. We call these *stock decoupling strategies*. These include energy efficiency, material efficiency, moderate lifestyle changes, and combinations thereof. We focused on three specific cases of emissions abatement in the major sectors buildings, transportation, and industry.

We formulated the following research questions:

1) How can existing dynamic stock models be modified and extended to assess climate change mitigation strategies that decouple the physical service provided by in-use stocks from energy and material throughput?

2) Are the emissions reductions from decoupling energy and material from physical service provided by in-use stocks sufficient to limit global warming to 2°C in the transport sector (focus on passenger vehicles in China), the dwelling sector (focus on dwellings in Norway), and the global steel industry?

3) What are the consequences of such transition scenarios for the industrial metabolism of the sectors and countries involved?

In section 2 we provide an overview of our choice of methodology, a systematic allocation of different impact mitigation options in the framework of the socio-economic metabolism, and an approach for benchmarking emissions reductions in a particular country and sector against global emissions reduction targets (question 1). We introduce the three case studies. In section 3 we present and assess the case-study specific strategies for emissions mitigation by decoupling provision of physical services from throughput (questions 2 and 3). In section 4 we discuss how better modeling of the properties and dynamics of in-use stocks would enhance our understanding of greenhouse gas emissions reduction in particular and the potential next social-metabolic transition in general.

## 2) Methodology

### 2.1) Model framework

The system definition of our modeling framework is shown in Figure 1. We use the size of in-use stocks, such as dwelling area, and the physical flows they enable, such as kilometers driven, as proxy for the physical service that in-use stocks provide to humans. To reflect the central role of in-use stocks in the socio-economic metabolism we chose a dynamic stock model to be at the model core (Part A in Figure 1). Unlike flow-driven dynamic stock models that do not quantify the link between stocks and service (Baccini and Bader, 1996; Brattebø et al., 2009; van der Voet et al., 2002), the model as it is used here is stock-driven, which means that we used the exogenous *stock* drivers population, stock per capita, and lifetime, to determine the *flows* of final demand and supply of end-of-life products (Elshkaki, 2005; Müller, 2006; Müller et al., 2004, Müller et al., 1998; Pauliuk, 2013; Sandberg and Brattebø, 2012). Different *vintages* or *cohorts* are tracked over time and according to the level of detail required, the cohorts can be sub-divided into different product types or technologies such as passenger cars of different segments or drive technologies. The dynamic stock model tracks the material content and the specific use phase energy demand for each product type and cohort. Total energy and material throughput is determined by multiplying the specific requirements by utilization parameters such as the number of kilometers driven every year.

The material flow system (Part B in Figure 1) contains the industrial processes required to supply products and materials to the end-user and to process post-consumer waste flows. It is driven by final demand and waste supply determined by the dynamic stock model. Main features of the model include the mass balance for all processes and the product balance for the use phase, the inclusion of material recycling loops, and a linear response of industry output to final demand and scrap supply. The different processes are described by technical parameters, which may change over time. Model parts A and B together form a material flow analysis (MFA) model of the anthropogenic cycles of the products or materials studied, similar to previous MFA work (Mao et al., 2008; Müller et al., 2006).

The different industrial processes in the MFA system rely on the supply of energy and ancillary inputs for their operation, which are supplied by processes beyond the boundary of the material and product foreground (Part C in Figure 1). A systematic assessment of the impact of flows from the industry background is a common task in life cycle assessment (EU JRC, 2010) and environmentally extended input-output analysis (Leontief, 1970; Miller and Blair, 2009), and both techniques are suitable to complement the estimation of direct impacts from the use phase (system A) and the system for manufacturing of goods, material production, and recycling (B). For the case studies presented below we compiled energy demand and case-study-specific ancillary supply from systems A and B into a final demand vector *Y* and scaled up existing impact assessment studies (LCAs) to meet the demand of each item listed in *Y*. Special care regarding the choice of system boundaries and allocation assumptions has to be taken when referring to existing impact assessments. This applies to the appropriate choice of regional specification, potential double-counting between the sub-systems A, B and C, and a harmonized allocation of impacts from by-products and recycling between systems B and C. These issues and the corresponding choices are specific for each case study and are discussed in Pauliuk (2013).

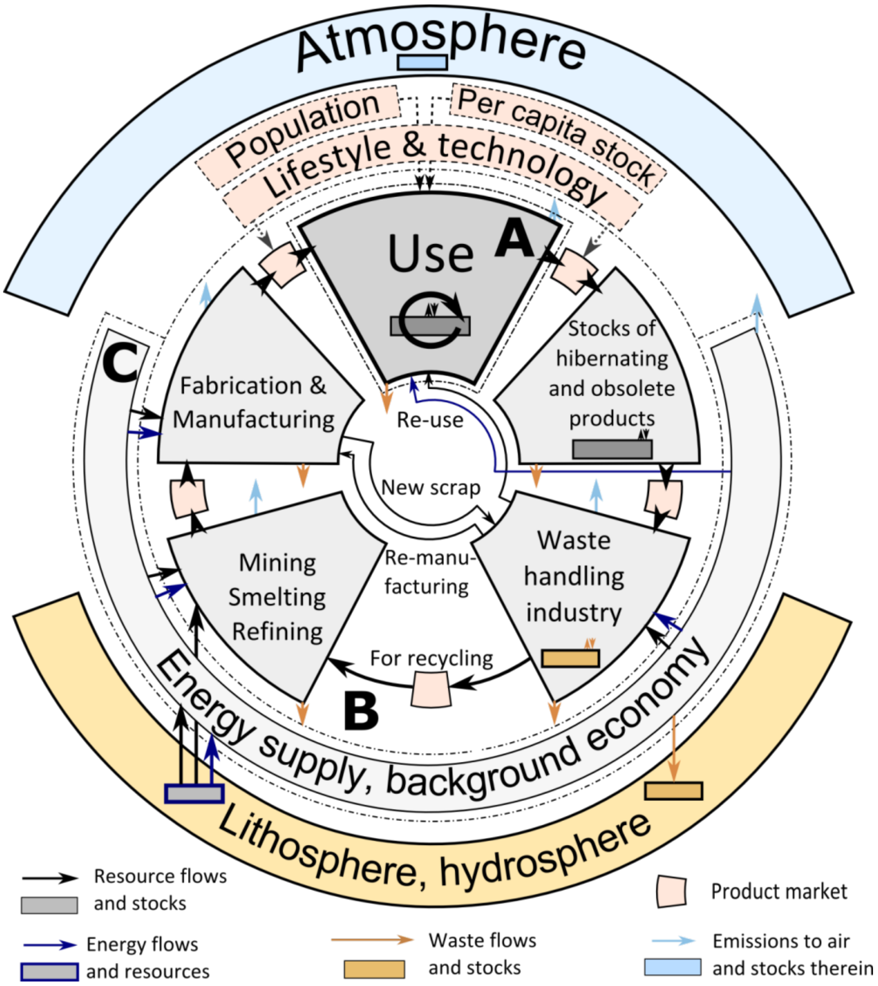

**Figure 1.** System definition with key exogenous drivers of the socio-economic metabolism (light red, dashed). System parts: A: dynamic model of in-use stock; B: material and product foreground system; C: energy supply and ancillary inputs to material production.

