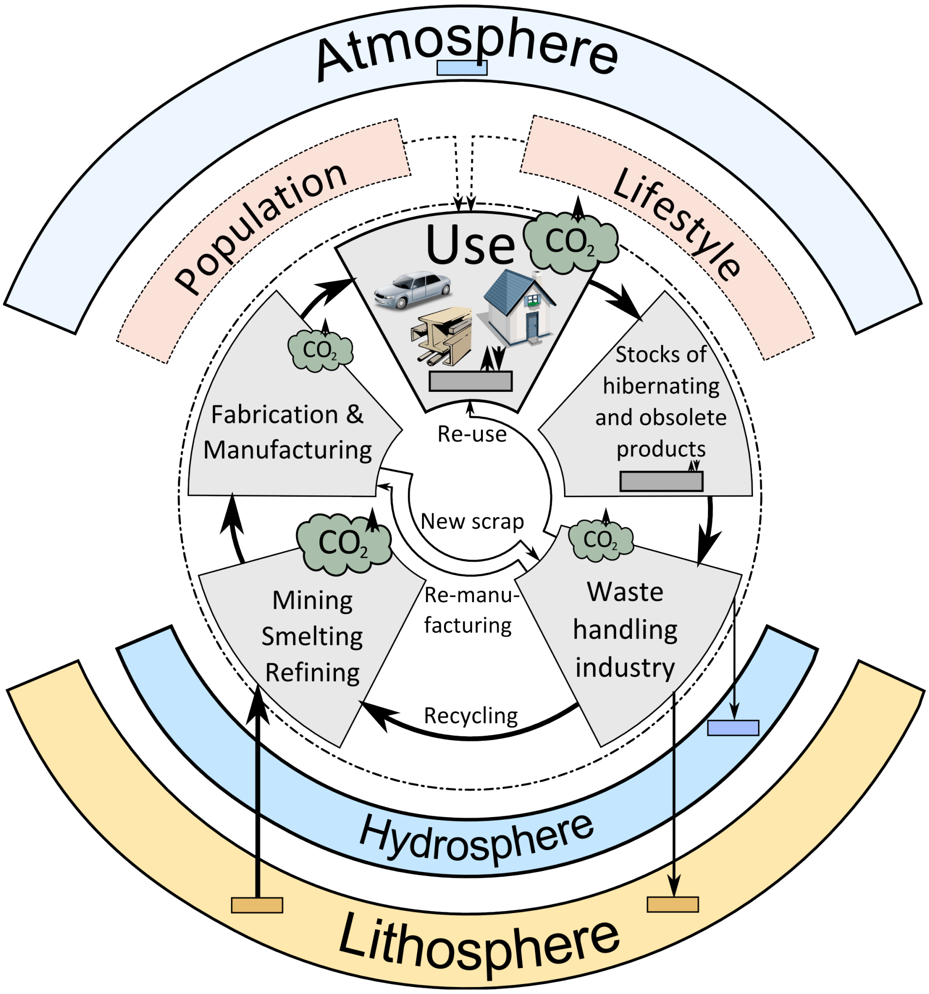
“Sustainability is a cultural phenomenon.”

John R. Ehrenfeld


Atmosphere
Population
Lifestyle
Use
CO2
Stocks of hibernating and obsolete products
Fabrication & Manufacturing
CO2
Re-use
New scrap
CO2
Mining Smelting Refining
CO2
Re-manu-facturing
Waste handling industry
Recycling
Hydrosphere
Lithosphere

The Role of Stock Dynamics in Climate Change Mitigation

Stefan Pauliuk

Doctoral thesis

Electronic version

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Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
Department of Hydraulic and Environmental Engineering

NTNU – Trondheim
Norwegian University of
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Sammendrag

”Dynamikken til produktmengder i bruk og deres betydning for å redusere global oppvarming”

Menneskeskapt klimaendring, også kalt global oppvarming, truer vår framtidige utvikling på jordkloden. I sin fjerde hovedrapport slår FNs klimapanel (IPCC) fast at hovedårsaken til global oppvarming er utslipp av drivhusgasser fra bruk av fossilt brensel og avskoging. For å unngå potensielt uhåndterlige konsekvenser, bør den gjennomsnittlige temperaturøkningen ikke overstige 2 °C sammenlignet med den førindustrielle tidsalderen. Dette betyr at menneskelige utslipp av drivhusgasser må reduseres med 50-85 % i perioden 2000-2050. Per i dag finnes det ingen internasjonal avtale for å oppnå dette klimamålet, og de globale karbonutslippene forstetter å stige:
Globale utslipp av energirelaterte drivhusgasser var 32 gigatonn CO_2-ekvivalenter i 2011. Tallet har økt med 35 % siden 2000. Industrien sto for 36 % av det totale utslippet, etterfulgt av bygninger med 33 %, transport med 23 %, og andre sektorer med 8 %.

Vi har utviklet en modell som kan vurdere ulike langsiktige strategier for å redusere karbonutslipp i ulike land og sektorer. Istedenfor å bruke økonomiske tall som bruttonasjonalprodukt som indikator for framtidig vekst, refererer vi til fysiske mål som bilparkens og bygningsmassens størrelse som velferdsindikatorer. Disse produktmengdene i bruk har flere sentrale funksjoner i samfunnet: a) de yter tjenester til innbyggerne, b) de endrer seg langsomt og påvirker den langsiktige dynamikken i samfunnets metabolisme, c) de kan brukes som indikatorer og eksterne modellparametere for framtidig utvikling.

Vi har laget en rekke strategier for å redusere karbonutslipp knyttet til produksjon, bruk, og avhending av produkter og materialer i de sentrale sektorene biltransport, boligbygg, og stålindustri. Vi har fokusert oss på strategier som skiller utviklingen i material- og energibruken fra produktmengdenes størrelse for å oppnå betydelige utslippsreduksjoner. Disse strategiene er delt inn i tre typer tiltak: (i) *Energieffektivisering* i dagens produkter og industrielle prosesser. (ii) *Hybride løsninger*

som omfatter energi- eller materialeffektive produkter i kombinasjon med atferds- eller holdningsendringer hos brukerne. Mikrobiler, passivhus og produkter med forlenget levetid er typiske eksempler. (iii) *Endringer i livsstil* over hele samfunnet som medfører at produktmengdene i bruk reduseres over tid. Her har vi referert til andre utviklede land der produktmengdene i bruk er lavere allerede i dag. Mindre boligareal per person, færre biler per person, eller mindre stålbruk per person er eksempler.

Vi har gjennomført kasusstudier på direkte utslipp fra den kinesiske bilparken, direkte og indirekte utslipp fra den norske boligmassen, og direkte og indirekte utslipp fra den globale stålindustrien.

Beregningene våre har vist at selv en massiv økning i energieffektiviteten ikke i noen av kasusstudiene har ført til utslippskutt som er nødvendig for å nå det globale 2 °C-målet. Men kombinasjonen av de tre typene tiltak beskrevet over førte til store utslippsreduksjoner: Ved å slå sammen potensialene for energieffektivisering, hybride løsninger og lavere produktmengder i bruk gjennom livsstilsendringer var det mulig å oppnå 2 °C-målet i boligbygg- og stålsstudien. Det totale reduksjonspotensialet for personbiler i Kina har blitt anslått til 75 % av de forventede utslipp uten tiltak, men det er ikke tilstrekkelig for å oppnå 2 °C-målet i denne sektoren.

Resultatene for den kinesiske bilparken for året 2050 kan overføres til alle land med en bilpark som i stor grad bruker bensin. Scenariene for boligbygg i Norge kan ikke direkte overføres til andre land på grunn av lokale klimaforhold og elektrisitetsmiksen.

Vi har ikke tatt hensyn til mulige endringer i karbonintensiteten i energimiksen over tid. Dette fremstår som en begrensing som må tas i betraktning når resultatene tolkes.

Material- og energieffektivisering, hybride løsninger, og moderate endringer i livsstil utvider verktøykassen med strategier for å bekjempe global oppvarming, som kan gjøre det mer sannsynlig at vi oppnår 2 °C-klimamålet. Strategier som skiller material- og energibruken fra produktmengdenes størrelse kan medføre en rekke andre miljøgevinster samt lavere ressursforbruk. Disse strategiene kan danne et alternativ til de mest risikofylte dekarboniseringstiltakene på forsyningssiden, som kjernekraft eller karbonfangst og -lagring. Denne fraskillingen innebærer imidlertid store utfordringer for industri og brukere, siden den utfordrer dagens økonomiske og sosiale paradigmer.

Summary

Man-made climate change or global warming represents a major threat to mankind's future development. At the 2010 UN Climate Change Conference in Cancún, the international community acknowledged that in order to prevent dangerous anthropogenic interference with the climate system, the global average temperature increase should be kept within 2°C relative to the pre-industrial level. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that anthropogenic greenhouse gas emissions are the main driver of global warming, and that in order to meet the 2°C climate target, annual anthropogenic emissions of greenhouse gases need to be reduced by 50-85% by 2050 compared to the 2000 level. A legally binding international commitment on achieving emissions reductions of that extent is not in place, and annual global greenhouse gas emissions continue to rise. In 2011, global energy- and process-related greenhouse gas emissions were estimated to be about 32 Gigatonnes of CO_2-equivalents, which is about 35% more than in 2000. Transportation accounted for 23% of total emissions, buildings for 33%, industry for 36%, and other sectors for 8%.

I developed a new modeling framework to assess different climate change mitigation pathways in different countries and sectors for the years until 2050. Instead of using projections on future GDP growth as exogenous model drivers, I referred to in-use stocks of passenger vehicles, buildings, infrastructure, or appliances as physical measures of affluence. These in-use-stocks of different products and materials play a threefold role in society: (i) they provide services to the end user; (ii) they have a slow turnover and determine the long-term dynamics of the social metabolism; (iii) they can serve as indicators for future development in industrializing countries.

I conducted three case studies on direct emissions from passenger cars in China, direct and indirect emissions from residential buildings in Norway, and direct and indirect emissions from the global steel industry. I investigated to what extent the throughput of material and energy can be *decoupled* from in-use stocks and considered three decoupling strategies (i)-(iii). (i) *Increased energy efficiency* in currently available products and industrial processes. (ii) *Hybrid solutions,* which are energy and/or material efficient products that require a change in the users' behavior or expectations.

Micro cars, passive houses, re-use of products, or product lifetime extension, are examples. (iii) *Society-wide lifestyle changes* that may cause countries to develop in-use stocks that lie in the lower range of the stocks currently observed in the developed world. Examples include lower car ownership levels, a smaller dwelling area per person, or lower steel stocks per person. To assess the strategies in individual sectors and countries with respect to the 2°C global climate target, I derived a set of *benchmarks* assuming that all sectors uniformly reduce emissions, and that all people on earth are allocated a uniform emissions quota for 2050.

My results showed that full-scale implementation of currently available more energy-efficient technologies (class (i)) could not lead to emissions reductions that are in line with the 2°C global climate target. But the combined mitigation potential of the three classes was large. When combining the strategies from classes (i)-(iii), the 2°C benchmark could be reached for residential buildings in Norway and the global steel industry. For passenger cars in China, the total emissions reduction potential in 2050 was 75% compared to development business-as usual, which, however, was not enough to reach the 2°C benchmark.

The 2050 scenario results for passenger cars in China can be applied to any country with a mature car stock that mostly consumes gasoline. The results for residential buildings in Norway cannot be directly applied elsewhere due to the country-specific climate and electricity mix, as the latter two determine the sectoral energy demand and its carbon intensity. I did not consider temporal changes in the carbon intensity of the energy supply in the case studies for transportation and buildings, which represents a central limitation that has to be kept in mind when interpreting my results.

Material and energy efficiency, hybrid solutions, and lifestyle changes extend the toolbox of emission abatement strategies, which may increase the probability of eventual success in fighting climate change. Moreover, the decoupling strategies reduce the overall energy and material throughput and thus, they lead to additional environmental benefits and lower the demand for mineral resources. These strategies may represent an alternative to the potentially most risky or most expensive supply-side measures, such as nuclear power or carbon capture and storage. Decoupling throughput from stocks, however, may pose huge challenges to both industry and end users as it, to some extent, may require a renunciation of present social and economic paradigms.

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Finally, I wish to thank my family and friends in Germany, who keep on longing for me to return, for their patience.

I dedicate this work to my parents, who always encouraged me to explore new pathways.

Trondheim, November 2012

Stefan Pauliuk

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Paper I	*Reconciling Sectoral Abatement Strategies with Global Climate Targets: The Case of the Chinese Passenger Vehicle Fleet* Stefan Pauliuk, Ni Made Arya Dhaniati, Daniel B. Müller, Environmental Science and Technology 2012, 46(1) pp. 140-147.	Data refining, model development, analysis, visualization, and writing
Paper II	*Transforming the Norwegian dwelling stock to reach the 2°C climate target – Combining MFA and LCA techniques* Stefan Pauliuk, Karin Sjöstrand, Daniel B. Müller, Journal of Industrial Ecology 2013. DOI: 10.1111/j.1530-9290.2012.00571.x	Research design, data refining, model design and development, analysis, visualization, and writing
Paper III	*Steel All Over the World: Estimating In-use Stocks of Iron for 200 Countries* Stefan Pauliuk, Tao Wang, Daniel B. Müller, Resources Conservation and Recycling 2013, 71(February 2013), pp. 22-30.	Research design, data collection, model design and development, analysis, visualization, and writing
Paper IV	*The Steel Scrap Age* Stefan Pauliuk, Rachel L. Milford, Daniel B. Müller, Julian M. Allwood, Environmental Science and Technology 2013. DOI: 10.1021/es303149z	Data collection, model design and development, analysis, visualization, and writing
Paper V	*The roles of energy and material efficiency in meeting steel industry CO_2 targets* Rachel L. Milford, Stefan Pauliuk, Julian M. Allwood, Daniel B. Müller, Environmental Science and Technology 2013. DOI: 10.1021/es3031424	Model design and development, parts of project documentation

1. Introduction

1.1 Human development under physical constraints

1.1.1 Human development and the Earth's carrying capacity

High human development with comprehensive and affordable access to water, food, education, health services, communication, and transport requires a stable political system, a functioning economy, and considerable amounts of energy and materials (UNDP 2010; Gaye 2007; Martinez and Ebenhack 2008). Different indices of human development indicate that only about 30% of the world's population have a high standard of living (UN Human Development Report Office 2011). Examples of global poverty problems include the share of humanity that currently does not have access to clean drinking water (11%), electricity (25%), or improved sanitation (36%) (Gronewold 2009; UNICEF/WHO 2012). Moreover, the Earth's population is expected to grow by about one to three billion by 2050 (UN Population Division 2011). Most of this increase is expected to occur in poorer countries (UN Population Division 2011), which may further exacerbate the global poverty problem.

Over large parts of the world, a lifestyle based on high consumption and the pursuit of material items, such as homes and cars, is the predominant role model for human development (Reusswig et al. 2003). Besides an increase in human prosperity, this lifestyle results in high levels of material demand, energy consumption, and waste generation (IEA 2007; USGS and Niggol Seo 2007; Hoornweg and Bhada-Tata 2012). The industries required to support this lifestyle interact with the environment in two ways. Upstream, material and energy resources such as water, crops, minerals, and fossil fuels are fed into the industrial processes. Downstream, waste flows such as tailings, exhaust, and wastewater are released into the environment. The current global industrial system uses more of these resources and emits more waste than Earth can supply or tolerate in the long run. Examples of resources that mankind may run short of already in the 21st century include crude oil, phosphate rocks and copper ore, and ecosystem services such as freshwater supply or arable land (Rockström et al. 2009; Meadows et al. 1972; WWF 2012). Another example that received global attention only about twenty years ago is global warming. This term describes a rise in the average temperature on the Earth's surface due to the atmospheric accumulation of anthropogenic emissions of carbon dioxide (CO_2) and other greenhouse gases. The main sources of these emissions are the combustion of fossil fuels and land use change (WMO 1986; Hansen 1988; Weart 2003).

This brief review can be summarized as follows:

(1) A significant fraction of the world's population lacks access to many of the services that are taken for granted in industrialized countries.

(2) At present, high human development is coupled to high levels of resource consumption and waste generation.

(3) There is much evidence that mankind's current utilization levels of several biotic and abiotic resources cannot be maintained throughout the entire 21st century; hence, these levels exceed Earth's long-term *carrying capacity*.

1.1.2 The ascent of sustainable development

The pursuit of high living standards without respecting the Earths carrying capacity may undermine mankind's future prosperity, and here, I present two seminal publications on this issue.

In his 1966 essay "The Economics of the Coming Spaceship Earth", Kenneth E. Boulding describes industrialized societies as 'Cowboy Economies', using the cowboy as symbol of "reckless, exploitative, romantic, and violent behavior", that, in his opinion, characterizes current economies (Boulding 1966). He anticipates the problem of global resource shortage in a world where all resources and ecosystem services have already been claimed, and proposes the alternative concept of the 'Spaceman Economy', which is a closed economy where resources are limited and waste flows remain within the system. He continues his analysis by showing that the Cowboy Economy is based on throughput in the form of consumption flows and the idea of unlimited resources and sinks. Contrarily, the Spaceman Economy has limited resource stocks and sinks to absorb human waste and, hence, throughput is precious and should be limited or even minimized. The Cowboy Economy strives to maximize throughput *flows*, whereas the Spaceman economy aims at preserving *stocks*. The duality of stocks and flows pointed out by Boulding will be a recurring theme throughout the entire thesis.

The report “Our Common Future”, issued by the United Nations World Commission on Environment and Development in 1987, introduces the concept of ‘sustainable development’ as a normative approach to mitigate the discrepancy between lack of development and resource overuse pointed out above. In that report, ‘sustainable development’ is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development 1987). The report recognizes that the multitude of current environmental problems is interlinked and closely related to how the present human society uses limited natural resources and ecosystem services. Sustainable development has an environmental, social, and economic component, with each being indispensable for reaching a sustainable regime (Scott Cato 2009).

1.2 Climate change – a pivotal challenge

This thesis focuses on a specific environmental aspect of sustainability, global warming. This term denotes the average temperature increase of the Earth’s atmosphere and the oceans since the 19th century.

In 1827, Fourier stated that the atmosphere raises the Earth’s surface temperature (Fourier 1827). Later, John Tyndall attributed this effect to certain molecules with alterable or inducible electric dipole moments such as water vapor, carbon dioxide, and methane (Tyndall 1872). In 1896, Arrhenius estimated the effect of a doubling of the CO_2 concentration in the atmosphere on Earths mean surface temperature (Arrhenius 1896). Given the anthropogenic greenhouse gas emissions at that time, he believed that such a doubling would take thousands of years. Between 1870 and 1970, global temperature records showed both rising and falling trends, which led to a scientific debate on whether human interference with the natural climate system eventually would lead to higher or lower average temperatures (Ehrlich 1968; Peterson et al. 2008).