The system in Figure 1 allows us to systematically locate the different emissions mitigation options in the socio-economic metabolism. Table 1 contains a list starting with reduction measures for the external drivers population (1) and service level (2), including more intense use of existing stocks, e.g., through a higher occupancy rate of passenger cars. The list continues with so-called *hybrid strategies* that combine technological solutions with alternate products and different user behavior and expectations ((3), examples shown in Table 1), energy efficiency in the use phase (4) and industry (5), material efficiency in the industry (6), lower carbon intensity of energy supply (7), and geo-engineering strategies (8).

**Table 1:** Classification of different GHG emission abatement measures based on the system in Figure 1 and mitigation strategies used for scenario development in the three case studies. The abbreviations in brackets are used in Figure 2.

| **No.** | **Measure, reference, location in system (Fig. 1)** | **Passenger cars in China** | **Dwellings in Norway** | **The global steel cycle** |
|---|---|---|---|---|
| **1** | **Reduce** population (Hardin, 1968; Malthus, 1798), Exogenous driver | Not considered | Not considered | Not considered |
| **2** | **Reduce** service levels or **intensify** use of existing stocks and keep service level, exogenous driver and use phase (A) | Fewer cars per capita (C)<br>Lower annual kilometrage (K) | More persons per dwelling<br>Lower heated floor area per dwelling | More intense use |
| **3** | **Decouple** affluence from material and energy throughput via technology *and* lifestyle (‘*hybrid strategies*’) (keep service level), Use phase (A) | Share of micro cars (T) | Share of passive houses in new construction<br>Share of passive renovation in total renovation<br>Energy consumption for domestic hot water generation<br>Energy consumption by appliances<br>Renovation rate<br>Demolition rate | Light-weighting of products<br>Lifetime extension of products<br>Re-use of products |
| **4** | **Decouple** affluence from material and energy throughput via technology (keep service level), Use phase (A) | Fuel consumption per 100 km (F) | Heating energy demand<br>Share of different heating systems | Considered under hybrid strategies |
| **5** | **Decouple:** Energy efficiency industry, Upstream processes (B, C) | Not considered | Not considered | Energy efficiency industry |
| **6** | **Decouple:** Material efficiency industry (Allwood et al., 2011), Upstream processes (B, C) | Not considered | Not considered | Fabrication yield improvement<br>Fabrication scrap diversion |
| **7** | **Decouple** energy supply from carbon, Upstream processes (B, C) | Not considered | Not considered | Not considered |
| **8** | **Geo-engineering:** $CO_2$ removal Upstream processes (B, C), partly beyond system boundary | Not considered | Not considered | Not considered |

## 2.2) Introduction of case studies

To demonstrate how the size, the lifetime, and the physical properties of in-use stocks determine energy and material throughput in different sectors we conducted three case studies for the sectors transport, buildings, and industry, which accounted for 23%, 33%, and 36% of global energy- and process-related greenhouse gas emissions in 2006, respectively (Allwood et al., 2010). To understand the mitigation options associated with a growing car stock, we studied direct emissions from passenger cars in China (Pauliuk et al., 2012). We then focused on direct and indirect emissions from building, operating, and demolishing residential buildings in Norway (Pauliuk et al., 2013b) to quantify the energy savings potential in a country where passive house standard may soon become mandatory for new buildings (Arnstad, 2010). Here a dynamic stock foreground model was combined with LCA studies on energy and material supply. Finally, we studied direct emissions and emissions from coking and electricity generation associated with the global steel industry (Milford et al., 2013; Pauliuk et al., 2013a), which is the largest industrial source of greenhouse gas emissions and accounts for 25% of industrial carbon emissions (Allwood et al., 2010). Here we combined a dynamic stock model for steel with an MFA model of the steel industry, and LCA studies for energy supply. The complete model approaches, including all equations, data sources, and data processing, documentation of assumptions, are reported in the respective journal papers and their supplementary materials.

In the case studies we examined how the service provided by in-use stocks can be decoupled from material and energy throughput (options (2)-(6) in Table 1). Hence, not all options in Table 1 were considered. This shall demonstrate to what extent emissions can be reduced by using in-use stocks more efficiently. Lower carbon emissions are only one environmental benefit of these strategies; throughput reduction leads to lower industrial emissions in all impact categories as well as lower use of mineral resources.

### 2.3) Parameter choice and scenario definition:

To assess the emissions reduction potential of the different strategies we developed a set of scenarios for each case study. For each model parameter we investigated plausible development under business-as-usual conditions and alternative development under the assumption that industry and society aim at effective emissions mitigation in line with 2°C target, as laid out by the IPCC Fourth Assessment report (Fisher et al., 2007). The parameter choices for the mitigation scenarios are based on the comparison of stock levels between different industrialized countries, case studies, prototypes, or best available technology. They are documented in the respective journal articles. Here, we compare selected scenarios and present them in wedge form: First, we considered energy and material efficiency (categories (4)-(6) in Table 1), then hybrid strategies (3) *in addition*, and finally, service reduction or more intense use (2) *in addition* to the previous measures. For passenger cars in China (Pauliuk et al., 2012), next to the baseline, we included higher fuel efficiency, a change to a fleet of mostly micro cars as hybrid strategy, and lower annual kilometrage and car ownership as service level reduction strategies. The latter can be compensated for by increasing the vehicles' occupancy rate. For dwellings in Norway (Pauliuk et al., 2013b), we selected from the publication the baseline (scenario 1), scenario 16 as efficiency strategy (renovating the entire existing building stock to present energy standards by 2050), scenarios 17 (renovating the entire existing building stock to passive house standard by 2050) and 25 (scenario 17 plus substantial energy savings for hot water generation, lighting, and appliances) as hybrid strategies, and the bottom line (scenario 26, which is scenario 25 plus a lower dwelling area per person) for lifestyle changes. From the case study on steel (Milford et al., 2013; Pauliuk et al., 2013a), we selected medium improvements in industrial energy efficiency and material efficiency for the industry implemented by 2050 as efficiency strategies, light-weighting, lifetime extension, and re-use as hybrid strategies, and more intense use as lifestyle change. All parameter values were taken from the 'Energy Efficiency – medium / Energy & Material Efficiency 2050' scenario in the original study, except that here, we did not consider changes in the carbon intensity of the electricity supply, since this strategy does not belong to the class of measures that decouple stocks from energy and material throughput. Specific choices for energy mix, electricity mix, and carbon emissions intensity of fuels were made for each case study and are documented in the respective articles.

### 2.4) Benchmarking of emissions reductions:

To assess the sectoral and regional mitigation pathways and the resulting carbon footprint of the system in Fig. 1 with respect to global warming targets, a benchmarking routine was developed as till this day, there is no established international guideline for breaking down emissions targets. We assessed sectoral emissions under the assumption that (i) the correspondence between GHG emissions levels in 2050 and temperature stabilization levels is as reported in Figure 3.38 in the IPCC Fourth Assessment Report (Fisher et al., 2007), (ii) in 2050, each individual is allocated the same share of global GHG emissions, and (iii) all sectors are expected to reduce GHG emissions by the same percentage over the period 2010-2050. We derived a set of emissions benchmarks for each temperature stabilization level, sector, and country, by multiplying global energy- and process-related emissions of 2000 of 23.6 gigatonnes per year (UN Statistics Division, 2012) with the temperature-correlated changes reported in Figure 3.38 in Fisher et al. (2007), the expected share of the country's population in the 2050 world population (United Nations, 2011), and the 2006 sectoral split reported by Allwood et al. (2010). We considered this assessment to be a purely technical step, as the comparison with an average represents an unbiased performance measure. The assumption of global contraction and convergence by 2050 (GCI, 2012) and a perspective of global equity (UNFCCC, 1992) also leads to assumption (ii), which can therefore be seen as manifestation of these two principles.

### 2.5) Validity of scenario analysis

The scenarios do not contain any predictions or forecasts of future development; they are if-then stories that combine a set of parameter assumptions with a stock-driven model of the social metabolism to assess the carbon footprint of a given sector. The scenarios were intended to be realistic, however: Whenever possible, we referred to reference cases when estimating the model parameters: This includes population scenarios from UN or IIASA (Lutz et al., 2007; United Nations, 2011), data from industrialized countries with lower car utilization (Pauliuk et al., 2012), case studies on light-weighting and re-use (Allwood et al., 2012), building codes for passive and standard houses (Standards Norway, 2007), or case studies on refurbishment to passive standard (Dokka and Klinski, 2009). The main assumption behind the mitigation scenarios is that small scale and local strategies such as the ones mentioned here can be scaled up to affect a significant share of final demand over the next decades. Trade-offs between different strategies or rebound effects are difficult to model, and only for the study on the global steel cycle, some corrections were made, as, for example, lifetime extension impedes re-use due to increased wear and tear. For case studies on dwellings and passenger cars, no such corrections were made.

## 3) Results

We first present the baseline emissions and then the mitigation wedges associated with energy and material efficiency, hybrid solutions, and lifestyle changes for each case study (question 2, Fig. 2), and then the throughput of passenger cars, dwelling space, and steel, to build up and maintain the respective in-use stocks (question 3, Fig. 3).

### 3.1) Emissions reduction by stock decoupling (question 2)

Emissions from the Chinese passenger vehicle fleet can be expected to rise substantially as car utilization continues to grow. For 2050, the baseline scenario reflects the typical car ownership and use of industrialized countries at present. Large emissions reductions of about one third of baseline emissions can be achieved by improved car design and engine efficiency (from 6l/100km to 4 l/100km), as several case studies showed (blue wedge in Fig. 2a),(Volkswagen AG, 2010). A shift to a fleet of 67% micro cars would represent a trend reversal, and could reduce baseline emissions by another 17% in 2050 (green wedge in Fig. 2a). The potential impact of lower car ownership (from 450/1000 to 300/1000) and kilometrage (from 15000 km/yr to 12000 km/yr), as observed in some industrialized countries, bears a reduction potential of about 25% of baseline emissions or about 50% of the emissions corresponding to the bottom of the green wedge. The bottom line represents a car fleet with the highest presently marketable fuel efficiency, a micro car share of 67%, and a size and annual kilometrage that correspond to the lower present levels in South Korea or Greece. If these emissions reductions represented the global average in 2050, the corresponding level of global warming would be about 3°C. Less successful implementation of the stock decoupling strategies would lead to even higher temperature benchmarks, and a regime lower than 3°C could only be reached by accepting lower service levels or taking additional supply-side measures such as a fuel shift or potentially bio-fuels.

Despite an anticipated growth of the Norwegian population of about one third between 2010 and 2050, the sectoral carbon footprint will decline slightly if the current building codes are implemented for new and demolished buildings according to the current demolishing rate of the dwelling stock of 0.6%/yr (Baseline in Fig. 2b),(Pauliuk et al., 2013b). We studied a hypothetical refurbishment of the entire existing dwelling stock to either the current building code (blue wedge) or passive house standard (blue + dark green wedge), and found that for the latter scenario, ca. 30% of baseline emissions could be saved by 2050. The effect of such a substantial intervention yielded surprisingly low emissions reductions. The reasons for this are the growing population and the fact that the building code only includes targets for reducing energy demand for space heating, and not for domestic hot water generation, appliances and lighting. For passive houses, the share of space heating in total direct energy consumption lies between 10 and 25% (Pauliuk et al., 2013b). The 2°C benchmark could only be reached after reducing the energy footprint of hot water generation, appliances, and lighting, and reducing the dwelling area per person by either reducing dwelling size or increasing the number of persons per dwelling. This is illustrated by the light green wedge and the red wedge in Figure 2b, respectively. The assumptions behind these two wedges are not based on cases studies, however. Some of the wedges in Figure 2b exceed baseline emissions before 2020 because upstream emissions from construction and construction material production rise significantly during the transformation of the building stock. Policies that focus on short-term reductions of sectoral emissions may therefore hinder the adoption of strategies where a short-term increase in emissions is a necessary investment for achieving long-term emissions savings. In Fig. 2b, the width of the red wedge is zero around 2043. This is because in the model, the turnover of the stock is proportional to the stock size. Since the bottom line scenario includes lifestyle changes and hence a smaller stock than all other scenarios, it takes a few years more to complete the transformation of the buildings of the pre-2010 cohorts, and indirect emissions remain on a high level for these few years.

For the baseline scenario of the global steel industry, emissions will remain within the range of 3-3.5 gigatonnes per year (Fig. 2c). Energy efficiency in the steel industry is already on a high level, and the expected improvements over time would lead to a relatively small reduction of about 14%. Material efficiency in the manufacturing sector bears an additional reduction potential of 8%, but to achieve substantial emissions reductions from stock decoupling, one would have to rely on light-weighting and more intense use of steel-containing products. Combined with lifetime extension and re-use, material efficiency has the potential to lower the carbon footprint of the sector to the 2°C benchmark even before 2040 (Fig. 2c). The rise in bottom line emissions after ca. 2035 is a result of the expected growing steel demand in Africa, India, and developing Asia.