Only about 35 years ago, a scientific consensus was reached that anthropogenic greenhouse gas emissions cause the Earth’s mean surface temperature to rise (Bryson 1971; Suomi et al. 1979; Peterson et al. 2008). This particular type of climate change has been called ‘global warming’ ever since, and the issue has entered the public debate and became relevant to policy makers, industry, and mainstream research. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established to compile scientific assessments of climate change, its possible consequences, and how mankind could respond to it through both mitigation and adaptation (IPCC 2012).

Throughout the rest of this work, I use the terms ‘global warming’, ‘man-made climate change’, and ‘climate change’ as synonyms.

There are three reasons why I focus on man-made climate change.

(1) The first one is the severity of its consequences. Uncurbed global warming may lead to large changes in temperature and precipitation patterns all over the world as well as rising sea levels due to partial melting of ice sheets (Parry et al. 2007). The consequences of such changes are hard to anticipate, but there is some agreement among scientists that excessive global warming may undermine many of the ecosystem services we benefit from today and lead to more extreme weather phenomena such as droughts and floods, biodiversity loss, or fires. Social and economic crises might follow, with poor regions like Africa being most vulnerable (Parry et al. 2007). Since weather is a nonlinear complex system, there is a poorly understood risk that exceeding a certain ‘tipping temperature’ might cause abrupt and irreversible changes such as self-enforcing temperature rise, cessation of the thermohaline circulation in the oceans, or critical transitions in the biosphere. (Houghton et al. 2001; Schneider et al. 2007; Barnosky et al. 2012).

(2) The second reason is that climate change is scientifically well understood. The causes and mechanisms were identified with high certainty and from model calculations, a non-linear relationship between the greenhouse gas concentration stabilization level and the average atmospheric temperature increase could be established. Atmospheric CO_2 concentrations from 350-790 parts per million (ppm) of CO_2 equivalents (CO_2eq) are likely to lead to a temperature increase in the range of 1.4-8.5K (Fig. 1, Table 1), (Fisher et al. 2007). In order to prevent dangerous anthropogenic interference with the climate system, the global average temperature increase should be kept within 2°C compared to the pre-industrial state (UN Climate Change Conference 2009). According to the IPCC Fourth Assessment Report (IPCC AR4), anthropogenic greenhouse gas emissions are the main driver of global warming (IPCC 2007a). In order to keep global warming within the 2°C range, the report suggests to reduce the annual anthropogenic emissions of greenhouse gases by 50-85% by 2050 compared to the 2000 level (Table 1),(Fisher et al. 2007).

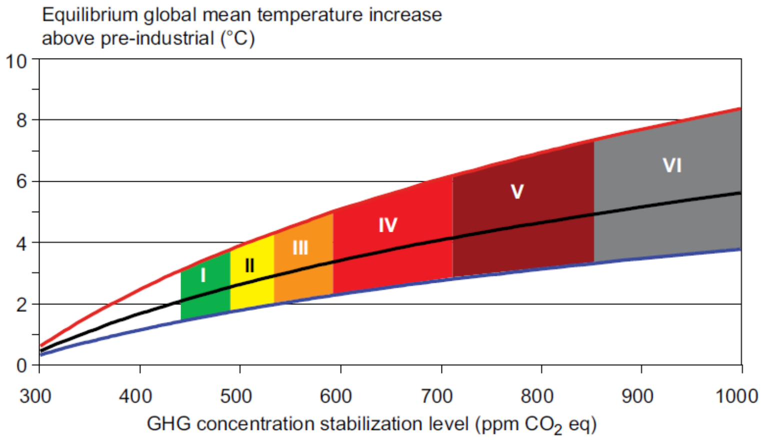
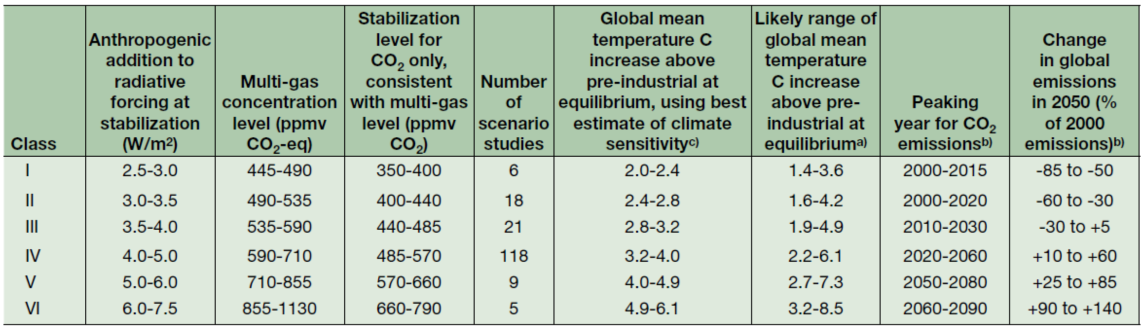


Figure 1: Global mean temperature increase over eventual greenhouse gas concentration in the atmosphere. From Table 3.10 in IPCC AR4. Source: (Fisher et al. 2007).

Table 1: The relationship between global mean temperature increase and emissions reduction targets. From Figure 3.38 in IPCC AR4. Source: (Fisher et al. 2007).



Class	Anthropogenic addition to radiative forcing at stabilization (W/m²)	Multi-gas concentration level (ppmv CO_2-eq)	Stabilization level for CO_2 only, consistent with multi-gas level (ppmv CO_2)	Number of scenario studies	Global mean temperature C increase above pre-industrial at equilibrium, using best estimate of climate sensitivity[c)]	Likely range of global mean temperature C increase above pre-industrial at equilibrium[a)]	Peaking year for CO_2 emissions[b)]	Change in global emissions in 2050 (% of 2000 emissions)[b)]
I	2.5-3.0	445-490	350-400	6	2.0-2.4	1.4-3.6	2000-2015	-85 to -50
II	3.0-3.5	490-535	400-440	18	2.4-2.8	1.6-4.2	2000-2020	-60 to -30
III	3.5-4.0	535-590	440-485	21	2.8-3.2	1.9-4.9	2010-2030	-30 to +5
IV	4.0-5.0	590-710	485-570	118	3.2-4.0	2.2-6.1	2020-2060	+10 to +60
V	5.0-6.0	710-855	570-660	9	4.0-4.9	2.7-7.3	2050-2080	+25 to +85
VI	6.0-7.5	855-1130	660-790	5	4.9-6.1	3.2-8.5	2060-2090	+90 to +140

(3) The third reason is the apparent difficulty of mitigating climate change. Emissions of carbon dioxide and other greenhouse gases are strongly coupled to industrialization and economic development (Jackson 2009) and have risen for more than two centuries in a row (Ghosh and Brand 2003). CO_2 is usually not a local pollutant and the atmospheric concentrations are two orders of magnitude below the toxicity level, which is at about 7 per cent by volume (US EPA 2010). Global warming is a typical *problem of scale*, where a large number of small emissions flows that are not considered harmful on the local scale add up to a global environmental challenge.

A legally binding international commitment on achieving emissions reductions that are in line with the 2°C target is not in place, and thus, annual global greenhouse gas emissions continue to rise (Olivier et al. 2012).

I provide a brief overview of the current levels of greenhouse gas emissions in different countries and sectors. In 2006, global energy- and process-related greenhouse gas emissions were 28.6 Gt/yr, where 23% stemmed from transportation, 33% from buildings, 36% from industry, and 8% from other sectors. Buildings, industry, and transport together accounted for more than 90% of all emissions (Fig. 2) (Allwood et al. 2010; IEA 2008; OECD/IEA 2007). The steel industry was the largest industrial emitter of carbon; it accounted for 25% of industrial emissions or about 9% of global energy- and process-related carbon emissions in 2006.

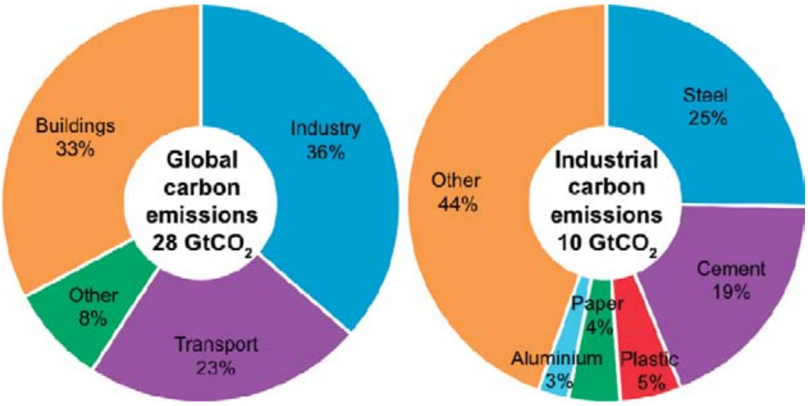


Figure 2: Global energy- and process related carbon emissions of 2006, broken down on different sectors. Source: (Allwood et al. 2010) Data sources: (IEA 2008; OECD/IEA 2007).

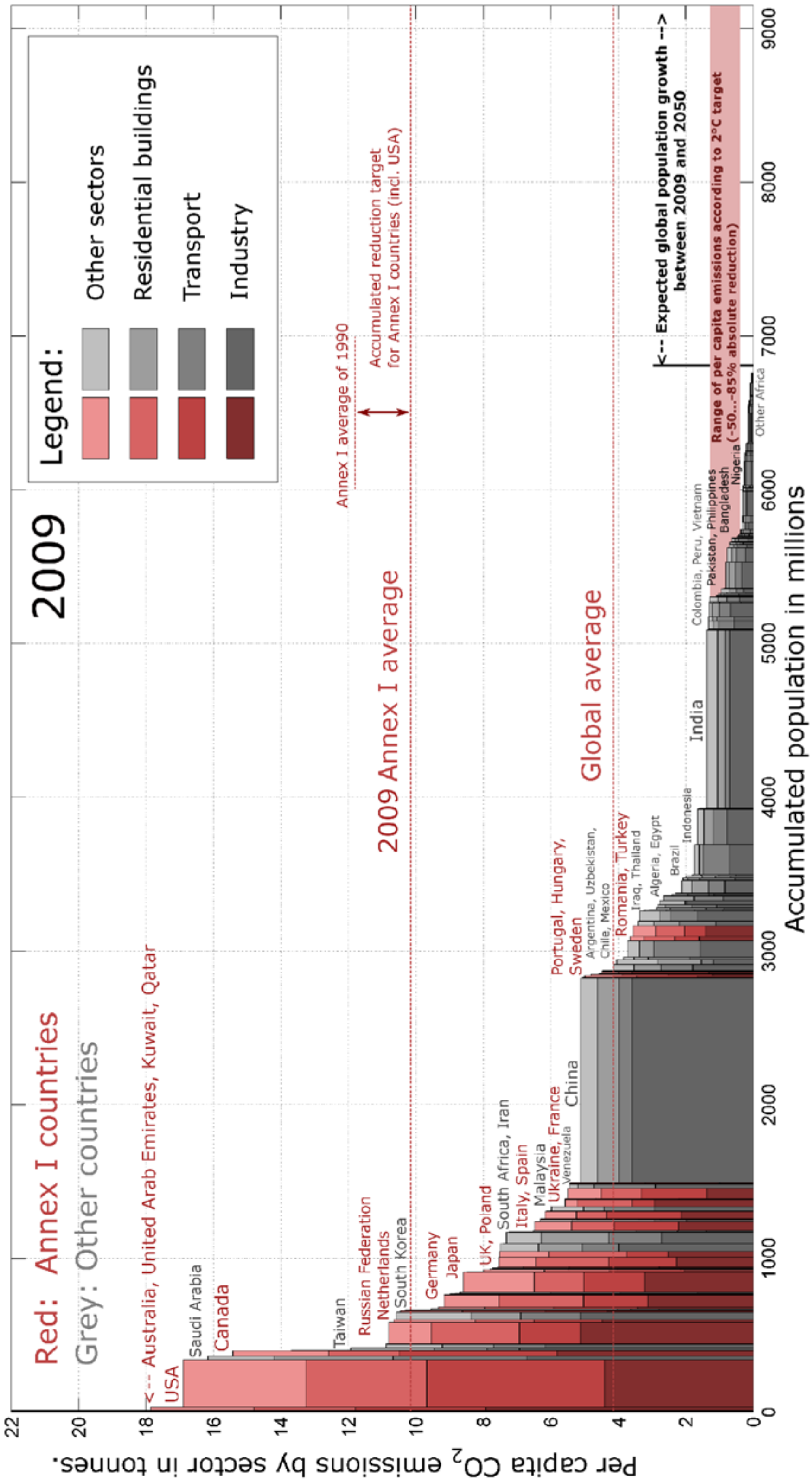


Figure 3: CO_2 emissions of 2009 by country and sector. Data sources: (International Energy Agency 2011; Olivier et al. 2011). The Kyoto target for the Annex I countries is almost identical to the 2009 Annex I average.

By 2009, emissions had risen to about 30 Gt/yr, and Figure 3 shows a breakdown of the global emissions by different countries and sectors. For most developed countries, emissions lay well above the global average. Industry dominated the carbon footprint of developing countries, whereas the shares of the different sectors were more balanced in the developed world. Taking into account that the Earth's population may increase by another 2 billion by 2050 according to the UN medium population scenario (UN Population Division 2011), the resulting per capita emissions quota that is in line with the 2°C target would be at 0.4-1.3 tonnes (Table 1).

Figure 3 illustrates the discrepancy between lack of economic development and current ecosystem overuse that was pointed out above. High economic development, as seen in the Annex I countries, entails per capita emissions that are between one and four times the current global average. But the current average is already three to ten times higher than the range required to curb global warming to 2°C.

1.3 Climate change and its reflection in policy, technology, economics, and environmental modeling

This section provides a review of legislation on climate change mitigation, the current spectrum of mitigation strategies, the current view in environmental and ecological economics, and the different modeling approaches that have evolved. At the end of each sub-section, I identify gaps in the existing knowledge and in section 1.4 I motivate my research questions based on these gaps.

1.3.1 Responses in policy

Policy makers all over the world have recognized the challenge that global warming represents, and already at the Rio summit in 1992, the UN Framework Convention on Climate Change (UNFCCC), that aims at mitigating severe changes of the earth's climate, was released (UNFCCC 2012b). In 1997, the Kyoto protocol came into force (UNFCCC 2012a). It contains specific emissions reduction targets for 37 developed countries (the so-called Annex-I countries) and was ratified by 192 states. Olivier et al. (2011) found that the Annex-I countries together are on their way to meet the Kyoto target for 2012. This is mainly due to the economic downturn in the countries of the former East Bloc after 1990. Emissions in the U.S., which did not ratify the Kyoto protocol, have increased by 11% since 1990 (Olivier et al. 2011). When re-allocating emissions abroad that can be attributed to domestic consumption – so-called emissions embodied in trade – the carbon footprint of several Annex-I countries increases significantly (Hertwich and Peters 2009; Steinberger et al. 2012; Peters et al. 2012). For example, the UK reduced its domestic carbon footprint by 6% over the period 1990-2004, but when including emissions abroad that can be attributed to customers in the UK, the carbon footprint rose by 11% (Jackson 2009). At the Copenhagen summit in 2009, negotiations for a successor of the Kyoto protocol ended without the member states of the UN agreeing on a binding agreement for different countries or sectors of energy use. Instead the Copenhagen Accord, a mere declaration of intent without legally binding status, was adopted (UN Climate Change Conference 2009). However, several individual states, where climate change mitigation has arrived in mainstream policy, have set up national targets at different ambition levels. Table 2 gives an overview of national greenhouse gas emissions reduction targets that were effective in 2012.

Table 2. Overview of national or regional emissions reduction targets that were in effect in 2012.

Country/ Region	**Emissions target**	**Reference**
Kyoto Protocol	Country-specific targets, 37 countries (Annex I) to reduce their carbon footprint by in total 5.2% over the period 2008-2012	(UNFCCC 2012a)
EU	≥ 20% reduction for the period 1990-2020	(Council of the European Union 2007)
UK	-80% reduction for period 1990-2050	(UK government 2008)
Norway	+ Over-achieve Kyoto-target by 10 percentage points + Reduce expected baseline emissions in 2020 by 30% of 1990 emissions, achieved by both national reduction and purchase of emission allowances from other countries + Become carbon-neutral by 2050	(Stortinget 2012)
California	Reach 1990 emissions level in 2020	(Pavley and Nunez 2006)

In addition to the commitments listed in Table 2, there are a large number of national or municipal incentives, emissions trading schemes, and declarations of intent. Table 2 only lists those countries and regions where an economy-wide target is part of the current legislation. Regulations that affect certain sectors or product categories only, such as fuel efficiency standards, are not included. In addition, the Montreal protocol, which was designed to preserve the ozone layer by phasing out or freezing the production levels of a large number of halogenated hydrocarbons, will as well contribute to climate change mitigation, as these substances represent strong greenhouse gases (UNEP Ozone Secretariat 2006).

A scheme or treaty, that distributes a global emissions reduction target onto different sectors such as transport, industry, or buildings, may facilitate emission abatement because the number of actors within a specific sector compared to society as a whole is smaller, and they can be easily identified and assigned a specific responsibility (Bodansky 2007; Schmidt et al. 2008). Thus, sectoral reduction targets may be a first step for many countries to enter a carbon-constrained regime that is limited to certain industries or end-use categories. Sector-specific reduction targets across countries could hinder companies from moving their operations to regions with higher emissions allowances. Disadvantages of the approach are that limiting the scope on certain sectors may exclude potentially easier and cheaper mitigation opportunities elsewhere, and that emissions might leak to sectors that are not part of the mitigation regime (Schmidt et al. 2008; Bodansky 2007).

Several sector-specific scenarios exist, showing how to achieve significant reductions in carbon emissions by 2050. Examples include the IEA’s Blue Map scenario, which is a global assessment of future energy supply and use that considers 11 world regions (International Energy Agency 2010), and a recent policy proposal issued for the EU Commission (EU Commission 2011), which covers the European Union as a whole. Both studies consider the sectors transportation, buildings, industry, power generation, and others, while the EU proposal considers non-CO_2 emissions from agriculture in addition. They contain different emissions reduction levels for the individual sectors.

Summary: There is a large discrepancy between the severity of man-made global warming and the way it is reflected in current policy. The Kyoto protocol can only be considered as a first step towards stabilized global emissions, as it stipulates only modest reduction targets for a limited number of countries, and has a limited time frame (Schmidt et al. 2008).