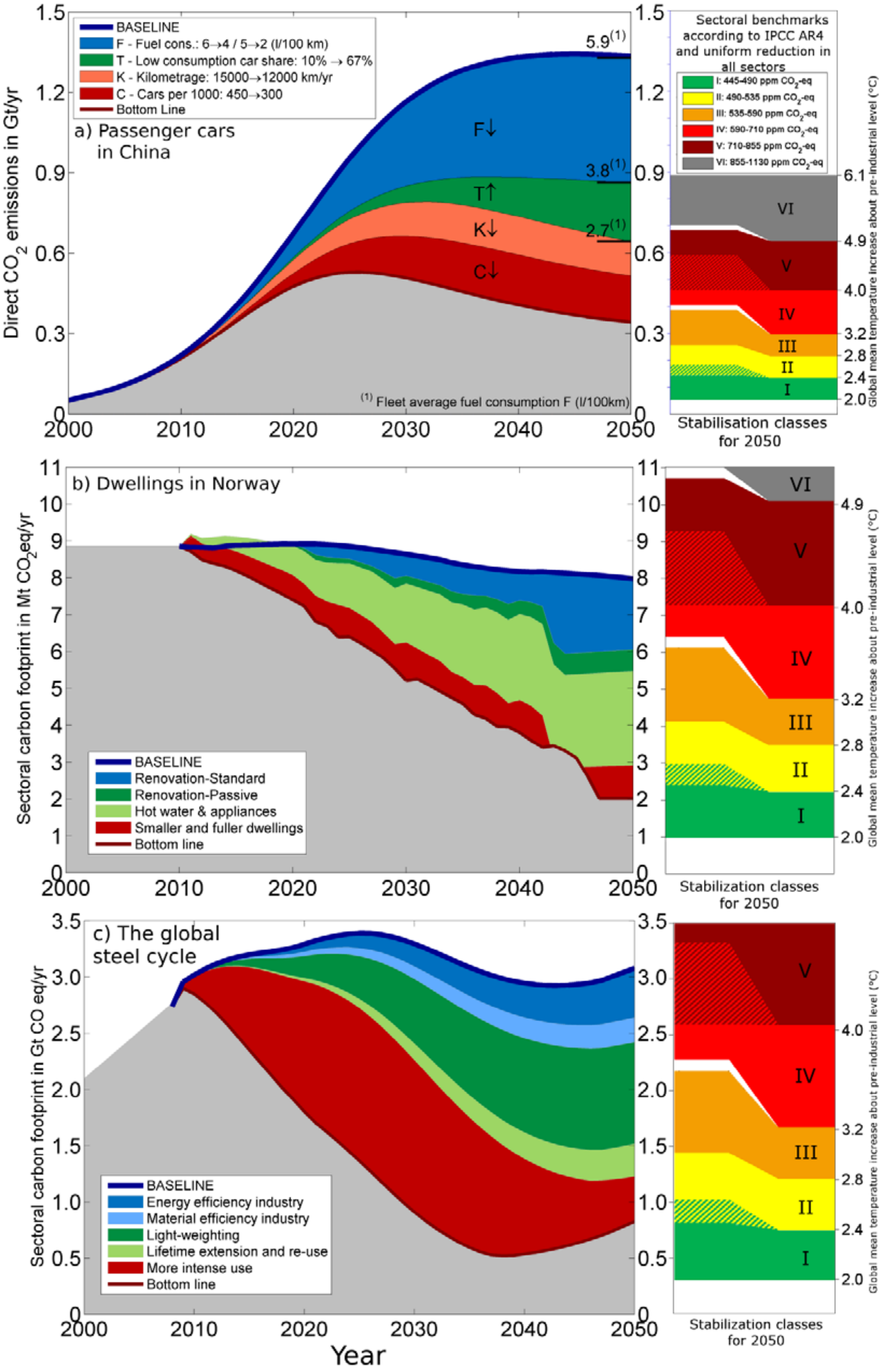

**Figure 2.** Emissions reduction scenarios by sector. Left side: blue wedges: efficiency, green wedges: hybrid solutions, red wedges: lifestyle changes. Right side: Correspondence between sectoral emissions and temperature stabilization benchmarks according to Figure 3.38 in the IPCC Fourth Assessment Report (Fisher et al., 2007), assuming even per capita distribution of global emissions and a split between sectors as in 2006 (Allwood et al., 2010).

### 3.2) Consequences of throughput reduction on industry production (question 3)

Next to the assessment of the carbon footprint in Figure 2, we studied the impact of the stock decoupling strategies on throughput of passenger cars, building space, and steel (Fig. 3). Under business as usual assumptions, passenger car registration in China will rise from the present 10 million units per year to about 40 million units per year (Fig 3a). Increased fuel efficiency, a higher share of micro cars and lower annual kilometrage do not impact the consumption of new vehicles (all represented by the blue lines in Fig. 3a), only a lower car ownership (red lines in Fig. 3a) would reduce the need for new cars by about one third. The flow of end-of-life vehicles follows the inflow with a delay of about 15 years, which is the average lifetime of passenger cars.

For dwellings in Norway (Fig. 3b) the new construction will decrease by about 30% by 2050 if one assumes that population growth slows down (Statistics Norway, 2011) and the dwelling area per person levels out (Bergsdal et al., 2007) (solid blue line in Fig 3b). If people reduced their living space by about 25% the demand for new dwellings could fall to zero by 2050 (solid red line in Fig. 3b). Under business-as-usual assumptions, the renovation showed a slight, but steady increase due to the growing size of the dwelling stock (dashed blue line in Fig. 3b). In the transformation scenarios, however, renovation activity would increase by a factor of 3-4 over the next decades to allow for complete transformation of the stock (dashed green and red lines in Fig. 3b). Once transformation is complete, no more renovation to reducing energy demand would be necessary, and the activity levels would drop to zero.

For the baseline and the efficiency scenarios, global primary steel production will peak around 2025 at a level that is 20-25% higher than the present output, and will settle at about present levels by 2050 (solid blue lines in Fig. 3c). Implementing hybrid strategies and more intense use will cause primary production to peak earlier and the subsequent decline to be larger. For the hybrid strategies, primary output in 2050 will be similar to 2000 levels, and implementing more intense use in addition may cause primary production to drop to levels below 250 Mt/yr. For the baseline and energy efficiency scenarios, secondary production will continue to rise at about the present speed. Implementing industrial material efficiency diverts new scrap away from re-melting and leads to lower future secondary steel production. In the use phase, lifetime extension and re-use delay and reduce the supply of old scrap with the consequence that in the bottom line scenario, secondary steel production would remain at present levels for the next decades.

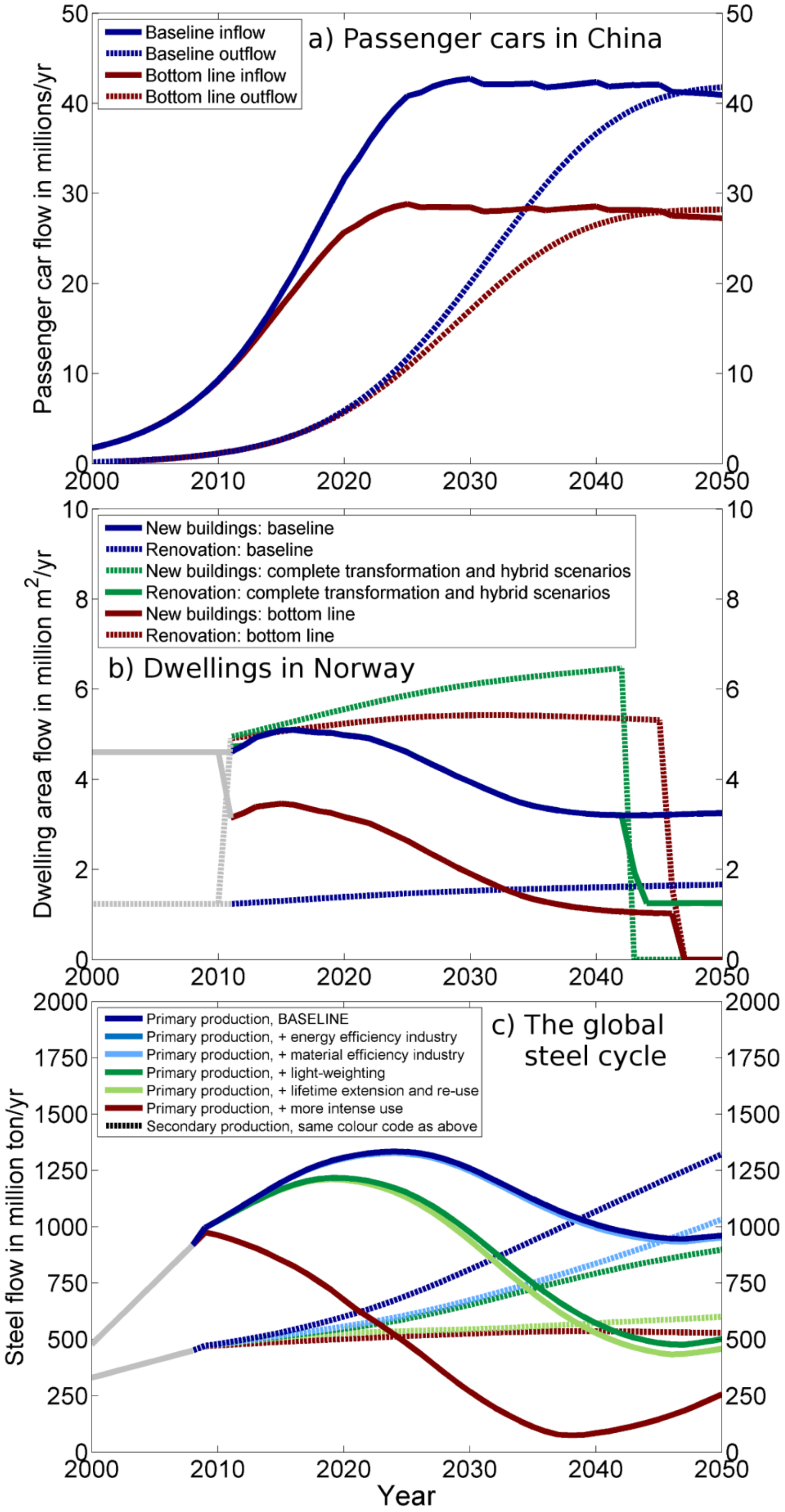

**Figure 3.** Industry output by sector. Passenger cars in China (a), dwellings in Norway (b), and the global steel cycle (c). The scenarios presented include cumulative parameter changes; each scenario includes all changes made in the scenarios higher up in the legend.

## 4) Discussion

### 4.1) Climate change and the role of stocks in climate change mitigation

More intense use of existing stocks, a wide spectrum of material and energy efficiency strategies in manufacturing and final consumption, and service lifetime changes, may extend our toolbox of emissions mitigation strategies, which may make climate change mitigation less dependent on contentious technological choices on the supply side such as an up-scaling of nuclear power or large-scale deployment of carbon capture and storage. The specific challenges of implementing the different strategies are discussed in the papers on the case studies (Milford et al., 2013; Pauliuk et al., 2013b, Pauliuk et al., 2012). Here we discuss policy-relevant conclusions on how to achieve substantial emissions cuts across countries and sectors, connect the case studies to the theme of stocks in the social metabolism, and point out future research options.

#### 4.1.1) What changes if we take the supply side into account?

Supply-side measures including new energy technologies are expected to bear a large potential for emissions reductions (GEA, 2012; OECD/IEA, 2008). There is some concern, however, about counter-trends such as increasing energy demand to extract industrial minerals (Norgate, 2010) and fossil fuels, especially from marginal reserves and tar sands (Unnasch and Pont, 2007), demand from new sectors as technology and culture develops (Arvesen et al., 2011), and rebound effects (Barker et al., 2009; Hertwich 2005; Madlener and Alcott, 2009). Decoupling stocks from service provision complements supply-side measures, which are at the focus of emissions mitigation today. The combined emissions reduction potential of supply side measures and stock decoupling may be higher than what is needed to reach the 2°C target, which makes it easier to consider other objectives than mere 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. Relying on only one of these four criteria, as for example in the abatement cost curve (McKinsey&Company, 2009) may oversimplify the challenge that climate change mitigation represents, as such assessment may not consider adverse environmental impacts of different mitigation measures, the material resources needed to implement the different strategies, or behavioral change required by some strategies. Stock decoupling provides new leverages to policy makers to reduce emissions and other impacts while keeping a high service level.

#### 4.1.2) Sectoral approaches as one way to break down global targets

As of today, there is no international treaty on climate change mitigation based on country-level quotas that are in line with the 2°C target. Emissions embodied in international trade change the footprint of many countries by 30% or more (Hertwich and Peters, 2009), and building up infrastructure stocks causes large emissions in developing countries (Müller et al., 2013). That casts into doubts whether national boundaries are the best criterion for breaking down a global reduction target. A global, sectoral approach, as demonstrated in the case study on steel, may represent a complementary approach for certain industries because it allows us to design portfolios of specific mitigation strategies and map them to the respective actors within each sector (Bodansky, 2007; Schmidt et al., 2008). On the downside, a focus on a certain industry makes it difficult to take into account innovation in materials and services and substitution of service provision between sectors, e.g., a potentially environmentally desirable substitution between steel, concrete, aluminum, carbon fibers, or timber. Sectoral break-downs of global emissions targets may give new impulses to the international negotiations on a global climate treaty.

#### 4.1.3) Contraction and convergence

Central in the benchmarking process was the assumption that per capita greenhouse gas emissions in all parts of the world will converge by 2050. If some world regions develop slower, emissions in the remaining parts of the world could be higher while the entire world would still be in line with the overall target.

The case study on the steel cycle showed a novel example of how the concept of contraction and convergence (GCI, 2012) could be realized for a specific material. More intense use and light-weighting could decouple service provision from steel stocks and eventually, this could lead to lower in-use stocks in developed countries. The amount of steel needed to provide the present service levels in many developed countries would *contract*, and global stock levels could *converge* by redistributing part of the already existing in-use stocks between the different world regions. Large amounts of steel scrap would become available in industrialized countries and could be shipped to the developing world, where the scrap could be recycled and used mainly in construction, which is the dominant application for secondary steel (Cullen et al., 2012). In this scenario the global primary steel production would be much lower than under business-as-usual assumptions (Milford et al., 2013), and so would be the carbon emissions. Material efficiency may be a central strategy to facilitate contraction of in-use stocks. Combined with suitable strategies on product lifetime and end-of-life recovery, material efficiency would lead to lower material throughput and associated carbon emissions.

#### 4.1.4) The role of stocks in the case studies

**Table 2:** The roles of stocks considered in the case studies

| | **Passenger Cars** | **Residential Buildings** | **The global steel cycle** |
|---|---|---|---|
| **‘Service Suppliers’** | x | x | x |
| **‘Capital Containers’** | - | - | - |
| **‘Resource Repositories’** | - | - | x |
| **‘Dynamics Determiners’** | x | x | x |
| **‘Wealth Watchers’** | x | x | x |
| **‘Consumption Couplers’** | x | x | - |
| **‘City Shapers’** | - | - | - |

The case studies consider only some aspects of in-use stocks listed above, which leaves much room for future improvement of the models (Table 2). All three case studies quantified the service supplied by in-use stocks, use the stock level as development indicator, and explicitly model stock dynamics. Coupling between the product and material layers, consideration of the monetary layer, and the arrangement of in-use stocks to the urban fabric were beyond the scope of the case studies. For future modeling efforts we refer to section 4.2.1.