To this day, there is no general agreement on how to break down global emissions reductions targets into different countries or sectors. In the absence of such an agreement, there is a need for a set of sectoral and country-level benchmarks that allow for assessing the contribution of sector- and country-specific emissions mitigation strategies to reaching a certain temperature stabilization level.

1.3.2 Overview of pathways for climate change mitigation

More energy-efficient technologies and new energy technologies are often seen as the main instrument to curb anthropogenic greenhouse gas emissions. The IPCC Fourth Assessment Report (AR4) contains a comprehensive literature review and finds " […] *high agreement and much evidence* that all [temperature] stabilization levels assessed can be achieved by deployment of a portfolio of technologies that are either currently available or expected to be commercialized in coming decades, […]" (Fisher et al. 2007).

The International Energy Agency (IEA) acknowledges the severity of climate change by stating that "A global revolution is needed in ways that energy is supplied and used." (IEA 2008) At a closer look, the term 'revolution' refers to an 'energy technology revolution', which comprises fuel and energy efficiency, fuel switching, nuclear power, renewable energies, and carbon capture and storage (CCS). These options constitute the BLUE MAP scenario, which is a target-oriented scenario to achieve a 50% reduction of energy-related CO_2 emissions over the period 2005-2050 (International Energy Agency 2010).

When reviewing the strategies in the BLUE MAP scenario in relation to their risks, ease of implementation, and expected contribution to emissions reduction, I found two problems.

(1) The first problem applies to new energy technologies. The possible future consequences of many of these technologies are insufficiently understood, and their development and deployment turned out to be more difficult than expected. The future role of nuclear power is vehemently debated and especially after the Fukushima catastrophe, the extent of its future deployment is viewed more critical (Platts 2011). The IEA has significantly reduced its estimate of the additional nuclear power generation capacity to be installed by 2035 (The Economist 2011; IEA 2012). The development of carbon capture and storage (CCS) turns out to be more difficult than expected (Reuters 2011) and recently lost governmental support in Germany (German Government 2012). Moreover, CCS is expected to be among the most expensive mitigation technologies (McKinsey&Company 2009). These facts and incidents could be perceived as drawbacks and fluctuations on the difficult and risky way to a different energy future, but there may be some systematic over-optimism in the assessment of the possible future contribution of these technologies. Upstream impacts may significantly reduce the net emissions savings of new energy technologies, especially CCS, and linkages between different environmental pressures may complicate climate change mitigation (Arvesen et al. 2011). New sectors of energy demand and an increasing energy demand to compensate for deteriorating mineral and biotic resources may partly outpace future mitigation efforts (Arvesen et al. 2011). Although there are already significant investments in renewable energy supply especially in the developed world and in China, the global average carbon intensity of energy started to increase again after 2000, mainly due to the massive use of coal in China and India (Pravettoni 2010).

(2) The second problem applies to energy efficiency gains. Improving efficiency often yields monetary savings that can cause rebound effects on different scales (Madlener and Alcott 2009; Barker et al. 2009; Hertwich 2005). On the demand side increasing energy efficiency leads to lower energy costs and the resulting monetary savings could be spent on other products and services. On the supply side savings from increasing energy efficiency may lower the market price for energy, which in turn may increase consumption. Even though many cost-efficient efficiency measures are known (McKinsey&Company 2009), many of them have not been implemented to a significant scale so far, which suggests that market failures and changes in social norms will have to be overcome as well (Eyre 1997).

Summary: At present, the solution space for achieving significant emissions reductions comprises energy efficiency and supply-side measures. There is no guarantee or mechanism that ensures that increasing energy efficiency and deploying new energy technologies alone will be sufficient to stabilize the average surface temperature on Earth. In order to reach the 2 degree target, it is therefore necessary to extend the solution space by complementing these measures with strategies that reduce energy and material consumption while aiming for a high quality of life at the same time. Examples for such strategies include a lower primary material production through material efficiency (Allwood et al. 2010), lifestyle changes leading to demand reduction (Jackson 2009), and potentially population control (Hardin 1968; Barnosky et al. 2012).

1.3.3 Responses in economics

a) Economic growth and carbon emissions

Perpetuated economic growth is one of the main pillars of industrialized societies (Jackson 2009). A central question in economics is whether economic growth is a threat or a means to achieve environmental improvement (Stern 2004), and in case it is a threat, which levels of economic development are *sufficient* to reach high human development (Steinberger and Roberts 2010). The school of classical environmental economics has advocated growth as a means to achieve both human and environmental prosperity. A good example is the following statement by (Beckerman 1992): "… the important environmental problems for the 75% of the world's population that live in developing countries are local problems of access to safe drinking water or decent sanitation, and urban degradation. Furthermore there is clear evidence that, although economic growth usually leads to environmental deterioration in the early stages of the process, in the end the best - and probably the only-way to attain a decent environment in most countries is to become rich."

Proponents of ecological economics consider economy as embedded into the system Earth and criticize the concept of everlasting economic growth. In 1974, Herman E. Daly stated that "Our economy is a subsystem of the Earth, and the Earth is apparently a steady-state open system. The subsystem cannot grow beyond the frontiers of the total system and, if it is not to disrupt the functioning of the latter, must at some much earlier point conform to the steady-state mode." (Daly 1974).

Historic evidence shows that a low-to-moderate per capita income is a necessary condition for low carbon emissions per capita (Steinberger and Roberts 2010; Steinberger et al. 2012). For countries with high per capita income and high carbon emissions per capita, the hypothesis of the 'environmental Kuznets curve' states that carbon emissions drop with rising income after certain per capita income was reached (Chertow 2001). Empirical evidence for the Kuznets curve in the case of CO_2 depends on the system boundary used for determining the personal carbon footprint. If the system boundary is the countries' border, CO_2 emissions grew slower than personal income in most developed countries for several decades in a row (International Energy Agency 2011; University of Pennsylvania 2012). In spite of this relative decoupling, current per capita emissions in developed countries are about a factor of 10-30 larger than the levels that are required to reach the 2°C target in 2050 (Fig. 3). When changing the accounting routine by including emissions embodied in trade, there is a strong positive correlation between per capita carbon footprint and per capita GDP that holds over several orders of magnitude of the latter, and there is no decoupling or Kuznets curve in that case (Hertwich and Peters 2009; Steinberger et al. 2012).

b) Affluence, service, and stocks

Personal well-being is often measured in economic terms, i.e., in gross domestic product (GDP) per capita, and the term 'affluence' has almost become a synonym for per capita GDP. However, several non-economic indicators of human development, such as life expectancy or education level, decouple from personal income in the range of 10.000-15.000 International $ per capita (Jackson 2009). This gave reason to a debate on the usefulness of economic indicators as measure of personal affluence in developed countries (UNDP 2010; Goossens et al. 2007). One alternative to economic affluence measures is to quantify the different physical services such as cars, dwellings, and different metals that people in developed countries benefit from. For several of these physical services, it is the in-use stock of products and materials, rather than their annual consumption flow that provides service to the end-users. The consumption of products and materials is not an end in itself, but serves the purpose of building up or maintaining in-use stocks, which are used throughout the lifetime of the products. One can say that in-use stocks bridge the gap between service and consumption. The concept of stocks as carrier of affluence was introduced by Boulding (1966), and was recently revitalized within the framework of material flow analysis (Müller 2006).

The size and the physical properties of different in-use stocks directly determine a significant fraction of mankind's carbon footprint. About 56% of all energy- and process-related greenhouse gas emissions can be attributed to transport and buildings (Fig. 2), more precisely, to the energy consumption of the rolling stock and the building stock. Almost 50% of all industrial emissions are related to the production of cement, steel, and aluminum, which accumulate in stocks of buildings, infrastructure, and products (Fig. 2).

Summary: Carbon emissions are positively correlated with GDP, and the relative decoupling seen in several developed countries over the last years has been far too weak to slow down the growth of global emissions. The role of per capita GDP as affluence measure has been put into question. Understanding and modeling stock dynamics may shed light on the connection between economic activities, final consumption, human development measured in terms of physical services, and global warming.

1.3.4 Modeling environmental impacts of human activities

Parallel to the rise of environmental concerns in the sixties and early seventies, three fundamental modeling concepts, which determine the way we look at environmental problems today, were developed or adopted from other sciences. After briefly presenting them, I will show how two of them can be merged into the framework of social metabolism, which forms the basis of several major impact and emissions mitigation modeling techniques. Global warming is an issue that rose after these concepts had been established. I will thus investigate whether and how the current methodologies must be extended in order to model and understand long-term environmental problems such as global warming.

1) **The IPAT-framework:** Provided that a quantitative global limit for a certain environmental impact I can be established, e.g., as upper limit of greenhouse gas emissions per year (Table 1), this limit I can be broken down into the three major drivers population (P), affluence per person (A), and technology (environmental impact per unit of affluence T) by the so-called *I-PAT* equation (Ehrlich and Holdren 1971):

$$I = P \cdot A \cdot T \qquad (1)$$

The *I-PAT* equation scales a single, average unit process described by T to the global level using P and A as scaling factors.

For a region with known emissions flow I, population P, and monetary affluence A, the *I-PAT* equation can always be formulated in an accounting manner (Fischer-Kowalsky and Amann 2001). It has been termed the 'master equation' of industrial ecology (Graedel and Allenby 1995).

The *I-PAT* equation does not distinguish between different technologies or sectors and lacks a systems context. This makes it difficult to assess the combined impact of different mitigation strategies and to account for the differences between different countries and sectors. Moreover, the variable A is often defined as GDP per capita, which does not allow us to consider physical services or stocks (section 1.3.3). Throughout this work I will therefore not use the *I-PAT* framework.

2) **Systems thinking:** The second important input to environmental science was the adaptation of the concept of systems. Open and closed systems and their respective boundaries have their origin in thermodynamics and were applied to economies by Boulding (1966) and later by Daly (1974). Von Bertalanffy (1968) and Forrester (1968) laid out the foundation of a general theory of systems. Any environmental problem can be formalized in a system, which includes the definition of the boundary of the problem and the logical connections between the actors and processes within. It helps to structure and to communicate the specific features of the problem studied.

3) **Physical aspects of economic activities:** Ayres and Kneese (1969) make clear that it is not economic activity as such that impacts the environment, but the flows of materials, waste, and energy mobilized by the economy. They point out the importance

of material and energy efficiency for decoupling economic development from environmental impacts.

All technical processes within the economy are subject to the laws of thermodynamics, in particular the second law, which states that a constant flow of low entropy materials and/or energy is required to maintain the disequilibrium between a given economic system and the surrounding environment (Daly 1974; Georgescu-Roegen 1971; Ayres and Kneese 1969). Another corollary to this law is that waste flows and dissipative losses are unavoidable side-effects of any economic activity, and that cleaning up these waste flows requires further exergy[1] input. An example is carbon capture and storage (CCS), whose implementation would increase primary energy requirement per kWh of electricity delivered by 10-40% (Rubin et al. 2005). While the second law of thermodynamics is an integral part of chemical and process engineering, this principle had not been applied to whole societies or economies until Ayres and Kneese (1969) and Georgescu-Roegen (1971) proposed to enlarge the boundary of macro-economics to include thermodynamic limits.

The synthesis of items 2 and 3, that is the study of anthropogenic flows and stocks of materials and energy in a systems context, is called the *social* or *anthropogenic metabolism* (Baccini and Brunner 1991; Fischer-Kowalsky and Amann 2001). In analogy to the metabolism of individual organisms or cells in biology, social metabolism considers the set of industrial and other man-made processes and the material and energy stocks and flows therein as the metabolism of the human society. Historically, concepts (2) and (3) were often used together, for example, in Baccini and Brunner (1991) and Meadows et al. (1972).

Since the 1970ies, several methods to quantify and to assess environmental impacts of human activities have been developed within the framework of social metabolism (Table 3). Next to the methods shown in Table 3, there is the field of risk analysis, which aims at assessing the probability and potential impacts of possible adverse

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[1] Exergy is that part of the internal energy of a thermodynamic system that can be extracted as mechanical work when the system reaches equilibrium with its environment.

effects, incidents, or catastrophes related to a certain product or a technology (Lerche and Glaesser 2006).

The methods in Table 3 have different purposes and hence, they differ in scale, the comprehensiveness of the system used, the way they deal with time, and the choice of exogenous model drivers. They also differ in the way they respect first order principles, such as the balance of mass or energy. I now discuss the methods and their suitability and possible shortcomings for modeling emission abatement in the long term.

Table 3: Different methods to assess the environmental impact of human activities in the framework of social metabolism.

Model	**Typical scale**	**Typical time frame**	**System boundary**	**Major exogenous driver/parameter**
Life cycle assessment (LCA) (ISO 2006)	Product level	Entire life cycle, condensed into timeless indicator	Entire life cycle, covers several to all upstream repercussions	Functional unit (1 unit of the product studied)
Environmentally extended input-output (EE-IO) (Leontief 1970; Duchin 1992; Wiedmann 2010)	Sector-Global	Snapshot	Upstream only (downstream in some cases: (Nakamura and Kondo 2002)), all upstream repercussions	Final demand *Y*
Material flow analysis (MFA) / Dynamic stock models (Baccini and Bader 1996; Müller 1998; Brunner and Rechberger 2004)	Process level-global	Dynamic, past and future (scenario modeling)	All product stages including the use phase, foreground only,	Production, demand, Stocks, population, service level indicators
Integrated assessment models (IAM) (Kelly and Kolstad 1999; Rotmans and van Asselt 2003)	Regional-global	Dynamic, scenario modeling	All upstream repercussions	Time discounting, GDP, response of economic agents (Kelly and Kolstad 1999)

Life cycle assessment (LCA) was designed as tool for decision makers and is used to assess individual products and processes. The system boundary of an LCA study consists of a product specific foreground system that is coupled to a generic background, for example an LCA database (Frischknecht et al. 2007), or an input/output model in the case of hybrid LCA (Suh et al. 2004). LCA studies can provide detailed information on individual products as the foreground system can be very specific and the background model allows for computing the economic repercussions in the value chain upstream and downstream to any tier. There are different limitations that need to be considered when using LCA to assess emissions mitigation strategies.

(1) Time: All greenhouse gas emissions occurring at different stages of a product's life cycle are condensed into single, timeless impact indicator (ISO 2006). This is not compatible with models with explicit time dimension. **(2) Allocation and scale:** The impacts and resource requirements of the different industrial processes involved in the value chain need to be allocated to the product under study. This allocation routine cannot be derived from first order principles; it is an additional model assumption. The benefits of recycling are not part of a product's life cycle, but are often allocated to the product. The process emissions reflect the current efficiency of scale of the industry; this information is lost when moving to the unit process. **(3) Data:** Life cycle inventory data typically are process data; they usually do not include historic or current investments into industrial and public infrastructure (Reap et al. 2008). Moreover, process inventories often only include the flows required to operate the production processes itself and not the entire facility with all its auxiliary functions. The processes are usually assumed to operate at full utilization (Allwood 2012b).

Environmentally extended input/output analysis (EE-IO) does not have a foreground system and therefore provides less detail on specific products than an LCA would do. It can be used to estimate impacts on any scale within the given resolution of the I/O table, from a single car to the consumption of the entire society. I/O models do not contain stocks and therefore they cannot connect final consumption to the total service level provided to the end-user (section 1.3.3). State-of-the-art EE-IO studies can allocate a country's carbon footprint onto different regions and sectors (trade-linked analysis, (Hertwich and Peters 2009)).

Material flow analysis (MFA) is typically applied to study specific materials or activities such as agriculture or wastewater treatment with a case-study-specific foreground system that comprises both stocks and flows (Brunner and Rechberger 2004). MFA is applied to a large number of substances and materials with spatial boundaries reaching from the process level to the global scale. Substance-level MFA is often conducted with comprehensive systems that include all life-cycle stages of the substance from mining to waste handling, e.g., in Wang et al. (2007). MFA must not be confused with material flow accounting, which quantifies the aggregate material inputs to economy, irrespective of their physical nature (Fischer-Kowalsky and Amann 2001; Ritthoff et al. 2003). Due to the limited number of system variables in MFA studies, dynamic analyses and scenario modeling are relatively easy to perform and commonly applied. Dynamic stock modeling combines MFA with system dynamics to investigate long-term trends in the different material cycles (Baccini and Bader 1996; Müller 1998; van der Voet et al. 2002; Müller et al. 2004; Elshkaki et al. 2005; Müller 2006).

Large parts of the material stocks in use have lifetimes from about 15 years for passenger cars up to many decades or even centuries for buildings and infrastructure (Bohne 2006; Müller et al. 2007). In-use stocks also serve as reservoirs for future material recycling. Thus, the process of building up and maintaining in-use stocks determines the long-term development of the material supply chains, the fabrication and manufacturing industries, and the waste management sector.

While MFA studies that contain the entire anthropogenic use of certain materials are common, there are only few studies that connect MFA and dynamic stock modeling in particular to energy use and carbon emissions (Sandberg and Brattebø 2012; Sandberg et al. 2011; Liu et al. 2011; Kohler and Hassler 2002). A major challenge is that a significant fraction of the total sectoral emissions may come from outside the MFA system, such as the emissions from electricity generation for producing aluminum (Liu et al. 2012). A generic approach on how to include both direct and indirect energy consumption and greenhouse gas emissions into MFA systems is lacking.

Integrated assessment models are defined rather widely as any model that combines scientific, social, and economic aspects to assess policy options for climate change mitigation (Kelly and Kolstad 1999). The ten models that were reviewed in

IPCC AR4 (Fisher et al. 2007) contain computable general equilibrium models that rely on exogenous GDP forecasts (Weyant et al. 2006), which makes it difficult to combine them with alternative affluence measures such as physical indicators. When connected to general equilibrium models, integrated assessment models are not dynamic, but use a new market equilibrium, that was determined by perturbing the old equilibrium, to estimate how energy supply and emissions respond to a given policy regulation (Burfisher 2011). Optimization routines can be applied to endogenously determine optimal policies (Kelly and Kolstad 1999).

Summary: Assessing the effect of different emissions mitigation pathways until 2050 requires an explicit time dimension in the model. In-use stocks need to be included because they determine the long-term dynamics of the industries within different sectors. Moreover, the historic development of in-use stocks in different countries can be used to derive *benchmarks* for future development (Müller et al. 2011). Both direct and indirect sources of greenhouse gas emissions that can be attributed to a certain sector or country need to be included.

1.3.5 The role of stocks in social metabolism

The review above revealed the different roles that in-use stocks play in the social metabolism, which are summarized here:

- In-use stocks provide *service* to the end user in several major sectors.
- In-use stocks link important physical services, such as shelter or mobility, to economic activity.
- Due to the long lifetime of products in-use, stocks determine the *long-term-dynamics* of the supplying industries, both upstream and downstream, including the potential for recycling.
- Observing the historic development of in-use stocks in different parts of the world gives information about utilization patterns of different end-use products that can serve as *benchmarks* for forecasting or scenario modeling.

1.4 Research motivation and research questions

Based on my findings summarized at the end of sections 1.3.1-1.3.4, I first explain my motivation and then formulate a set of specific research questions.

Policy (1.3.1): Ultimately, I intend to contribute to the debate on how to break down the global emissions reduction targets into different countries and sectors. A science-based breakdown may facilitate a future global treaty on climate change mitigation.

Mitigation pathways (1.3.2): When agreeing upon a set of sector and country-specific reduction targets in a future global treaty, the parties must be reasonably certain that the targets are politically and practically viable. A breakdown of the global emissions reduction target that considers the *full spectrum* of mitigation options and their risks and barriers, may be easier to accept than a breakdown obtained from a limited portfolio of strategies. Alongside energy efficiency, I study 1) mitigation strategies that combine technological change with changes in user behavior (I call them '*hybrid solutions*'), 2) lifestyle changes that lead to lower stocks at levels that are currently observed in some developed countries, and 3) strategies that reduce primary material production by decoupling material consumption from the service provided by material stocks (*material efficiency*).

I create a set of scenarios including the different mitigation strategies listed above and conduct a case study in each of the three major energy-consuming sectors: transportation (passenger cars in China); buildings (residential buildings in Norway); industry (the global steel cycle). Studying both developed and developing countries allows me to identify specific challenges related to development pathways in different world regions.

Affluence measures (1.3.3): I consider the size of the different stocks in use as a physical affluence measure and use stocks as exogenous drivers when modeling emission abatement in different end-use sectors.

Methodology (1.3.4): I provide a stock-driven model to compute the direct and indirect emissions savings in different countries and sectors that can be achieved by implementing the different decoupling strategies. I create a benchmark method to assess the contribution of different sectors and countries to mitigate global warming.

Research questions:

(i) Methodology:

How can dynamic stock models be extended to include both direct and indirect energy consumption and carbon emissions, and what are the critical assumptions and variables?

How can emissions reductions in different countries and sectors be benchmarked against the 2°C target and other global climate targets?

(ii) Final consumption and waste flows:

The historical development of in-use stocks in industrialized countries has followed certain patterns. These stock patterns can be used as reference values for future development and can serve as exogenous model drivers for future scenarios.

How do final demand and discard of products in the different case studies develop over time under the assumption that the entire world will eventually build up the same in-use stocks as currently observed in industrialized countries? How do demand and discard change once different climate change mitigation strategies are implemented?

(iii) Decoupling strategies and climate change mitigation:

How big are the emissions reductions resulting from implementing energy efficiency, hybrid solutions, material efficiency, and lower stock levels in the different case studies? How do the emissions scenarios in the case studies relate to the different levels of global warming, and the 2°C target in particular?

(iv) Outlook:

How do my findings relate to some of the underlying challenges of sustainable development?

1.5 Thesis structure and overview of case studies

The methodology section addresses question (i) and introduces the three case studies. The results section addresses questions (ii) and (iii) by compiling the findings from the case studies. Section 4 discusses the findings for research questions (i)-(iii), and addresses some underlying problems of sustainable development (question iv). Compare with Figure 4 for an overview. Table 4 presents the three case studies conducted and the respective journal articles.

Table 4: Overview of case studies and research articles appended.

Description	**Reference**
Transportation (T): Direct emissions from passenger cars in China	Paper I
Buildings (B): Direct and indirect emissions from dwellings in Norway	Paper II
Industry (I): World-wide emissions from making and recycling steel	Paper III, IV, and V

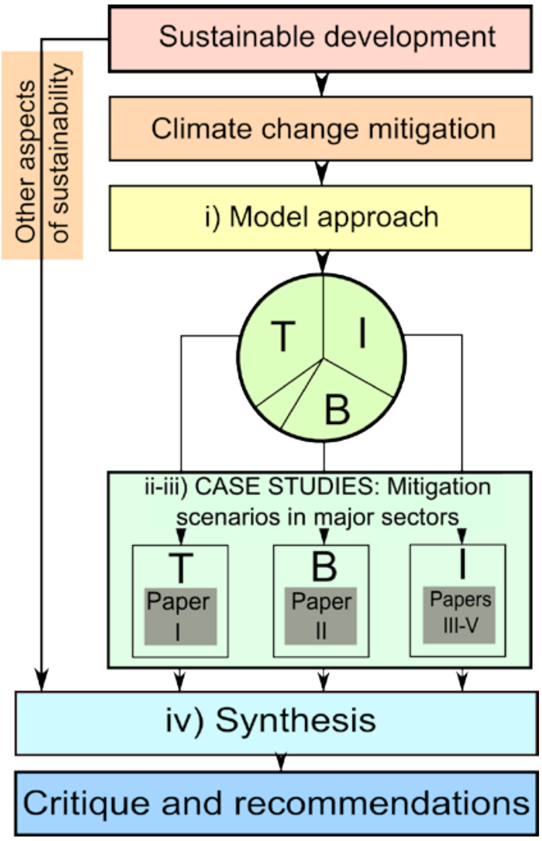

Figure 4: Thesis structure. The three sectors studied are transportation (T), buildings (B), and industry (I).

I briefly explain how the case studies relate to the different sectors.

Emissions from passenger cars account for about 50% of direct emissions from transportation (IEA 2009). I assumed that over the next decades, car ownership in China will rise to the level currently observed in industrialized countries. Hence, the model results for 2050 may be representative for other industrialized countries with similar car ownership level.

Households account for ca 25% of global final energy consumption (IEA 2008). I focused on Norway because the current Norwegian building policy has a strong focus on energy efficiency. Passive houses shall become standard from 2015 on (Norwegian Ministry of the Environment 2012) and rehabilitation to passive house standard has been proposed as the default renovation measure for the future (Arnstad 2010). The heating energy demand can be minimized by transforming the entire dwelling stock to passive house standard by either demolition and subsequent re-construction or renovation. By creating scenarios for how such a transformation could be accomplished by 2050, I could estimate the maximum emissions savings potential from efficiency measures within the dwelling stock. This estimate may serve as indicator for the possible contribution of the dwelling sector to nation-wide emissions reductions both in Norway and in other countries.

Steel production alone accounts for 25% of all industrial emissions (Fig. 2). The steel industry has a large spectrum of challenges and opportunities that are typical of many industries. Challenges include the huge capital requirement of this industry, which leads to very long asset lifetimes (Paper IV). Opportunities to reduce emissions include energy efficiency, recycling, fuel switching, and carbon capture and storage (Paper V). A comprehensive study of emission abatement within the global steel cycle may give insights that apply to other industries as well.

Each of the case studies contains a review of the relevant literature and a specific system definition with detailed documentation of model approach, data treatment, and scenario assumptions. The project on the global steel cycle is comprehensive and was split onto three publications. One paper (III) covers the historic development of steel stocks, another paper (IV) presents a new method describing how to extrapolate stock patterns into the future and determines the steel industry’s response to the future demand for in-use stocks, and the last paper (V) introduces material efficiency strategies, adds the emissions layer, and contains scenarios on future carbon emissions.

The journal articles are not part of this summary. The printed version of this thesis includes Papers I-V as appendices. In the electronic version the hyperlinks to the proprietary online versions are provided.

2. Methodology

I first present the common model framework (2.1) and the case-study-specific model features (2.2). Then I define the model drivers, describe the scenarios, and present the future development of the in-use stocks for the different cases (2.3).

2.1 The common model framework

Central to the concept of social metabolism is the notion of a system of processes such as industries, mineral deposits, or markets, which are connected by material and energy flows. Figure 5 shows a generic system of the anthropogenic metabolism in the notion of material flow analysis (Brunner and Rechberger 2004). This purely physical system contains all industrial processes, the use phase, and the material flows from and to the environment, but does not reveal the economic and social aspects of the product cycles. People as beneficiaries of the products in use and the markets for products and factors of production are not included in the system.

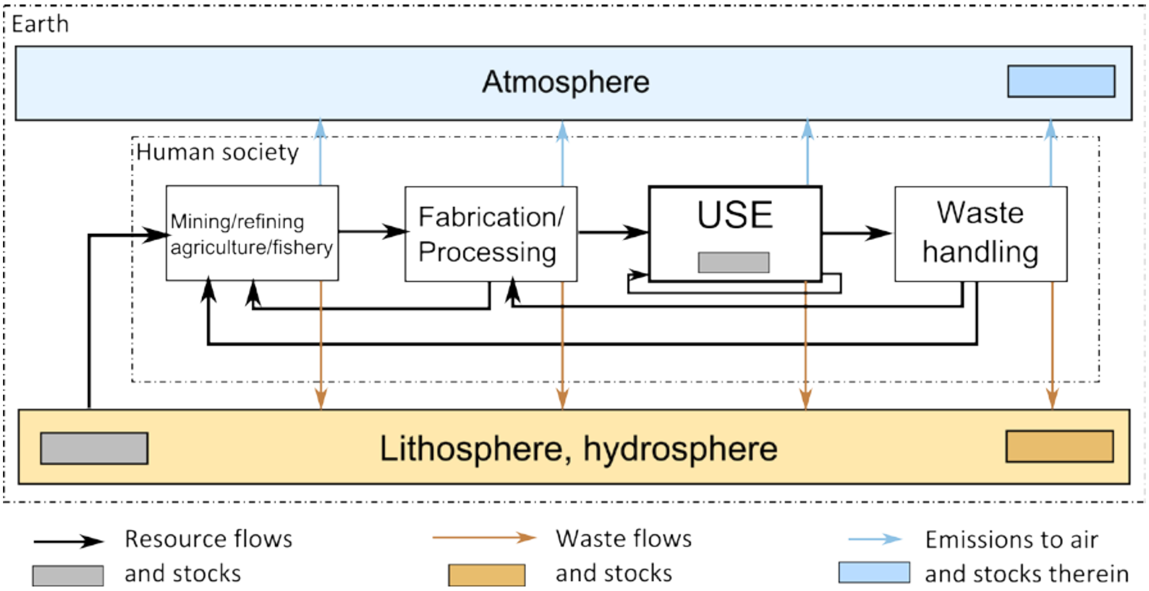

Figure 5: The system of the anthropogenic metabolism.

To allow for more detailed and comprehensive assessment of different emission abatement strategies I specified and extended the generic system in Figure 5 in two directions.

(1) In order to include emissions into existing MFA models I added two new layers to the ones already present in the system of material flows (Fig. 6).

Service layer: People enjoy different services such as having and using a car, a certain living space, or a certain amount of steel per person. These services are provided by in-use stocks. The service layer contains the main model drivers population and per capita stock, which together yield the total stock demand at a given time.

Final products layer: Services need to be transformed into products such as different types of cars, buildings, or the large variety of steel-containing products. Central to this layer is the product lifetime model, which tracks different cohorts over time and determines the end-of-life flows. The split into different product types and the intensity of use of individual products is taken into account here.

Materials layer: Products in use represent stocks of different materials. Making and disposing of the different products creates demand for material production, waste treatment, and offers the possibility of recycling. Different model parameters such as material intensity or the extent of light-weighting describe the connection between products and materials. The industries upstream and downstream are characterized by parameters like the fabrication yield rate and the end-of-life recovery rate, and the split between primary and secondary material production.

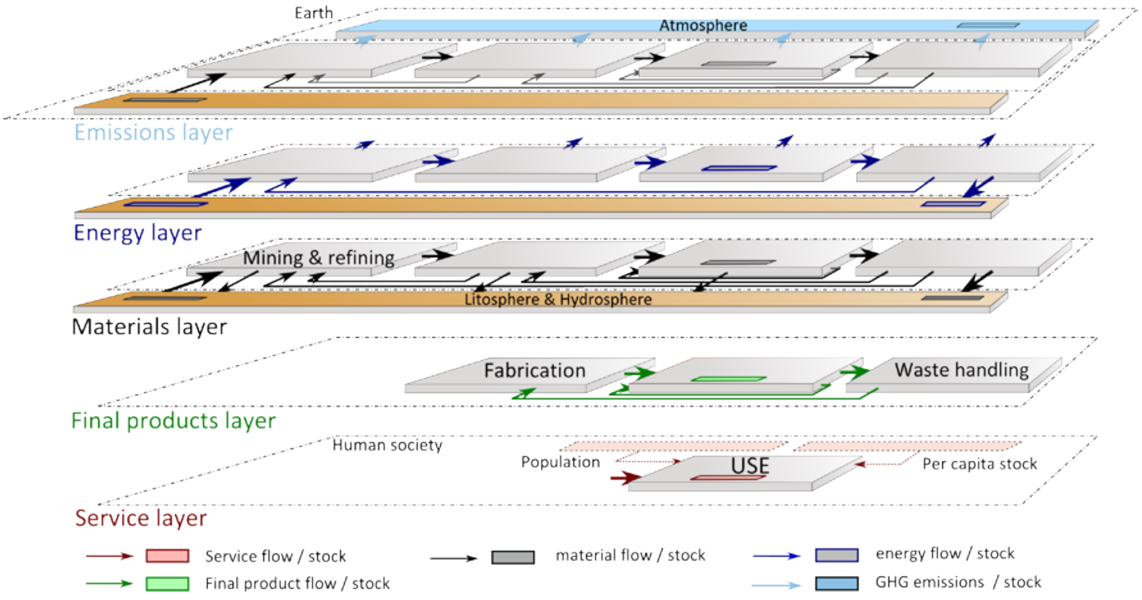

Figure 6: The five layers: Generic approach to model the social metabolism of products and related materials, waste and energy flows, and emissions.

Energy layer (new): Products and materials represent exergy flows and stocks. But at least equally important are the energy flows that are required to operate the different industrial processes and in-use stocks, such as gasoline for cars, heating oil for buildings, or coke for steelmaking.

Emissions layer (new): All processes in the system can release carbon dioxide or other greenhouse gases, which are kept track of in the upper layer. Emissions can be related to either energy or material flows.

Table 5 shows the layers included in the different cases studies.

Table 5: Layers covered by the three case studies

	Passenger cars in China	**Dwellings in Norway**	**The global steel cycle**
Time frame	1910-2050	2011-2060	1700-2100
Geographical scope	China	Norway	Ten world regions
Service layer	Yes	Yes	No
Product layer	Yes	Yes	[yes][2]
Material layer	No	[yes][3]	Yes
Energy layer	Yes	Yes	No
Emissions layer	Yes	Yes	Yes
Background (cf. 2.1.3.)	No	Yes	[yes][4]

(2) The second direction of expansion allows for dynamic modeling and for including upstream emissions and other impacts that do not occur within a specific material cycle, such as emissions from electricity generation. I created Figure 7 to show how the generic system definition in Figure 5 was extended. I considered dynamic stocks and connected them to the exogenous drivers population and lifestyle (Fig. 7, system A). The foreground system (B) contains the relevant industries for the specific case study, and includes the major feedback loops for re-use, re-manufacturing, and

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[2] Four end-use sectors transportation, machinery, construction, and products were considered.

[3] Only for future buildings; the material content of the existing stock was not included, but was partly covered by previous work (Bergsdal et al. 2007).

[4] Electricity generation only

recycling. Most sectors are connected to external suppliers of energy and materials, which again emit greenhouse gases. In order to include these indirect impacts, I included the upstream suppliers beyond the sectoral boundary in an aggregate way (Fig. 7, system C). I now describe the three blocks A-C of the system in Figure 7 and how the different layers in Figure 6 are included in the respective blocks.

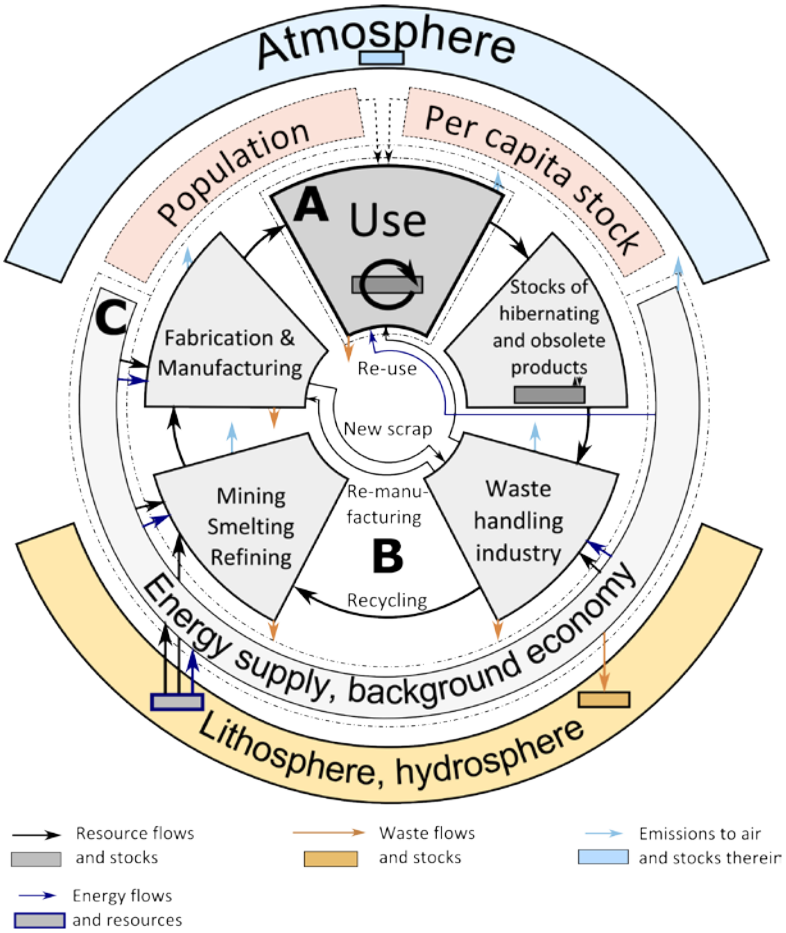

Figure 7: The three modules of my assessment framework. (A) Dynamic stock model, (B) MFA foreground, (C) Background system.

2.1.1 Dynamic stock models (A)

Dynamic models of the in-use stock (Baccini and Bader 1996; Müller 1998; van der Voet et al. 2002; Müller et al. 2004; Elshkaki et al. 2005; Müller 2006) represent the core of the entire model. Müller (2006) linked in-use stocks directly to the exogenous drivers through the following equation:

$$Total\ stock = Population \ \cdot \ Stock\,/\,capita \qquad (2)$$

Since the model is dynamic, different cohorts within the stock can be tracked over time. Case-study-specific lifetime models were applied to determine the in- and outflows from the product lifetime distribution or vice versa. In addition, the individual cohorts were split onto different product types such as standard or small cars, single family houses or blocks, or different applications of steel. Further subdivision, e.g., a split into different drive technologies or different energy standards for buildings, is possible and was applied in some cases.