#### 4.1.5) Deliberate design of in-use stocks to bridge the gap between techno-sphere and user sphere

Dividing emissions mitigation into technological and behavior- or lifestyle related aspects has a long tradition. Examples include the IPAT framework (Chertow, 2001; Ehrlich and Holdren, 1971; Graedel and Allenby 1995), and the statement of the role of technology in climate change mitigation in the 4th IPCC assessment report and IEA's Energy Technology Perspectives cited above (IPCC, 2007c; OECD/IEA, 2008). Our work showed that by retaining this divide one may overlook a large spectrum of what we called hybrid strategies that combine technological and behavioral change and that could account for 20% of the potential throughput reductions on the demand side for the passenger vehicle fleet (via a shift to smaller cars) and as much as 50% of the emissions reductions from the Norwegian dwelling stock (via passive houses and reduced energy consumption for hot water generation and appliances) and from the global steel industry (via light-weighting, lifetime extension, and re-use). In order to realize the full potential of these strategies, one will have to take an integrated perspective considering the interplay between human agents and technology (Owens and Driffill, 2008). A technologically optimal product may yield lower net emissions reductions than a solution designed to yield maximal emissions savings in a system that comprises both the functionality of the product and the user behavior. The case studies showed the importance of stock dynamics and the coupling between stocks and service provision for emissions mitigation. Full utilization of the emissions reduction potential of hybrid strategies requires not only deliberate product design but also careful long-term planning of entire stocks including their dynamics and spatial arrangement. Policy makers would have to consider systems that not only comprise the supply chain and use phase of the product but also the users and the linkages to other sectors and in-use stocks.

### 4.2) The role of in-use stocks in the social metabolism (continued)

#### 4.2.1) Stocks as couplers between different sectors:

The systems defined in the case studies are not independent of each other; there is some overlap in form of stocks. Steel, for example, is contained in buildings and vehicles, and more intense use and lifetime extension of steel-containing product stocks directly translates into changing parameters in the building and transportation sectors (stocks as 'consumption couplers'). Other links are more indirect, for example does the location of buildings and industries determine transportation distances and with it the service demanded from the passenger vehicle fleet (stocks as ‘city shapers’). To allow for an integrated assessment of material cycles across different end-use sectors and to determine the impact of location on transportation demand, we envision a global, multi-regional, dynamic stock model of all major product categories with high spatial resolution. Combined with the assessment of indirect impacts as shown in the case studies, this framework would allow for assessing the consequences of different environmental policies and impact mitigation strategies on the different material cycles, on regional distribution of production capacities, and on settlement structures. Such a model could provide complementary insights to integrated assessment or general equilibrium models, which have comprehensive market modeling capacity but limited coverage of material and spatial aspects. Careful and sophisticated modeling of in-use stocks is necessary to understand the linkages between different end-use sectors and to determine the impact of these linkages on emissions mitigation strategies.

#### 4.2.2.) Physical and capital stocks

Our model does not contain a monetary dimension; it is purely physical. This was sufficient for a macro level analysis of in-use stocks, where only the total future service level and emissions reductions, but not their distribution within society, were quantified. Most stock decoupling strategies have substantial impact on material and commodity production (cf. Fig. 3), which would require certain sectors to reduce their output. To reconcile economic development with throughput reduction researches developed visions and business models that shift away the focus from throughput maximization to maintenance of in-use stocks (Boulding, 1966; Stahel, 2006). A first step towards better understanding the economic consequences of decoupling in-use stocks from material and energy throughput is to build a common framework for modeling the physical *and* monetary aspects of in-use stocks in general and fixed capital stocks in particular (stocks as ‘Capital Containers’, ‘Resource Repositories’, and ‘Consumption Couplers’). This framework would allow modelers to explicitly consider the different roles of in-use stocks pointed out here in economic models. This refers to model families that contain detailed models of capital stocks, such as integrated assessment or general equilibrium models and those that consider capital formation only, such as multi-regional input-output models. With a combined economic and physical representation of in-use stocks at the core, such integration would enable researchers and practitioners to address both environmental and economic aspects of sustainability within a harmonized and integrated model framework, which could help to fully embed the physical layer into currently prevailing economic principles.

#### 4.2.3) In-use stocks and the metabolic transition to sustainability

The transition to a sustainable anthropogenic metabolism can be perceived as metabolic state shift or transition between different socio-metabolic regimes (Marina Fischer-Kowalski, 2011). A central aspect of this transition is the transformation of current in-use stocks and the surrounding industrial system into a new state with higher energy and material efficiency, deployment of alternative technologies, and potentially different spatial arrangement (stocks as ‘Service Suppliers’, ‘Consumption Couplers’, ‘Dynamics Determiners’, and ‘City Shapers’). Such transformation is a necessary, but not sufficient condition for the next metabolic transition to happen. Not sufficient, because the drivers behind stock dynamics, such as the paradigm of perpetuated economic growth, may have to change as well.

### 4.3) Conclusion

In-use stocks supply services to people and their dynamics determine the speed at which technological change can be implemented on the large scale. In-use stocks couple physical services with demand for energy and materials. We showed that decoupling service from stocks and stocks from throughput bears a substantial emissions mitigation potential, which demonstrates that adequate long-term planning and management of in-use stocks may be essential to reaching ambitious climate targets. The combined emissions reduction potential of supply side measures and stock decoupling may be higher than what is needed to reach the 2°C target, which makes it easier to consider other objectives than mere 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.

### References

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Material efficiency: A white paper. Resources, Conservation and Recycling 55, 362–381.

Allwood, J.M., Cullen, J.M., Carruth, M.A., Cooper, D.R., McBrien, M., Milford, R.L., Moynihan, M., Patel, A.C.H., 2012. Sustainable Materials: with both eyes open. UIT Cambridge, UK, Cambridge, UK.

Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for achieving a 50% cut in industrial carbon emissions by 2050. Environmental Science & Technology 44, 1888–94.

Arnstad, E., 2010. Making buildings energy-efficient. An ambitous and realistic plan for 2040 (Original title: Energieffektivistering av bygg. En ambisiøs og realistisk plan mot 2040). Task force under the Norwegian Ministry of Local Government and Regional Development, Oslo, Norway.

Arvesen, A., Bright, R.M., Hertwich, E G, 2011. Considering only first-order effects? How simplifications lead to unrealistic technology optimism in climate change mitigation. Energy Policy 39, 7448–7454.

Ayres, R.U., Simonis, U.E., 1994. Industrial Metabolism: Restructuring for Sustainable Development. United Nations University Press, Tokyo.

Baccini, P, Brunner, P H, 1991. Metabolism of the Anthroposphere. Springer-Verlag, Berlin.

Baccini, Peter, Bader, Hans-Peter, 1996. Regionaler Stoffhaushalt. Erfassung, Bewertung und Steuerung. Spektrum, Heidelberg.

Barker, T., Dagoumas, A., Rubin, J., 2009. The macroeconomic rebound effect and the world economy. Energy Efficiency 2, 411–427.