To create scenarios for future development, I applied stock-driven modeling (Müller 2006). First, the total demand for the stock in use was determined from Equation 2. Then I applied a lifetime model (section 2.2) to determine how many existing products leave the use phase because they reached the end of their life. Finally, the mass balance of the use phase was used to determine the required production volume:

$$Inflow(t) = Outflow(t) \ + \ Stock\ change\ (t) \qquad (3)$$

This model block covers all layers: service; products; materials (e.g., steel in use); energy and carbon emissions. The latter two represent direct energy demand and emissions and correspond to scope 1 emissions in LCA studies.

2.1.2 Material and product flow foreground systems (B)

The foreground system allows us to study the connection between service, products, materials, wastes, and material recycling. In the case of stock-driven modeling, the upstream and downstream processes respond linearly to the in- and outflows calculated by model block A.

The mass balance and other balances are central to connecting stocks and flows, the processes within the different sub-systems, and the different layers. Different processes respect different balances. While the use phase of passenger cars can be balanced for vehicles, car manufacturing and shredding do not respect this balance. Both processes, however, respect the balance for steel and all other substances. The steel industry cannot be balanced in terms of steel, but in terms of iron. Mass balance checks are central to assure the correctness of the quantification of the different processes.

The foreground system contains the layers for products, materials, energy, and emissions. There are two ways of adding the energy and emissions layers. 1) Energy and emissions flows can be quantified in MFA manner, with each process respecting the energy and carbon balance. 2) Energy and emissions can be introduced in LCA manner in form of coefficients per unit of output of the individual processes. The first approach is useful when the material layer is strongly interwoven with either energy or carbon, e.g. in an oil refinery or a biomass plantation. The second approach is easier and preferable in cases where the material layer does not carry significant amounts of energy or carbon or where process-based coefficients are readily available.

Since the model is solved dynamically, i.e., for many years in a row, one can develop capacity models to track different production facilities through their lifetime.

Case studies can be refined to the regional or country level, provided sufficient historic data are available and consistent scenarios for the future development can be created. The regional breakdown combined with the production capacity model allows us to determine how climate change mitigation measures may impact regional capacity development and utilization (Papers IV and V).

2.1.3 Completing the system: Modeling the background (C)

The material layer includes the stages mining, refining/recycling, fabrication, use, end-of-life treatment, and obsolete or hibernating stocks. The foreground system (B) is comprehensive with respect to products and the major materials, but may lack coverage for energy and emissions. In modern industrialized societies energy supply is spatially and organizationally separated from energy use, and emissions associated with energy supply may therefore happen beyond the boundary of the foreground system. Electricity generation is the most prominent example. Upstream impacts such as carbon emissions from electricity generation can account for a significant part of the life cycle impact of a product (Liu et al. 2011; Thomas 2009; Dahlstrøm et al. 2012; Hawkins et al. 2012). I identified three ways of how the system boundary B can be enlarged by including upstream impacts from other assessment models in the framework of social metabolism:

- The impact of the material and energy flows and other products and services entering the foreground system is determined by scaling up the resource requirements of individual functional units. These requirements are taken from inventories that are typically part of LCA studies or from LCA databases.
- The entire material and energy exchange of the foreground with the background is grouped by sector and listed in form of a final demand vector *Y*. An LCA database is used to determine the background impacts associated with the demand listed in *Y*, which are then scaled up to the level of the entire sector.
- Environmentally extended Input/Output models can be used to determine the total impact of *Y*, provided that the IO table used has appropriate resolution (Weinzettel and Kovanda 2009).

For each case study, I made a specific choice on which processes to include in the background system C. A major limitation to this approach is that both, LCA and I/O-datasets, are static since they represent a snapshot of the economy for a given point in time. Applying these inventories in a dynamic model neglects possible changes in the energy mix and industry technology in the background system C over time.

2.1.4 Placing the different emission abatement strategies into the model framework

The different abatement strategies can be categorized according to what actors within society and what technical processes they affect. This may help to identify specific challenges and barriers related to the strategies and may facilitate the development of implementation policies. It may also help to rank the strategies according to the expected ease of their implementation. There are different ways of grouping emission abatement strategies:

1) The IPAT-framework includes the categories population, affluence, and technology. ‘Hybrid solutions’, which affect affluence and technology at the same time, cannot be grouped unambiguously; the IPAT-framework excludes this group of strategies in the first place. ‘Affluence’ is typically expressed in monetary terms, which makes it difficult to include strategies that are expressed in physical units, such as lowering the car ownership rate or changing the dwelling space per person.
2) Many established terms to group emission abatement strategies exist. Examples include ‘energy efficiency’ (International Energy Agency 2008), ‘material efficiency’ (Allwood et al. 2012; Jochem 2000), or ‘new energy technology’ (Hottel and Howard 1971). These terms emphasize specific aspects of emission abatement, but when allocated in the framework of social metabolism, they turn out to be inhomogeneous because they affect different processes within society. Energy efficiency, for example, affects both industrial processes and consumer goods. Material efficiency as defined by Allwood et al. (2012) covers lifestyle changes such as more intense use of existing in-use stocks, business model changes, e.g., the diversion of fabrication scrap, and technological changes such as fabrication yield improvements.
3) The different strategies can be allocated in the system of social metabolism (Fig. 7). This allocation links each strategy to one or more processes that are directly affected. Since the system definition comprises the entire social metabolism, it can be used to systematize the different mitigation options and to identify processes or sub-systems that are insufficiently covered. Table 6 shows an overview of the different groups of emission abatement strategies that cover the entire system in Figure 7.

Categorizing a given parameter as either ‘lifestyle’ or ‘technology’ may be ambiguous. Consider for example the energy required for domestic hot water generation. It can be reduced either by recovering the heat from the waste water stream (technology deployment) or by lowering consumption (affluence). Other measures have both a technology and a lifestyle component. A micro car, for example, significantly reduces material and fuel consumption, but may be less suited as status symbol and for long-distance travelling. I called strategies that cannot be categorized unambiguously onto either technology or lifestyle or that affect technology and lifestyle simultaneously as *hybrid solutions*. This category forms a separate class in Table 6.

Table 6: Classifying GHG emission abatement measures based on the generic system of social metabolism.

No.	Method, reference	Description, examples	Location in system
1	**Reduce** population (Malthus 1798; Hardin 1968)	Population is a main driver of emissions	Exogenous driver
2	**Reduce** service level per person	Avoid unnecessary consumption	Exogenous driver
3	**Decouple** affluence from material and energy throughput via lifestyle changes (keep service level)	More intense use of products, re-use of products, transport mode shift	Use phase (A)
4	**Decouple** affluence from material and energy throughput via technology (keep service level)	Light-weighting, fuel efficiency, thermal insulation	Use phase (A)
5	**Decouple** affluence from material and energy throughput via technology *and* lifestyle (hybrid solutions) (keep service level)	Passive houses, micro cars, product lifetime extension	Use phase (A)
6	**Decouple** Energy efficiency industry	Process efficiency	Upstream processes (B, C)
7	**Decouple** Material efficiency industry (Allwood et al. 2011)	Recycling, reducing yield losses, divert scrap flows	Upstream processes (B,C)
8	**Decouple** energy supply from carbon	Fuel switching, renewable energies, new energy technologies	Upstream processes (B, C)
9	**Geoengineering** CO_2 removal	Carbon capture and storage (CCS)[5], mineralization, ocean fertilization, afforestation etc.	Upstream processes (B, C), partly beyond system boundary

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[5] Not all commentators consider CCS to be part of geoengineering.

2.1.5 Benchmarking sectoral and national carbon footprints

As pointed out in the introduction, there is no established set of emissions reduction targets for different countries and sectors. Still, one needs to assess whether a certain combination of mitigation strategies within a sector or country is sufficient to keep global warming within the 2°C range. I therefore chose to *benchmark* the reductions in a certain sector or country *against the average reduction* that is required if all sectors and countries would contribute in the same manner.

The benchmarks for the different countries and sectors are derived from the following assumptions:

- Global emissions are to be reduced according to Table 1, which gives a relationship between emissions reduction and average global temperature increase.
- All sectors uniformly reduce their emissions according to Table 1.
- All countries are assigned a quota according to the expected share of their population in the world's population in 2050.

In this work the choice of country-level benchmarks on a population basis is considered a purely technical step. Under this assumption, each individual is assigned the same emissions quota in 2050, which ignores current and possible future differences in economic development between different countries. This choice can therefore be seen as manifestation of global equity (UNFCCC 1992) or the principle of contraction and convergence (GCI 2012). The latter is a mitigation framework that combines emissions reductions in line with a climate target (contraction) with the eventual convergence of per capita emissions in all countries (convergence) (GCI 2012). The question whether some sectors can over-achieve the target and give more room for growth in other sectors must be looked at with great caution. I will come back to these issues in the discussion section. Each sector in each country was assigned a set of emissions quotas for the different levels of global warming shown in Table 1 by multiplying the global emissions in 2000 of 23.6 Gigatonnes CO_2eq/yr (UN Statistics Division 2012) with the reduction targets in Table 1, the sectoral split for 2006 taken from Allwood et al. (2010), and the expected share of the country's population in the world population in 2050 (UN Population Division 2011).

2.2 Case-study-specific methodology

2.2.1 Passenger cars in China (Paper I)

Direct emissions from fuel combustion account for 70-85% of the life-cycle emissions of a contemporary passenger car (Kagawa et al. 2011; Ma et al. 2012), and direct emissions of the entire transportation sector account for about one fourth of global energy-related carbon emissions (Fig. 2). Given this relevance of direct emissions, I applied a simplified system that only contains the use phase of cars.

The system (Fig. 8) shows the car stock and the model parameters related to the stock. A special feature of this model is the division of each cohort into different types. Here I considered conventional gasoline cars and micro cars. The latter type runs on gasoline as well but has significantly lower fuel consumption due to smaller weight and size. Any number of different vehicle types with specific annual kilometrage, fuel types, and carbon intensities can be tracked by this model. The age structure of the existing stock was determined from time series on historic car ownership and population using the stock-driven approach with a normally distributed lifetime.

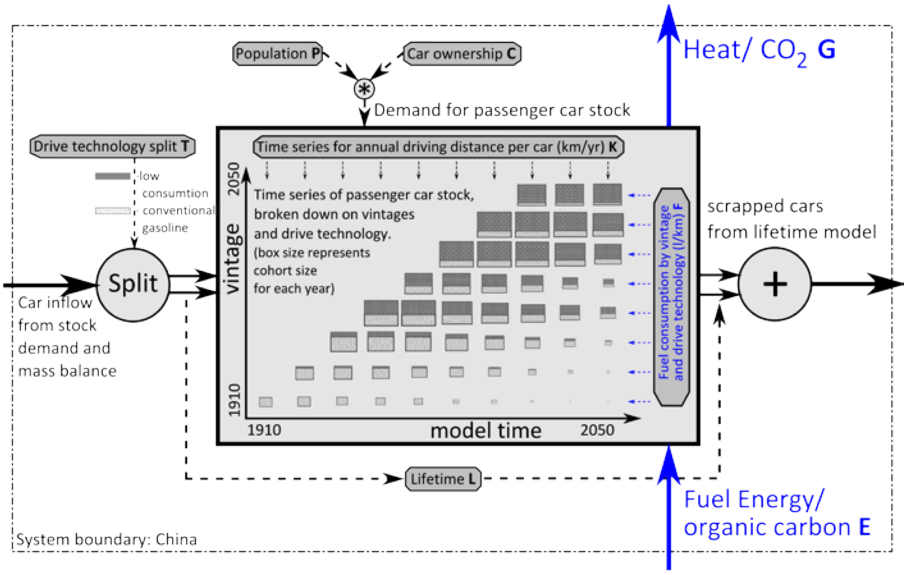

Figure 8: System definition for the case study on passenger cars in China (Paper I). Source: Paper I.

2.2.2 Dwellings in Norway (Paper II)

The dwelling stock model breaks down the stock into different cohorts, three building types, seven heating systems, and six energy standards (Fig. 9). For 2010, a breakdown of the entire stock into the mentioned indices was determined from dwelling statistics and the literature. The lifetime of residential buildings in Norway may be around 120 years (Bohne et al. 2006), which means that most of the present stock would still be standing in 2050. That would make it impossible to realize the energy savings potential from a complete replacement. I therefore created scenarios with shorter lifetimes by applying exogenous rates for demolition and renovation. An optimization routine was applied to identify the buildings whose renovation or demolition would yield the largest energy savings for a given year. This way, the shortening of the lifetime could be kept minimal. The combination of external turnover rates and an optimization routine that computes the cohort lifetimes can be considered as a bridge between the cohort/lifetime model and the leaching model, which are the two main types of dynamic stock models (van der Voet et al. 2002). My approach differs significantly from the previous models for the Norwegian dwelling stock, which include a cohort-lifetime model with exogenous lifetime assumptions (Bergsdal et al. 2007; Sartori 2008; Sartori et al. 2009; Sandberg et al. 2011; Sandberg and Brattebø 2012).

Renovation, demolition, and new construction cause material and energy demand upstream. To quantify these impacts, I added a static background to the dynamic stock model by adopting the system definition of an extensive LCA study by Dahlstrøm et al. (2012) on the upstream and downstream impacts of a typical standard and passive house. To determine the impact of the total flow of new construction I scaled up Dahlstrøm’s inventory of a single house to the national level. For renovation I created a detailed inventory of the insulation materials needed and determined its upstream impact from EcoInvent (Frischknecht et al. 2005). I added those parts of Dahlstrøm’s inventory that are common for new construction and renovation, such as windows, doors, and the façade. Finally, I scaled up the impact of renovating a single square meter of dwelling area to the national level.

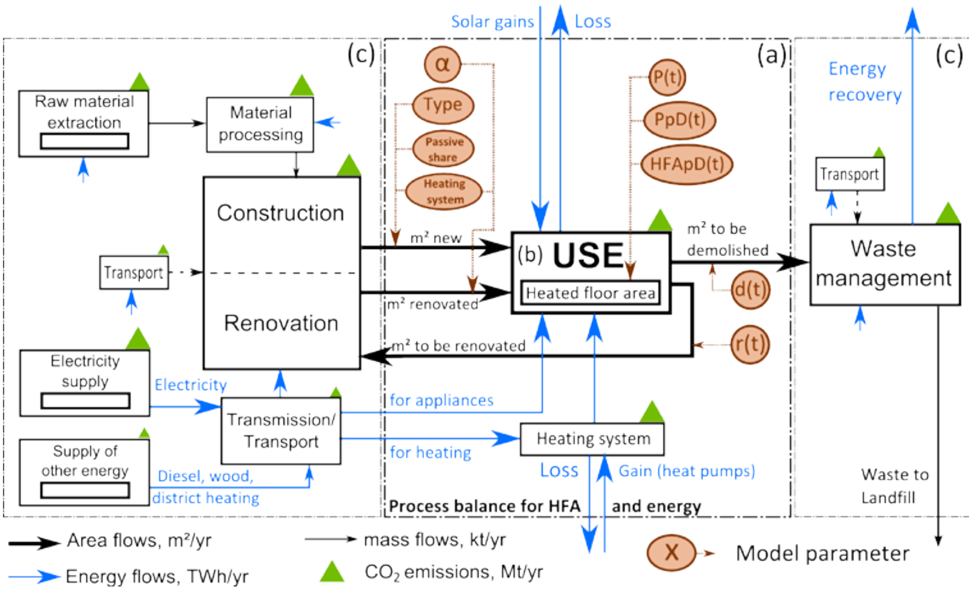

Figure 9: System definition for the case study on dwellings in Norway. (a): Dynamic stock model, (b): heat loss model for individual buildings, (c): background model. The different parameter abbreviations are defined in Table 7. Source: Paper II.

2.2.3 The global steel cycle (Papers III-V)

The system for the global steel cycle (Fig. 10) corresponds best to the general framework given in Figure 7. The MFA foreground shown in Figure 10 includes all major technical processes that transform or process iron. The global in-use stock of iron is at the core of the model; it was broken down into ten global regions and the four end-use sectors transportation, machinery, construction, and products. The model was quantified over the time period 1700-2100 by building upon the previous work on the anthropogenic iron cycle (Müller et al. 2006; Wang et al. 2007; Hatayama et al. 2010; Müller et al. 2011; Cullen et al. 2012). The foreground system is extensive; it covers primary and secondary steel production, forming, fabrication, use, and end-of-life recovery. Major indirect greenhouse gas emissions come from electricity generation, coking, and sintering. These three processes form the background system. Unlike with the stocks in the other case studies, in-use stocks of steel are not recorded by statistical offices and needed to be estimated first. This was done in paper III by using a simplified version of the system shown in Figure 10. Pig iron and crude steel production were compiled for all producing countries, in some cases back to the 18th century. Using average loss rates for forming, fabrication, and end-of-life, the model estimated the in-use stock of iron in 2008. To break down the estimates for the total stock into the four sectors, I used an optimization routine that selects the sector split and the lifetime from a pre-defined set, so that the accumulated mass balance mismatch in the cycle over the period 1700-2008 is minimized. In a number of industrialized countries I observed that per capita stocks saturated after ca. 1980, and I used this observation to propose a benchmark for future development of stocks in other countries. My estimates of the historic in-use stocks and saturation levels were used in the scenario analysis in Paper IV to calculate the future in-use stocks in ten world regions until 2100. I computed regional final steel demand and scrap supply as well as the global demand for primary and secondary steel production. Different pathways to significantly reduce the carbon footprint of the steel cycle were explored in Paper V and a set of six specific material efficiency strategies was introduced (Allwood et al. 2012). The stock model decouples stocks from service by considering light-weighting and more intense use of the different products. The other four material efficiency strategies include lifetime extension, re-use, fabrication yield improvement, and fabrication scrap diversion. Energy efficiency improvements in the steel industry and electricity decarbonization were included as well. The emissions layer was added to each upstream process and the sectoral emissions for different implementation levels of both energy and material efficiency were computed.