Barnosky, A.D., Hadly, E. a, Bascompte, J., Berlow, E.L., Brown, J.H., Fortelius, M., Getz, W.M., Harte, J., Hastings, A., Marquet, P. a, Martinez, N.D., Mooers, A., Roopnarine, P., Vermeij, G., Williams, J.W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D.P., Revilla, E., Smith, A.B., 2012. Approaching a state shift in Earth’s biosphere. Nature 486, 52–8.

Bergsdal, H., Brattebø, H, Bohne, R.A., Müller, D B, 2007. Dynamic material flow analysis for Norway’s dwelling stock. Building Research and Information 35, 557–570.

Bodansky, D., 2007. International Sectoral Agreements in a Post-2012 Climate Framework, SSRN Electronic Journal. Arlington, VA.

Boulding, K.E., 1966. The Economics of the Coming Spaceship Earth, in: Jarret, H. (Ed.), Environmental Quality in a Growing Economy. Johns Hopkins University Press, Baltimore.

Brattebø, Helge, Bergsdal, H., Sandberg, Nina Holck, Hammervold, J., Müller, Daniel B., 2009. Exploring built environment stock metabolism and sustainability by systems analysis approaches. Building Research & Information 37, 569–582.

Brunner, Paul H, Rechberger, Helmut, 2004. Practical Handbook of Material Flow Analysis. CRC/Lewis, Boca Raton, FL.

Burfisher, M.E., 2011. Introduction to Computable General Equilibrium Models. Cambridge University Press, New York.

Chertow, M.R., 2001. The IPAT Equation and Its Variants: Changing Views of Technology and Environmental Impact. Journal of Industrial Ecology 4, 13–29.

Cullen, J.M., Allwood, J.M., Bambach, M.D., 2012. Mapping the global flow of steel: from steel making to end-use goods. Environmental Science & Technology 46, 13048–55.

Dokka, T.H., Klinski, M., 2009. Myhrerenga housing cooperation: Ambitious renovation of blocks from the 60ies with passive house components (Myhrerenga borettslag: Ambisiøs rehabilitering av 1960-talls blokker med passivhuskomponenter), Passivhus Norden 2009. Oslo, Norway.

Duchin, F., Szyld, D.B., 1985. A Dynamic Input Output Model With Assured Positive Output. Metroeconomica 14.

Ehrlich, P.R., Holdren, J.P., 1971. Impact of population growth. Science 171, 1212–1217.

Elshkaki, a, 2005. Dynamic stock modelling: A method for the identification and estimation of future waste streams and emissions based on past production and product stock characteristics. Energy 30, 1353–1363.

EU JRC, 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment. European Union, Luxembourg.

European Commission, 2008. Eurostat Manual of Supply, Use and Input-Output Tables, 2008 edition. Eurostat, Luxembourg.

Fischer-Kowalski, M, Huttler, W., 1999. Society’s Metabolism: The Intellectual History of Materials Flow Analysis, Part II, 1970-1 998. Journal of Industrial Ecology 2, 107–136.

Fischer-Kowalski, M., 1997. Basic methodological questions (Methodische Grundsatzfragen), in: Fischer-Kowalski, M. (Ed.), Gesellschaftlicher Stoffwechsel Und Kolonisierung Von Natur. Gordon and Breach Fakultas, Amsterdam, pp. 57–66.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, a., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and Indicators of Economy-wide Material Flow Accounting. Journal of Industrial Ecology 15, 855–876.

Fischer-Kowalski, M., Weisz, H., 1999. Society as Hybrid between Material and Symbolic Realms: Toward a Theoretical Framework of Society-Nature Interaction. Advances in Human Ecology 8, 215–251.

Fischer-Kowalski, Marina, 2011. Analyzing sustainability transitions as a shift between socio-metabolic regimes. Environmental Innovation and Societal Transitions 1, 152–159.

Fisher, B.S., Nakicenovic, N., Alfsen, K., Corfee Morlot, J., De la Chesnaye, F., Hourcade, J.-C., Jiang, K., Kainuma, M., La Rovere, E., Matysek, A., Rana, A., Riahi, K., Richels, R., Rose, S., Van Vuuren, D., Warren, R.;, 2007. Issues related to mitigation in the long-term context., in: B. Metz P.R. Bosch, R. Dave, L.A. Meyer;, O.R.D. (Ed.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental; Cambridge University Press., Cambridge, United Kingdom and New York, NY, USA.

GCI, 2012. Contraction and Convergence (C&C) - Climate Justice without vengeance [WWW Document]. URL http://www.gci.org.uk/endorsements.html (accessed 3.10.13).

GEA, 2012. Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Goossens, Y., Mäkipää, A., Schepelmann, P., Van de Sand, I., Kuhndtand, M., Herrndorf, M., 2007. Alternative progress indicators to Gross Domestic Product (GDP) as a means towards sustainable development. EU Parliament, Policy Department, Economic and Scientific Policy, Strassbourg, France.

Graedel, T E, Allenby, B.R., 1995. Industrial Ecology. Prentice Hall, Upper Saddle River, NJ.

Graedel, T E, Van Beers, D., Bertram, M., Fuse, K., Gordon, R.B., Gritsinin, A., Kapur, A., Klee, R.J., Lifset, R.J., Memon, L., Rechberger, H, Spatari, S., Vexler, D., 2004. Multilevel cycle of anthropogenic copper. Environmental Science & Technology 38, 1242–1252.

Haberl, H., Fischer-Kowalsky, M., Krausmann, Fridolin, Martinez-Alier, J., Winiwarter, V., 2011. A Socio-metabolic Transition towards Sustainability? Challenges for Another Great Transformation. Sustainable Development 19, 1–14.

Hardin, G., 1968. Tragedy of Commons. Science 162, 1243–&.

Hatayama, H., Daigo, I., Matsuno, Y., Adachi, Y., 2010. Outlook of the world steel cycle based on the stock and flow dynamics. Environmental Science & Technology 44, 6457–63.

Hertwich, E G, 2005. Consumption and the Rebound Effect: An Industrial Ecology Perspective. Journal of Industrial Ecology 9, 85–98.

Hertwich, Edgar G, Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. Environmental Science & Technology 43, 6414–20.

Hidalgo, I., Szabo, L., Calleja, I., Císcar, J.C., Russ, P., Soria, A., 2003. Energy consumption and CO2 emissions from the world iron and steel industry, Technical Report Series. European Comission - Joint Reasearch Centre / IPTS, Report EUR 20686 EN, Seville, Spain.

IPCC, 2007a. Summary for Policymakers., in: B. Metz P.R. Bosch, R. Dave, L.A. Meyer, O.R.D. (Ed.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press., Cambridge, UK.

IPCC, 2007b. Climate Change 2007: Synthesis Report, Summary for Policymakers. Cambridge University Press., Cambridge, UK.

IPCC, 2007c. Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jackson, T., 2009. Prosperity without growth. Routledge, London.

Kennedy, C., Cuddihy, J., Engel-Yan, J., Univ Toronto, D.C.E.T.O.N.M.S.A.C., 2007. The changing metabolism of cities. Journal of Industrial Ecology 11, 43–59.

Krausmann, Fridolin, 2011. The socio-metabolic transition . Long term historical trends and patterns in global material and energy use. Institute of Social Ecology, Vienna.