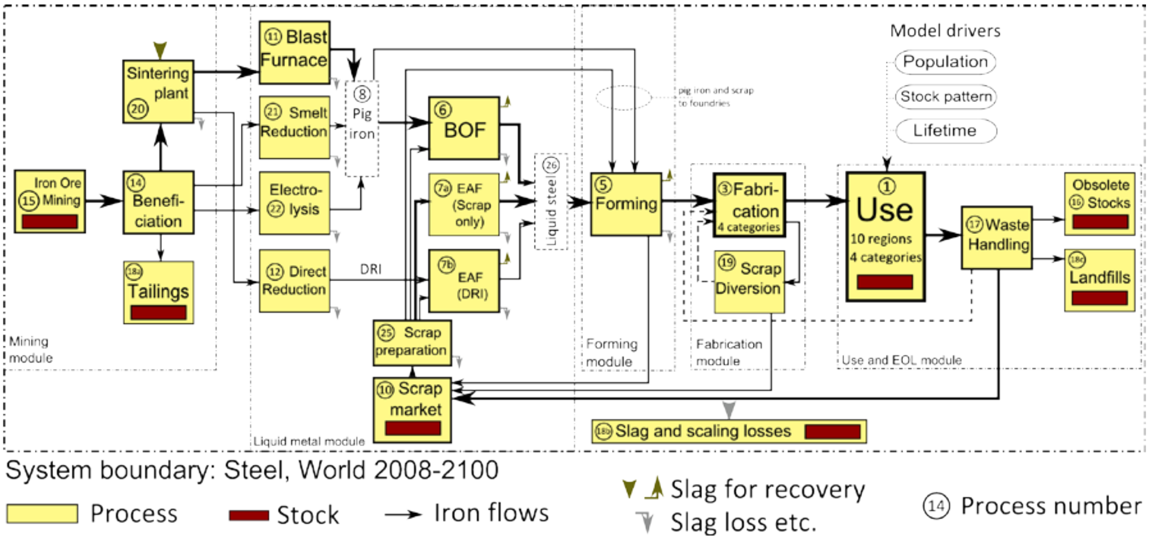

Figure 10: System definition for the global steel cycle. Source: Paper IV.

2.3 Data: Overview on model drivers, other parameters, and scenario definition

Table 7 shows the scenario parameters (exogenous variables), grouped by the categories defined in Table 6. I refer to the attached papers for the details regarding the case-study-specific model approach. The actual number of model parameters is higher, and most of them can be expected to change over time. The changes of parameters that are not listed here, such as a possible increase in the end-of-life recovery rate for steel, were assumed to be part of the respective baseline scenarios.

For each case study the potential contribution of each individual parameter in Table 7 to reducing the carbon footprint of the sector studied was assessed and a set of scenarios based upon the individual parameter variations was created. The scenarios have two main features:

(1) Each model parameter was studied carefully to establish reference values for its future development. Wherever possible, these values were taken from work done by experts such as the WellMet2050 project (Allwood 2012a), were derived from historic trends observed in industrialized countries, were estimated from prototypes and pilot projects, or were taken from already established scenarios. This process made sure that the scenarios proposed have a solid empirical foundation.

(2) Any assessment of the likelihood of the different scenarios is beyond the scope of this work. The scenarios shall help to explore the ‘solution space’ for emission abatement. The potential risks and barriers for implementing the strategies are discussed in the papers and in section 4. Next to the uncertainties related to future development, there are uncertainties in the historic data and limitations resulting from the different model assumptions, which are discussed in section 4.3.

In all three cases the baseline represented development ‘business-as-usual’. It was modeled by extrapolating historic turnover rates, applying stock levels of industrialized countries as benchmarks for growth in the developing world, and anticipating some improvements in energy efficiency. For a detailed reasoning for the different parameter choices I refer to the papers attached.

Table 7: Scenario-specific emission mitigation strategies for the three case studies, grouped by the categories in Table 6. The abbreviations in brackets are used in the scenario definition and Figure 11.

No.	**Passenger cars in China**	**Dwellings in Norway**	**The global steel cycle**
1: Reduce Population	Lower population (P)	Not considered	Not considered
2: Reduce service level	Fewer cars per capita (C) Lower annual kilometrage (K)	More persons per dwelling (PpD) Lower heated floor area per dwelling (HFApD)	Not considered
3: Decouple via lifestyle changes		Building type: share of single family houses in new construction (TYPE)	More intense use (MIU)[6]
4: Decouple via technology	Fuel consumption per 100 km (F)	Heating energy demand (HEAT) Share of different heating systems (HS)	Light-weighting of products (LWE)
5: Decouple via hybrid solutions	Share of micro cars (T) Lifetime (L)	Share of passive houses in new construction (PH) Share of passive renovation in total renovation (α) Energy consumption for domestic hot water generation (DHW) Energy consumption by appliances (Appl) Renovation rate (r) Demolition rate (d)	Lifetime extension of products (LTE) Re-use of products (RU)
6: Energy efficiency industry	Not considered	Not considered	Energy efficiency industry (EE)
7: Material efficiency industry	Not considered	Not considered	Fabrication yield improvement (FYI) Fabrication scrap diversion (FSD)
8: Decouple energy supply from carbon	Not considered	Not considered	Not considered
9: CO_2 removal	Not considered	Not considered	Not considered

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[6] More intense use means that the total service level remains constant but it is distributed onto fewer products, which leads to lower in-use stocks. Examples include increasing the occupancy rate of passenger cars or a reduction in dwelling area per person.

To compare the results from the three case studies, I selected the key scenarios from papers I, II, and V, and list the specific parameter changes below. The scenarios partly form a cascade, where energy efficiency was implemented first, followed by hybrid solutions and the other decoupling strategies. Finally, the lifestyle parameters were changed to their respective bottom line values.

Transportation:

T-Baseline: Default values for all six scenario parameters. Starting from the baseline I analyzed the following cascade of measures

T-1: T-Baseline plus a decrease in fuel consumption (F) from 6 l/100 km to 4 l/100km.

T-2: T-1 plus an increase in share of micro cars (T) to first 33% and then 66%.

T-3: T-2 plus a decrease in annual kilometrage (K) from 15000 km/yr to 12000 km/yr.

T-4: T-3 plus a decrease in car ownership (C) from 450 to 300 per thousand people.

T-5: T-4 plus a decrease in lifetime (L) from 15 to 12 years.

T-Bottom: T-5 plus a decrease in population (P) from 1.42 to 1.25 billion people.

All values listed are end values in 2050.

Buildings:

B-Baseline: Default values for all 11 scenario parameters. Starting from the baseline I analyzed the following measures:

B-Demolition: B-Baseline plus an increase in the demolition rate to 2%/yr and a mandatory passive house standard for buildings erected after 2020. The demolition rate was chosen so that the transformation of the stock will be accomplished by 2050.

B-Renovation-Standard: B-Baseline plus an increase in the renovation rate to 2%/yr and a mandatory passive house standard for buildings erected after 2020. The renovation rate was chosen so that the transformation of the stock will be accomplished by 2050.

B-Renovation-Passive: B-Baseline plus an increase in the renovation rate to 2%/yr and a mandatory passive house standard for buildings erected after 2020. The renovation rate was chosen so that the transformation of the stock will be accomplished by 2050. Passive rehabilitation was applied to 90% of all renovated buildings.

B-Lifestyle: B-Renovation-Passive plus a reduction in floor area per dwelling by 15% and an increase in the number of persons per dwelling by 15% (end values by 2050).

B-Water&Appliances: B-Renovation-Passive plus a 50% reduction in energy demand for hot water generation and appliances in all new or renovated buildings.

B-Bottom: Combine B-Lifestyle and B-Water&Appliances.

Industry/Steel:

I-Baseline: Default values for all model parameters. The baseline includes an increase of the end-of-life recovery efficiency to 90%, an increase of the scrap share in basic oxygen furnaces to 20%, and the deployment of the best available technology at full scale by 2050. Starting from the baseline I analyzed the following measures.

I-EE1: Energy efficiency – low deployment: Energy efficiency (EE) measures including top-gas recycling, fuel substitution, direct reduction, smelt reduction, and electricity decarbonization, are implemented to a low level by 2050. For the specific parameter values chosen we refer to Paper V.

I-EE2: Energy efficiency, medium deployment level by 2050, same measures as above.

I-EE3: Energy efficiency, high deployment level by 2050, same measures as above.

I-ME1: I-EE2 plus the implementation of the identified possible ranges of all material efficiency strategies (UI, RU, LTE, LWE, FYI, FSD) by 2150.

I-ME2: I-EE2 plus the implementation of the identified possible ranges of all material efficiency strategies by 2100.

I-ME3: I-EE3 plus the implementation of the identified possible ranges of all material efficiency strategies by 2050.

Figure 11 shows the relative changes of the different scenario parameters. Although this figure does not show the influence the different parameters have on the model results, it still allows us to identify where the largest changes are to be expected, where the largest improvement potentials may lie, and which of the categories defined in Table 6 may contribute most to changing stocks, energy demand, and emissions.

For transportation in China, car ownership and the share of micro cars may increase drastically (C-Baseline, C-bottom, T-bottom), which dwarfs the development of all other parameters. The biggest relative parameter changes between the different scenarios are seen for fuel efficiency (F-Baseline vs. F-Bottom) and the affluence parameters car ownership (C-Baseline vs. C-Bottom), annual kilometrage (K-Baseline vs. K-Bottom), and share of micro cars (T-Baseline vs. T-Bottom). Relative changes in population (P-Baseline vs. P-Bottom) are significantly smaller than changes in the other parameters.

For buildings in Norway, Figure 11 shows that population may increase by 35% over the period studied (P-Baseline), and that several lifestyle and technology parameters hold a large reduction potential of up to 50% (HEAT, DHW, TYPE).

For the global steel cycle the plot has to be read in a different way. It is only in the case of population, that the figure shows a relative change from the 2010 value (P-Baseline). For the six material efficiency strategies, the present implementation rate is zero, and the graph shows the maximum future change of these rates in percentage points. There is a high potential for re-use of fabrication scrap, more intense use, and light-weighting.

Future in-use stocks are determined by multiplying population with per capita stock. They represent the main model driver and are therefore presented at the end of this section (Fig. 12). Not all scenario parameters affect the stock level and hence, the stock trajectory for several scenarios may be the same. Energy efficiency measures, for example, do not affect the size of the in-use stock in the model. Due to continued population growth as well as industrialization or urbanization, the total in-use stocks for the baseline scenarios in all three case studies grow for the foreseeable future. The difference between the development in China and Norway stands out. The population in both countries is expected to grow further, but in China, per capita stocks are growing from very low levels, whereas in Norway they are high and are already leveling out. All case studies include scenarios where total stocks level off before 2100. As a consequence of the different emissions mitigation strategies applied, stocks in the bottom line scenarios are between 25% and 40% lower than the respective baselines.

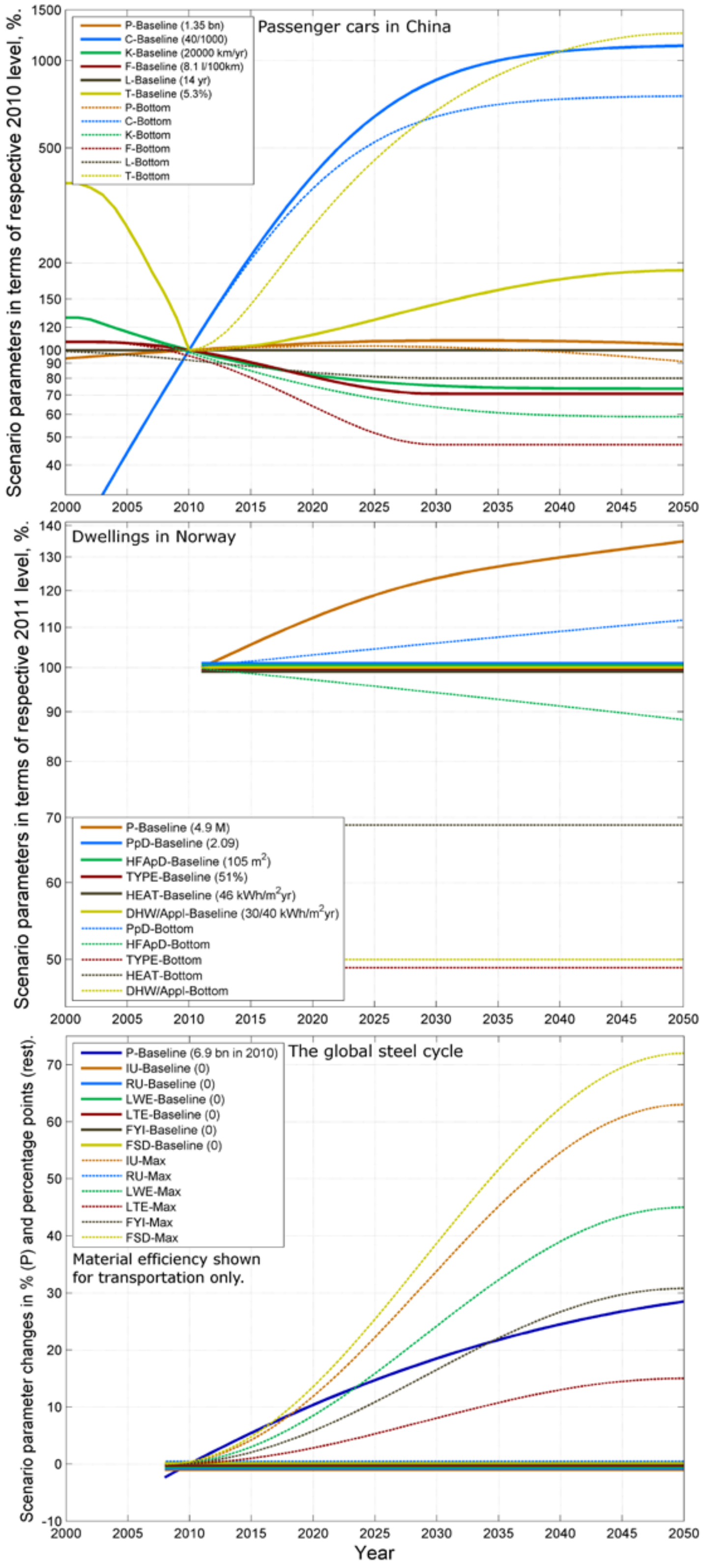

Figure 11: Overview on scenario parameters by case study. From top to bottom: Transportation, Buildings, Steel. The abbreviations for the different model parameters are explained in Table 7.

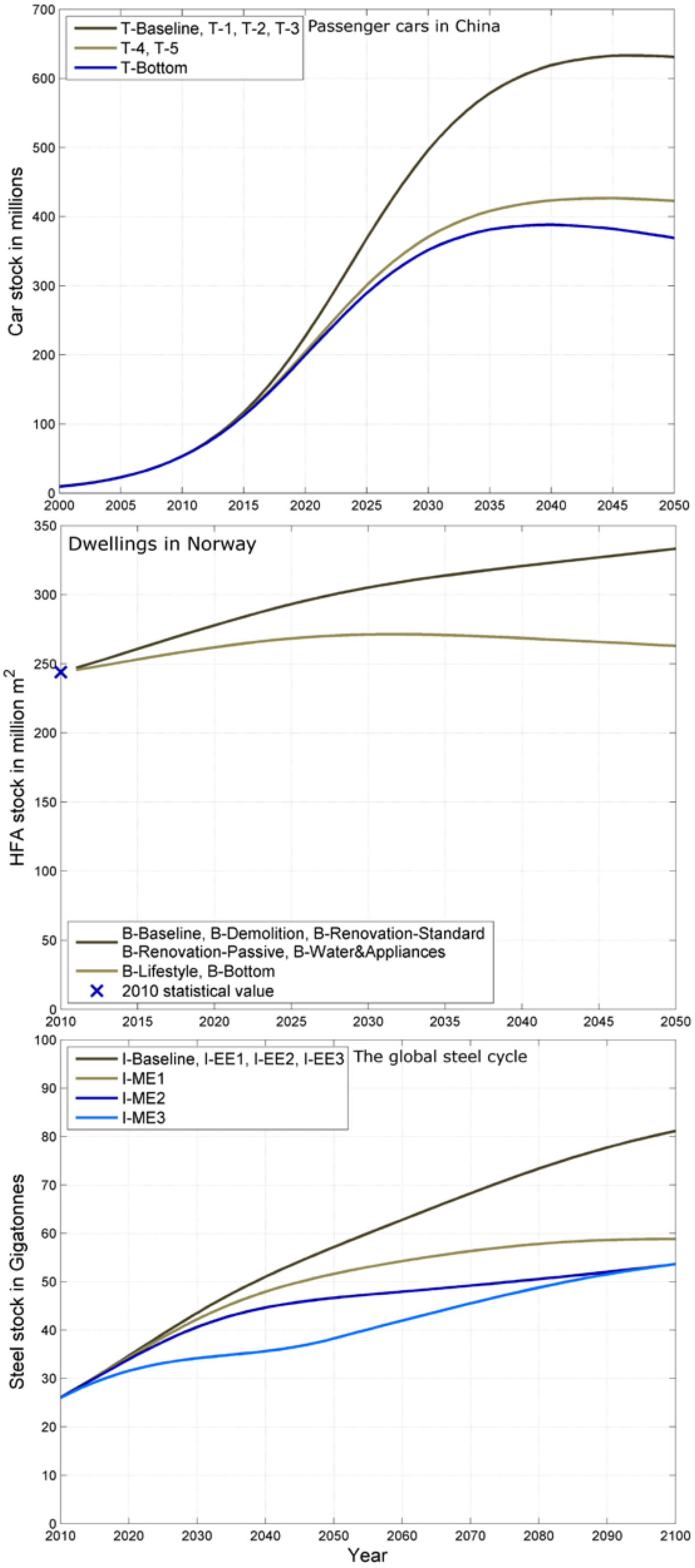

Figure 12: Scenario for stocks by case study. From top to bottom: Transportation, Buildings, Steel.

3. Results

The results section covers research questions (ii) and (iii) and presents the major findings from the three case studies on transportation in China, dwellings in Norway, and the global steel cycle. First, I present the results on final demand and end-of-life flows for cars, dwellings, and steel (section 3.1). In section 3.2 I present the scenario results on greenhouse gas emissions reductions, and show how the results relate to the different levels of global warming reported by the IPCC AR4 (IPCC 2007a).

3.1 Final demand, disposal, and energy demand by case study

3.1.1 Passenger cars in China (Paper I)

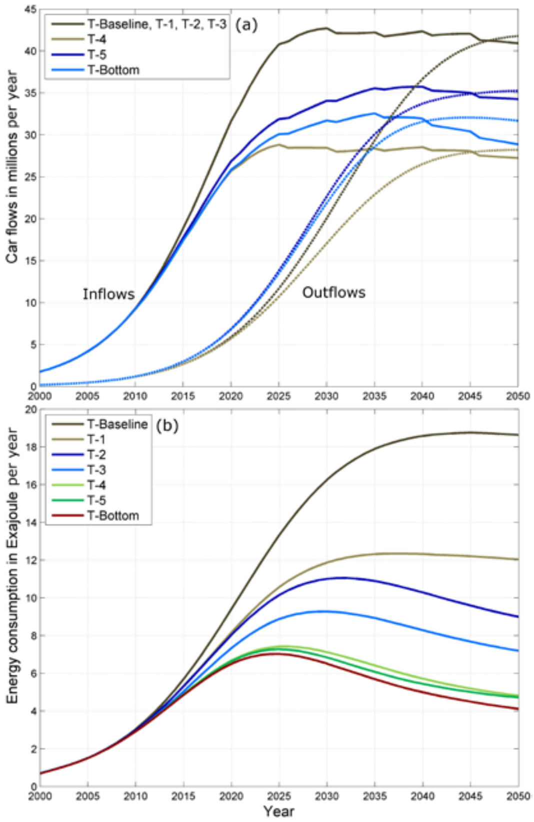

Figure 13: Final demand and total discards of passenger cars in China (a) and direct energy consumption (b). The scenarios are defined in section 2.3.

As consequence of the stock patterns shown in Figure 12, the demand for passenger cars in China rises sharply until about 2025. Thereafter, it levels out between 28 to 43 million units per year, which corresponds to 35-55% of the 2011 world automobile production (Fig. 13a) (OICA 2012). As population is expected to decline and the number of cars per capita is leveling out after 2025, demand stabilizes on a high level. China is experiencing the onset of a gigantic consumption boom, and as a consequence, the waste flows and the associated recycling potential rise with a delay of the average lifetime of the cars, which is about 15 years.

The present direct energy consumption from passenger cars in China is about 3 Exajoules pear year (EJ/yr) (Fig. 13b). This value grows six-fold by around 2040, which means that the energy consumption grows slower than the car stock shown in Figure 12. This is due to increases in the average fuel efficiency that is already included in the baseline scenario. One third of the baseline energy demand can be saved by lowering the average specific fuel consumption of the fleet from 6 l/100 km to 4 l/100km (T-1). Another third can be saved by building up a car fleet that is largely composed of micro-cars and implementing lower annual kilometrage and lower car ownership (T-4). The energy consumption for the scenarios involving a shorter lifetime (T-5) and lower population (T-Bottom) is almost the same as for T-4. When quantified in terms of car ownership and kilometers driven per car and year, the service provided in the T-Bottom-scenario is comparable to the present service levels in Japan or Switzerland, though with much more efficient vehicles.

3.1.2 Dwellings in Norway (Paper II)

For the baseline scenario, the construction of new buildings peaks before 2020 and then declines gradually until it reaches about 65% of the 2011 level in 2050 (Fig. 14a, solid lines). If the entire stock was to be transformed to passive house standard by 2050 by demolition and subsequent new construction (scenario B-Demolition), the new construction rate would have to double for the next 35 years. A lifestyle where people move together more densely and share smaller flats can reduce the inflow by about one third. The current renovation rate is about 1.5 million m^2 per year, and in order to achieve a complete transformation of the stock by renovation by 2050, this rate would have to triple. For all scenarios except B-Demolition, the demolition flow slowly rises from 1.5 million m^2/yr in 2011 to about 2 million m^2/yr in 2050. These rates result from extrapolating the present demolition rate, which lies within the range of demolition rates observed in several other European countries (IEA 2008). Once the transformation of the stock is accomplished, the renovation and demolition rates drop significantly. With the assumed turnover rate of 2%, this will happen around 2045.

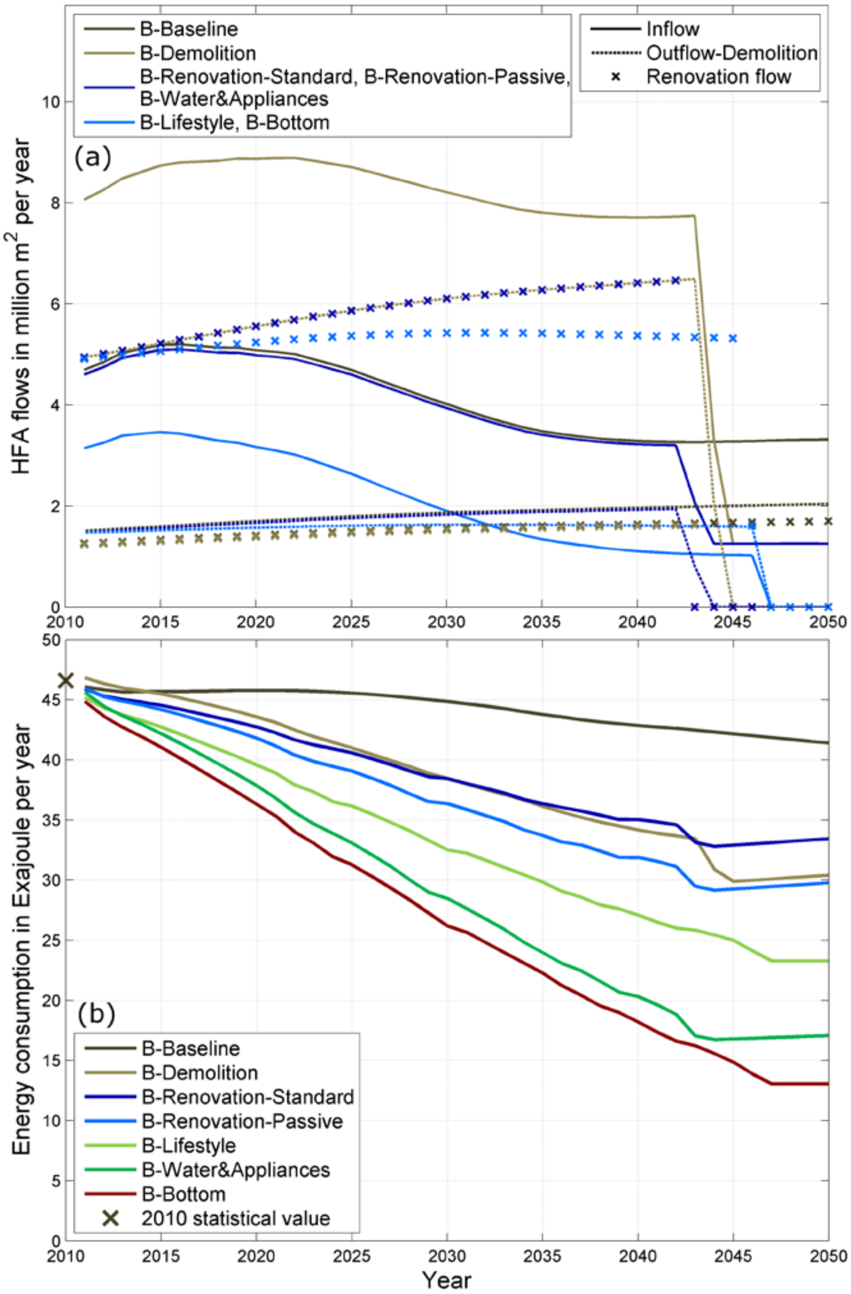

Figure 14: Flows of new, demolished, and renovated heated floor area (HFA) (a), and total sectoral energy consumption (b). The scenarios are defined in section 2.3.

For all scenarios, including the baseline, energy demand falls after 2011 (Fig. 14b). The three transformation scenarios result in a similar energy demand, which by 2050, will be only about a third lower than the 2010 level. This reduction can be considered small given that these scenarios include the implementation of the most recent building codes to the entire stock. The first reason for this result is that population growth leads to an additional demand for heated living space and energy consumption. Even more important is the second reason. The demand from hot water generation and appliances is not affected by new building codes and therefore it remains on a high level. In 2010, the average ratio of specific heating energy demand to specific energy demand for hot water plus appliances was about 1.6:1. For a fully transformed stock this ratio may be as low as 0.3:1, which means that about 75% of the direct energy demand in passive houses come from hot water generation, appliances, and lighting. Unless additional measures are taken, the sectoral energy demand cannot fall below the threshold of about 30 EJ/yr. Figure 14b shows that a significant additional reduction in energy consumption could be achieved by slight changes in the heated floor area per person and the number of persons per dwelling (B-Lifestyle) or by 50% savings in demand from hot water generation and appliances (B-Water&Appliances). Despite a population growth of more than 30% over the period 2010-2050, the combination of the two latter scenarios could reduce the sectoral energy demand by more than two thirds during that time.

3.1.3 The global steel cycle (Papers III and IV)

Under business-as-usual assumptions, final steel demand will continue to rise throughout the entire 21st century, though at a slower pace than during the boom period between 2000 and 2010 (Fig. 15). The different energy efficiency strategies only affect the supply side and do not change the material turnover in the cycle. Implementing material efficiency means that final steel demand and with it the material turnover in the entire steel cycle is decoupled from the service provided by the stocks in use. Figure 15 shows that even the slowest implementation of material efficiency (I-ME1) will lead to a peak and subsequent decline in final steel demand, so that from about 2060 onwards, global final steel demand will be below the 2010 level. A more rapid implementation of the material efficiency strategies (I-ME2 and I-ME3) exacerbates the decline in throughput and from 2050 on, global final demand will be similar to the 2005 level. In all scenarios, the flow of steel contained in discarded products will continue to rise. For the material efficiency scenarios, the amount of steel in discarded products will be similar to final demand during some periods. In these years the global in-use stock of steel will be about constant, and through recycling, re-manufacturing, or re-use, the discarded steel could satisfy most of the demand for new material. The energy layer has not been assessed for this case study and hence, Figure 15 only shows the mass flows.

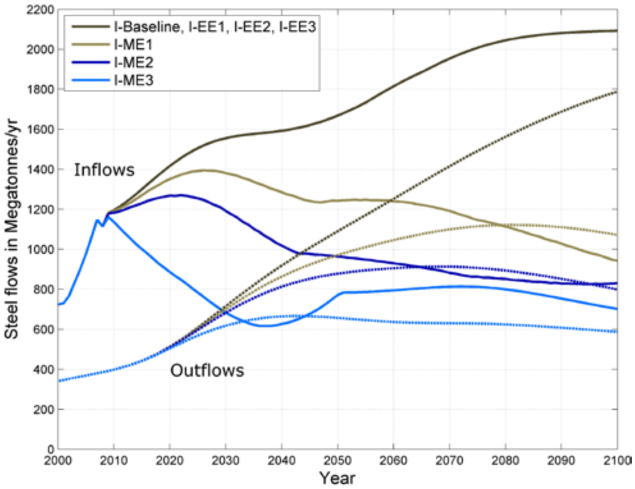

Figure 15: Total final demand and total discards of steel. The scenarios are defined in section 2.3.

Provided that the steel industry shifts the production technology mix so that all available scrap can be processed, secondary steel production will quadruple by the end of the century compared to present levels (green wedge in Figure 16a). The fraction of the global flow of liquid steel that can be sourced from old scrap will exceed 50% between 2030 and 2060, which is why I called this period the *steel scrap age*.

Rising scrap flows may put primary steel producers under pressure as the declining demand for BOF steel may lead to the closure of existing primary production assets in the long run (blue wedge in Figure 16a). This problem may first hit the developed world, where stocks are about to saturate and large amounts of scrap are already available. The economic lifetime of integrated steel mills and the connected infrastructure is typically between 60 and 100 years, and their owners have a strong incentive to avoid their assets from running idle before that age. One way to achieve this is to export excessive steel output to supply growing demand elsewhere in the world. To understand the interplay between asset lifetime and demand trends in different world regions, I developed a capacity model that tracks the steel production facilities from the different years and regions through their lifetime. I fed the model with the scenario results on global primary steel demand and explored how this demand is split onto the ten regions under different boundary conditions.

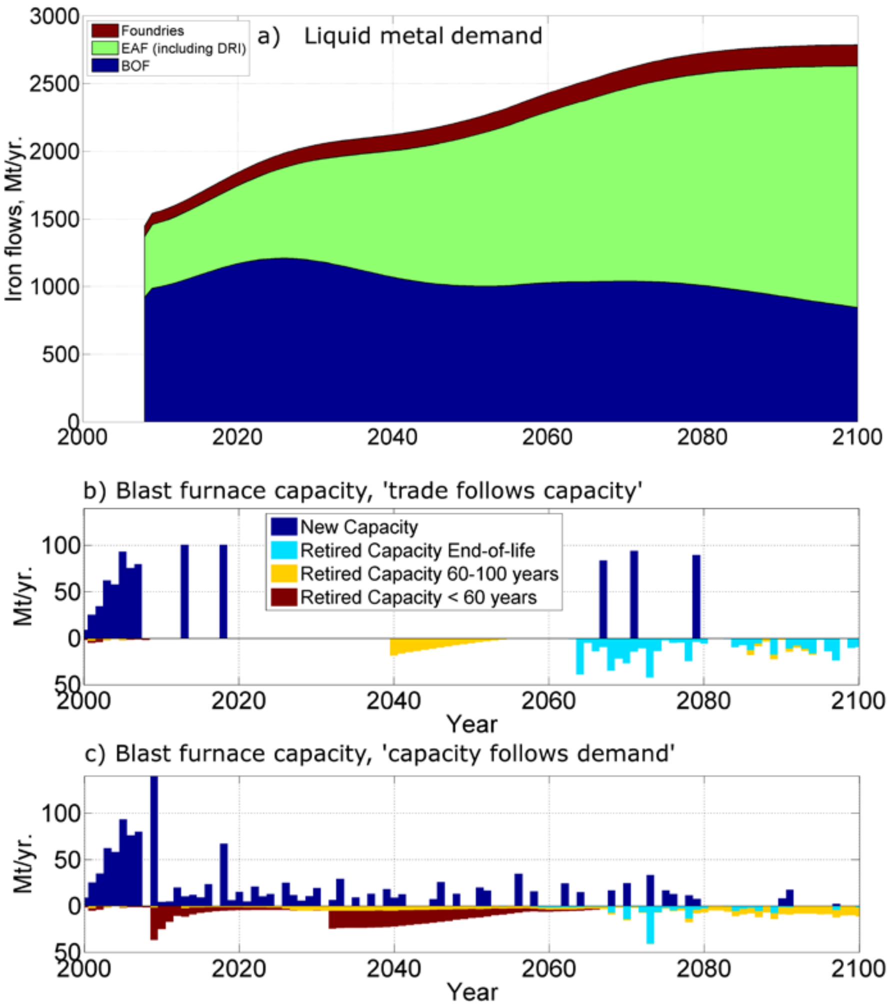

Figure 16: (a) Liquid metal demand by source, scenario I-Baseline. (b, c): Construction and decommission of blast furnace capacity, scenario I-Baseline. BOF: basic oxygen furnace (primary production), EAF: electric arc furnace (secondary production), DRI: direct reduction. Source: Paper IV.

Figure 16 shows two extreme cases. For ‘trade follows capacity’ (Fig. 16b), existing production assets are used irrespective of their location, and international trade is assumed to allocate the steel to those domestic markets where it is needed. Uneconomic decommissioning of primary production assets can be avoided and for more than 50 years in a row, no new blast furnaces need to be built. In the case of ‘capacity follows demand’, new production facilities are erected in the regions where steel is required, and consequentially, elder assets in other regions will have to be taken out of use (Fig. 16c). Here, the situation looks much different. As many new blast furnaces are built in regions with growing demand (mainly in India, South America, and Africa), existing assets in China and the OECD countries may soon run idle due to saturating stocks in those regions. For ‘capacity follows demand’, up to 500 Mt/yr of blast furnace capacities may have to be torn down before reaching the end of their economic life over the period 2010-2060.

The two cases show that optimizing capacity utilization with different system boundaries can lead to significantly different outcomes. On a globalized steel market the existing primary production assets could supply the entire world with steel for more than 50 years to come. Contrarily, developing regions may want more control over steel supply and create policies that foster domestic steel production, which may cause significant overcapacities elsewhere.

The model at hand allows us to explore the ‘option space’ for future capacity development with the given forecasts on final steel demand and total scrap supply from the scenarios in papers IV and V. To assess the social, economic, and environmental consequences of the different pathways the current modeling framework would have to be extended.

3.2 Carbon footprint and climate targets by sector (Papers I, II, V)

The three plots (a)-(c) on the left side of Figure 17 show the sectoral greenhouse gas emissions for the three case studies and the different scenarios. For each case study, the benchmarks that relate the sectoral carbon footprint to the different temperature ranges of global warming are shown on the right side of Figure 17, with absolute greenhouse gas emissions on the left axis and the corresponding global average temperature increase on the right axis.

As expected, baseline emissions will vastly exceed the 2°C benchmarks in all case studies. For buildings in Norway and the global steel cycle the baseline emissions correspond to a temperature increase of 3-4°C. For passenger cars in China, the corresponding temperature increase is beyond the temperature range studied by the climate model.

We now have a look at the scenarios that include energy efficiency. A fleet of very fuel efficient cars can yield substantial emissions reductions of about 35% for the case of passenger cars in China, but still, the corresponding temperature increase is in the upper range of the scale (6°C).

Over the period 2000-2050, the carbon footprint of the Norwegian dwelling stock for the different transformation scenarios decreases by about one third compared to the baseline. For the demolition scenario, however, upstream emissions are substantial, and the sectoral footprint of the B-Demolition scenario remains higher than baseline emissions until the transformation will be complete between 2040 and 2050. The three transformation scenarios include the application of the current building code or passive house standard to the entire dwelling stock, and it is astonishing that emissions do not decline further. The reasons for that were already mentioned in section 3.1: Population growth and demand from hot water generation and appliances counteract the reductions resulting from reducing heating energy demand per dwelling area.

For the steel cycle, the different levels of industrial energy efficiency and implementation of carbon capture and storage in the electricity supply may yield emissions reductions between 0.35 and 0.8 Gt of CO_2-eq per year in 2050. For the case of maximal energy efficiency improvements (I-EE3), the sectoral carbon footprint will decline to the 2000 level in 2050, which corresponds to a 3.2°C average temperature increase.

I concluded that in none of the countries and sectors studied, the present portfolio of energy efficiency measures can yield emission reductions that are near the 2°C benchmark.

I evaluated the emissions reductions that result from implementing the additional measures proposed in section 2.3. For passenger cars in China, a large scale transition to micro-cars yields another 25% reduction of direct emissions, and even bigger reductions can be achieved by reducing kilometrage and car ownership (Fig. 17). A change in lifetime and a different population trajectory would only have a small impact.