Krausmann, Fridolin, Fischer-Kowalski, Marina, Schandl, Heinz, Eisenmenger, N., 2008. The Global Sociometabolic Transition. Journal of Industrial Ecology 12, 637–656.

Kytzia, S., Faist, M., Baccini, Peter, 2004. Economically extended—MFA: a material flow approach for a better understanding of food production chain. Journal of Cleaner Production 12, 877–889.

Lenzen, M., Treloar, G.J., 2005. Endogenising Capital: A comparison of Two Methods. Journal of Applied Input-Output Analysis 10, 1–11.

Leontief, W., 1970. Environmental repercussions and the economic structure: An input-output approach. The Review of Economics and Statistics 52, 262–271.

Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. Documentation for the TIMES Model. Paris, France.

Lutz, W., Sanderson, W., Scherbov, S., 2007. IIASA's 2007 Probabilistic World Population Projections, IIASA World Population Program Online Data Base of Results 2008. IIASA, Laxenburg, Austria.

Madlener, R., Alcott, B., 2009. Energy rebound and economic growth: A review of the main issues and research needs. Energy 34, 370–376.

Malthus, T.R., 1798. An Essay on the Principle of Population. J. Johnson, London.

Mao, J.S., Dong, J., Graedel, T.E., 2008. The multilevel cycle of anthropogenic lead. Resources, Conservation and Recycling 52, 1058–1064.

McKinsey&Company, 2009. Pathways to a Low-Carbon Economy - Version 2 of the Global Greenhouse Gas Abatement Cost Curve. McKinsey&Company, New York.

Milford, R.L., Pauliuk, S., Allwood, J.M., Müller, D B, 2013. The Roles of Energy and Material Efficiency in Meeting Steel Industry CO2 Targets. Environmental Science & Technology 47, 3455–3462.

Miller, R.E., Blair, P.D., 2009. Input-Output Analysis Foundations and Extensions. Cambridge University Press, New York.

Müller, D B, 2006. Stock dynamics for forecasting material flows - Case study for housing in The Netherlands. Ecological Economics 59, 142–156.

Müller, D B, Baccini, P, Heinimann, H.R., Bader, H.P., 1998. Modellierung, Simulation und Bewertung des regionalen Holzhaushaltes. D-BAUG. ETH, Zurich.

Müller, D B, Bader, H-P, Baccini, P, 2004. Long-term Coordination of Timber Production and Consumption Using a Dynamic Material and Energy Flow Analysis. Journal of Industrial Ecology 8, 65–87.

Müller, D B, Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F., Brattebø, H, 2013. Carbon Emissions of Infrastructure Development. Environ. Sci. Technol., http://dx.doi.org/10.1021/es402618m.

Müller, D B, Wang, T, Duval, B, 2011. Patterns of iron use in societal evolution. Environmental Science & Technology 45, 182–188.

Müller, Daniel B, Wang, Tao, Duval, Benjamin, Graedel, T E, 2006. Exploring the engine of anthropogenic iron cycles. Proceedings of the National Academy of Sciences of the United States of America 103, 16111–6.

Nathani, C., 2009. Analysing the Economic Impacts of a Material Efficiency Strategy, in: Suh, S. (Ed.), Handbook of Input-Output Economics in Industrial Ecology. Springer, Dordrecht.

Norgate, T., 2010. Deteriorating ore resources. Energy and water impacts., in: Graedel, T.E., van der Voet, E. (Eds.), Linkages of Sustainability. The MIT Press, Cambridge, Mass.

OECD, 2003. Glossary of statistical terms [WWW Document]. URL http://stats.oecd.org/glossary/detail.asp?ID=998 (accessed 3.10.13).

OECD/IEA, 2008. Energy Technology Perspectives: Scenarios and Strategies to 2050. Paris, France.

Owens, S., Driffill, L., 2008. How to change attitudes and behaviours in the context of energy. Energy Policy 36, 4412–4418.

Pauliuk, S., 2013. The Role of Stock Dynamics in Climate Change Mitigation. PhD Thesis, NTNU, Trondheim, Norway.

Pauliuk, S., Dhaniati, N.M.A., Müller, D B, 2012. Reconciling sectoral abatement strategies with global climate targets: the case of the Chinese passenger vehicle fleet. Environmental Science & Technology 46, 140–7.

Pauliuk, S., Milford, R.L., Müller, D B, Allwood, J.M., 2013a. The Steel Scrap Age. Environmental Science & Technology 47, 3448–3454.

Pauliuk, S., Sjöstrand, K., Müller, D B, 2013b. Transforming the Norwegian Dwelling Stock to Reach the 2 Degrees Celsius Climate Target. Journal of Industrial Ecology 17, 542–554.

Peters, G.P., Andrew, R.M., Boden, T., Canadell, J.G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M.R., Wilson, C., 2012. The challenge to keep global warming below 2 °C. Nature Climate Change 3, 4–6.

Rechberger, H, Graedel, T E, 2002. The contemporary European copper cycle: statistical entropy analysis. Ecol. Econ. 42, 59–72.

Riden, P., Owen, J.G., 1995. British Blast Furnace Statistics 1790-1980. Merton Priory Press, Cardiff.

Rockström, J., Steffen, W., Noone, S., Persson, Å., 2009. A safe operating space for humanity. Nature 461, 472–475.

Sandberg, N H, Brattebø, H, 2012. Analysis of energy and carbon flows in the future Norwegian dwelling stock. Building Research and Information 40, 123–139.

Schmidt, J., Helme, N., Lee, J., Houdashelt, M., 2008. Sector-based approach to the post-2012 climate change policy architecture. Climate Policy 8, 494–515.

Stahel, W., 2006. The Performance Economy. Palgrave Macmillan, London.

Standards Norway, 2007. Determination of the energy performance of buildings, methods and data (Beregning av bygningers energiytelse Metode og data). Standard Norge, Lysaker, Norway.

Statistics Norway, 2011. Population projections. National and regional figures, 2011-2060. Statistics Norway, Kongsvinger, Norway.

UN, 2013. The Millennium Development Goals Report 2013. New York.

UN Statistics Division, 2012. Millenium Development Goals Indicators - Carbon dioxide emissions [WWW Document]. URL http://mdgs.un.org/unsd/mdg/ (accessed 3.10.13).

UNDP, 2010. Human Development Report 2010, 20th Anniversary Edition. UN Human Development Report Office, New York.

UNFCCC, 1992. United Nations Framework Convention on Climate Change, Article 3: Principles. Geneva, Switzerland.

United Nations, 2011. World Urbanization Prospects, the 2011 Revision [WWW Document]. URL http://esa.un.org/unup/CD-ROM/Urban-Rural-Population.htm (accessed 3.10.13).

Unnasch, S., Pont, J., 2007. Full Fuel Cycle Assessment, Well to Tank Energy Inputs, Emissions, and Water Impacts. Cupertino, CA.

Van der Voet, E., Kleijn, R., Huele, R., Ishikawa, M., Verkuijlen, E., 2002. Predicting future emissions based on characteristics of stocks. Ecological Economics 41, 223–234.

Volkswagen AG, 2010. Technical data of the new XL1. Wolfsburg, Germany.

World Commission on Environment and Development, 1987. Our Common Future. UN, Oxford.