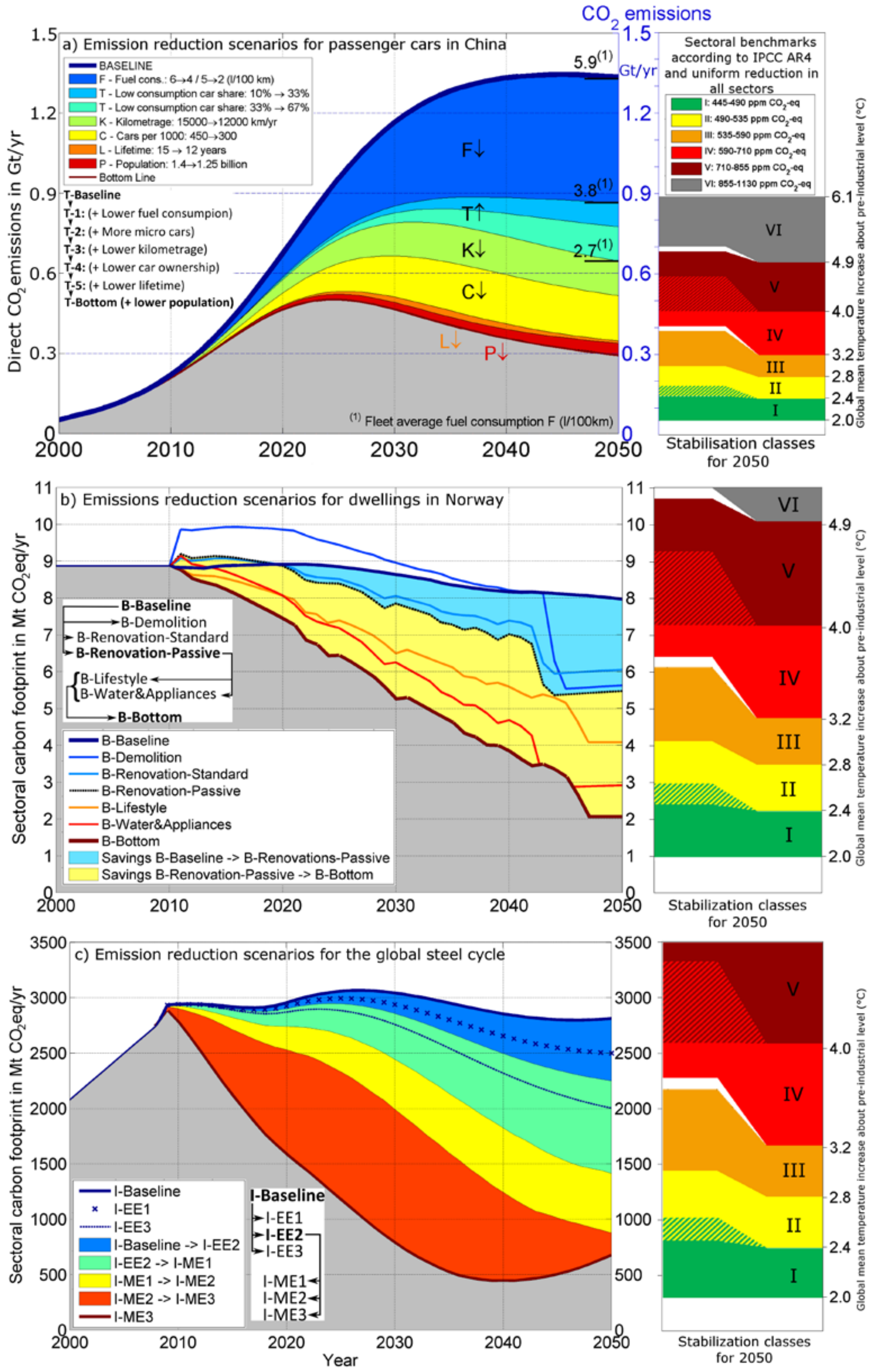

Figure 17: Total sectoral carbon emissions by case study and their relation to the IPCC targets. a) Passenger cars in China, b) Dwellings in Norway, c) The global steel cycle. The different scenarios are defined in section 2.3. For each case study the structure of the scenario tree is shown.

When combining all technological and lifestyle measures, direct emissions can be reduced to about 22% of the baseline emissions, which corresponds to a 3°C temperature increase. This illustrates the challenge related to climate change mitigation in the transportation sector. Efficient car utilization as observed in some industrialized countries combined with very fuel efficient cars and smaller vehicles still leads to emissions that are 1.5-4 times higher than the benchmark for 2°C.

For buildings in Norway, additional reductions of up to 2.5 Mt CO_2eq/yr could be achieved by reducing consumption from hot water generation and appliances. A different lifestyle with a 15% increase in the number of persons per dwelling and a decrease in dwelling size of 15% could save about 1.5 Mt CO_2eq/yr in 2050. Combining these measures with a full transformation to passive house standard would lower the sectoral carbon footprint to about 2 Mt CO_2eq/yr. This represents a 75% reduction compared to the 2011 level, and it is well within the 2°C regime.

For the global steel cycle I explored the three material efficiency scenarios. Implementing the estimated savings potential from the six material efficiency strategies by 2150 (green wedge) would yield larger emissions savings than each of the three energy efficiency scenarios. In 2050, emissions would be about 30% lower than in 2000 when combined with I-EE2. Still, this would only correspond to the 3°C benchmark. In Paper V we therefore explored the consequences of realizing the full savings potential from material efficiency at an earlier stage (2100: yellow wedge, I-ME2; and 2050: red wedge, I-ME3), and found that both target years were sufficient to bring 2050 emissions into the 2°C regime. Though I-ME2 and I-ME3 had similar emissions in 2050, the accumulated emissions from I-ME3 were significantly lower. In the bottom line scenario steel will be used so efficiently that around 2050, global scrap flows will be too small to supply growth in Developing Asia and Africa, which will cause primary production to rise again.

Using the assumptions chosen for the model parameters, I found that a combination of energy efficiency, hybrid solutions, material efficiency, and moderate lifestyle changes, can reduce emissions down to the 2°C benchmark for buildings in Norway and the global steel cycle, but not for individual transportation in China.

4. Discussion

I compare my results with other studies and discuss to what extent the case-study-specific results can be generalized (sections 4.1 and 4.2). I compile and discuss my findings for questions (i)-(iii) (section 4.3), and demonstrate how my work relates to three underlying problems of sustainable development (question (iv), section 4.4).

4.1 Comparing the carbon footprint with other studies and policy proposals

I compare my findings to the IEA BAU (business-as-usual) and BLUE MAP scenarios (International Energy Agency 2010) and a recent policy proposal issued for the EU Commission (EU Commission 2011), (Table 8). These scenarios were chosen because they cover the entire energy- and process related anthropogenic carbon footprint. They differ, however, in which sectors, greenhouse gases and emissions scopes are included, and in the portfolio of mitigation strategies evaluated (Table 8). The emissions target for the BLUE MAP scenario is a 50% reduction of global carbon emissions over the period 2005-2050. The proposal from the EU commission is more ambitious. It envisions an 80-95% reduction of the EU's emissions over the period 1990-2050 to allow for growing emissions in developing countries. The targets for the BLUE MAP and the EU scenario were re-calculated using historic data on emissions, so that 2000 is the common base year for all numbers. To allow for better comparison, I scaled the national carbon emissions for passenger cars in China and dwellings in Norway to the global level, assuming that all people would cause similar emissions in 2050.

For transportation, my BAU scenario shows a much higher increase than the IEA-BAU one (Table 8). This is partly a result of the different sectoral boundaries. I considered passenger cars only, whereas the IEA scenario covers the entire transportation sector. For my energy efficiency scenario T-1, direct carbon emission grow by 110% over the period 2000-2050, which is 40 percentage points less than the growth in the IEA-BAU scenario. My bottom line scenario corresponds well with the BLUE MAP scenario. That means that the proposed portfolio of energy efficiency, hybrid solutions, and moderate lifestyle changes can lead to similar emissions reductions in the passenger car fleet as the BLUE MAP scenario, which includes large-scale deployment of hydrogen, electric, and plug-in electric vehicles (International Energy Agency 2010). The EU proposal is even more ambitious with a reduction of -62% to -73%, and mentions the deployment of biofuels and an almost completely de-carbonized energy supply sector as measures in addition to the strategies included in the BLUE MAP scenario. Neither the BLUE MAP scenario nor the EU proposal explicitly considers hybrid solutions or moderate lifestyle changes as part of their portfolio.

The BAU emissions from residential buildings increase by 40% over the period 2000-2050 (Table 8). Energy efficiency in the building stock can keep emissions at about the same level (-6%), and additional savings and lifestyle changes could lead to a reduction of up to 65%. The latter reduction is about twice as large as the savings potential for the BLUE MAP scenario, which covers all buildings. One reason for this difference may be that substantial savings in residential buildings are easier to achieve than in commercial buildings (Reinås 2009), which may lead to higher emissions reductions in a study that only covers residential buildings. Similar to the transportation sector, the implementation of the proposed portfolio of decoupling strategies to buildings leads to emissions reductions that are similar to or exceed the reductions from the BLUE MAP scenario. The EU proposal assumes even higher reductions, which are to be achieved by a switch to low-carbon energy carriers (EU Commission 2011).

The industry scenarios cover the steel sector only, and one can expect the resulting emissions reductions to be different from the other two studies (Table 8). It is still interesting to see that the energy efficient scenario I-EE2 roughly corresponds to the BLUE MAP scenario for industry (-4% vs. -13% reduction), without the set of material efficiency strategies presented in Paper V being implemented. Material efficiency therefore represents an opportunity a) to achieve additional reductions of industrial carbon emissions or b) to replace the potentially more risky supply-side technologies such as carbon capture and storage and nuclear power, which are an integral part of the BLUE MAP scenario. The reductions of industrial emissions in the EU proposal are larger than the result for I-ME3. The EU proposal does not provide a specific set of mitigation strategies for industry, but mentions that carbon capture and storage on broad scale will be necessary to reach the given sectoral target.

Table 8: Comparison of own findings with previous studies and proposals.

Relative changes in the emissions over the period 2000-2050 (in % of 2000 sectoral emissions)	**My findings, scaled up to the global level**			**ETP**		**EU Commission proposal (EU-wide)**
	BAU	**Energy efficiency only**	**Bottom**	**BAU (global)**	**BLUE MAP (global)**	
Transportation	**+260**[7]	**+110**[7] **(T-1)**	**-8**[7]	+150	-11	-62 to -73%
Buildings	**+40**[8]	**-6**[8] **(B-Renovation-Passive)**	**-65**[8]	+72	-34	-87 to -90%[9]
Industry	**+35**[10]	**-4**[10] **(I-EE2)**	**-68**[10] **(I-ME3)**	+80	-13	-80 to -85%[9]
Power generation	-	-	-	+140	-71	-93 to -99%[9]
Agriculture	-	-	-	-	-	-33 to -41%[11]
Other	-	-	-	+600	-70	-63 to -73%

4.2 How representative are the results and to what extent could they be applied to other countries or sectors?

Passenger cars in China: The lifetime of passenger cars in several countries is 12-17 years (Paper I), which is twice the average age of a car fleet of constant size. I assumed that the passenger car stock in China will stop growing around 2050. With an average car age of 6-8 years, the stock in 2050 consists mainly of the cohorts produced after 2040. Such a stock could be assumed for any developed country for 2050, and since the emissions benchmarks were derived on a per-capita basis, the scenario results can be directly transferred to other countries. The major limitations of the case study are that only direct emissions are included and that the entire fleet is assumed to use gasoline as fuel. A shift toward a fleet of electric or hybrid vehicles or to biofuels could significantly change the results. Upstream emissions from new drive technologies should be included in the sectoral carbon footprint, as they may be substantially higher than the impact of cars with internal combustion engines (Hawkins et al. 2012). Given

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[7] Passenger cars only

[8] Residential buildings only

[9] CO_2 only

[10] Steel industry only

[11] Only non-CO_2

that the 2°C benchmark could not be reached with the strategy portfolio developed in paper I, the present case study should be combined with studies that cover alternative fuels and drive technologies.

Dwellings in Norway: The emissions scenarios for Norway cannot directly be applied to other regions for the following reasons:

(1) The local climate directly impacts the heating energy demand.

(2) Each country has a specific fuel mix for heating purposes, and in Norway, most of the heating energy is supplied by electricity. I applied the Nordic electricity mix, whose carbon intensity is about 70% lower than the European mix (Dones et al. 2007).

(3) The lifetime of residential buildings in developed countries can be longer than 100 years (Bohne et al. 2006; Müller et al. 2007), which means that most of the existing dwelling stock in Norway would still stand in 2050. This situation is different from developing countries, where the present floor area per capita is much smaller than in the western world (Hu et al. 2010). Developing countries therefore could build up a stock of passive or low energy houses from the beginning on, whereas for countries with a mature stock, demolition or renovation programs need to be put into place to achieve significant energy savings in the existing stock.

The 2°C benchmark could be reached under Norway-specific assumptions, and conducting similar case studies for other countries could show whether implementing the portfolio of decoupling strategies in other climates and energy mixes could be successful as well.

The global steel cycle: The success of material efficiency in reaching the 2°C benchmark is mainly determined by two effects:

(1) Under the assumption of stock saturation, final steel demand may decline once stocks have matured, and reducing in-use stocks by light-weighting or more intense use allows for transferring the accruing old scrap to regions with lower stocks. In-use stock saturation allows steel producers to develop from an industry that builds up steel inventories to a one that maintains them. Saturation, however, seems to be a steel-specific phenomenon; it could not be observed for two other major materials. In-use stocks of aluminum (Liu et al. 2012) and cement (Müller et al. 2013) continue to grow all over the world. This means that there is no empirical indication that a certain amount

of aluminum or cement in use is *sufficient* for the average person in a developed country.

(2) Recycling steel displaces primary production and leads to large emissions savings. Concrete, in contrast, cannot be recycled, but modular construction and re-use of concrete blocks represents an opportunity to close the cycle for this material (Allwood et al. 2012).

Previous work indicates that by applying the same set of material efficiency strategies to the aluminum cycle, the 2°C benchmark cannot be reached (Allwood et al. 2012). It seems that the historic use pattern and the recyclability of steel facilitated the success of material efficiency in the model calculations. Other material industries may face even bigger challenges than the steel industry when trying to reduce their carbon footprint, and may depend on carbon capture and storage to reach the 2°C benchmark.

4.3 My findings for research questions (i)-(iii)

I first discuss the mitigation scenarios for reaching the 2°C target and the other temperature benchmarks (question (iii)), then move on to final demand and waste flows (question (ii)), and close with a critical discussion of the methodology (question (i)).

(iii) How big are the emissions reductions resulting from implementing energy efficiency, hybrid solutions, material efficiency, and lower stock levels in the different case studies? How do the emissions scenarios in the case studies relate to the different levels of global warming, and the 2°C target in particular?

In section 3.2 I found that "*[...] in none of the countries and sectors studied, the present portfolio of energy efficiency measures can yield emission reductions that are near the 2°C benchmark.*"

Although increased energy efficiency can yield substantial impact reductions especially in transportation and buildings, it cannot compensate for the growing demand in the different sectors. Energy efficiency can contribute about 20-50% to the emissions reductions required to reach the 2°C regime. This agrees with other assessments, e.g., the BLUE MAP scenario, which requires the deployment of nuclear power and carbon capture and storage in addition to energy efficiency in order to reach the target.

In the steel industry, where energy accounts for a substantial fraction of total costs, energy efficiency improvements have been an issue for the past fifty years, long before the public became aware of climate change (Yellishetty et al. 2010). As a consequence, the remaining potential for improvements is considered low compared to historic achievements (Paper V). In contrast, a trend reversal is required in order to realize the identified savings potential for residential buildings and passenger cars. Although there is a danger of rebound effects (section 1.3.2), energy efficiency is a widely accepted mitigation strategy. The case studies, the BLUE MAP scenario, and the EU proposal discussed in section 4.1 consider energy efficiency a major building block for reaching a carbon-constrained regime.

Figure 17 shows that *hybrid technologies (technologies that may require behavioral changes with the users), material efficiency, and moderate lifestyle changes, combined with improved energy efficiency, can lead to significant emissions reductions, but only for residential buildings in Norway and the global steel cycle, the 2°C benchmark can be reached.*

Unlike energy efficiency, which is a result of improvements within specific processes, the additional decoupling strategies stretch across several parts of the anthropogenic metabolism or require changes in the model drivers, which are beyond the realm of the techno-sphere. Their implementation requires better coordination and interaction between producers, the waste management industries, and the end-users. Below I compile my main conclusions on decoupling beyond energy efficiency from the different case studies and the major barriers related to the implementation of decoupling strategies:

Steel: Scaling up the material efficiency gains that were found in case studies on the product level to the entire steel cycle has the potential to yield emissions savings that are three to five times as large as those resulting from a further increase in process energy efficiency. But implementing material efficiency would require significant changes with the steel producers. While steel production is expected to double over the period 2010-2050 under business-as-usual assumptions (Allwood et al. 2010), implementing the material efficiency strategies would lead to a gradual phasing out of primary steel production over the same period. To facilitate scrap recovery and sorting in the waste management industries, significant changes are required in how the different types of steel are tracked through their respective life cycles. Changes in technical norms and specifications could facilitate light-weight design (Allwood et al. 2012). In addition, one would have to consider measures that allow for more intense use of the existing stocks, such as increasing the occupancy rate in passenger cars.

Buildings: In the building sector, passive and other types of low energy houses can be considered as hybrid solutions as they typically require an automatic system that controls heating and ventilation and that should be designed for maximum user acceptance and comfort. Ill-designed building solutions may be rejected by the users and loose much of their savings potential (Melvær 2012; Passive house users 2012). Hence not the technical systems themselves, but the unity of technology and users needs to be understood and considered in the design process to allow for maximal savings.

Without substantial energy savings in the *existing* dwelling stock, the 2°C benchmark is out of reach. Complete demolition and subsequent rebuild of the stock using passive house technology would yield large savings, but this measure would entail upstream emissions that are similar to the accumulated savings over the period 2015-2050. It may as well be considered unfeasible for economic and cultural reasons. Renovating the existing stock to passive house standard may represent a feasible alternative, and is currently promoted and investigated within Norway (Arnstad 2010). Significant reductions in energy consumption from appliances and hot water generation may be indispensable to reach the 2°C benchmark within the dwelling sector.

Transportation: A shift to micro cars as alternative to conventional passenger vehicles may make cars less attractive as status symbols. But it would better reflect the way cars are used today. The typical occupancy rate of passenger cars in developed countries is between 1.1 and 1.7 (Broca 2012), which leads to the conjecture that two-seated micro-cars would provide sufficient service for the majority of all car journeys. For those journeys where micro-cars are not sufficient, car sharing systems could provide access to conventional cars. The factors determining the difference in car ownership and kilometrage between the different developed countries are poorly understood, but urban structure and density were found to have a big influence (Broca 2012). This emphasizes the role of urban planning on the long-term evolution of car utilization. The three measures micro cars, lower kilometrage, and lower car ownership account for about 50% of the identified emissions savings potential. The social and urban planning aspects of these measures lie beyond the system boundary.

Even after implementing the entire portfolio of decoupling strategies, the sectoral emissions are at least twice as high as the 2°C benchmark. Additional emission abatement may thus be necessary, and there are three principal options for achieving this: Further reductions of annual kilometrage and car ownership; savings in other sectors; and fuel decarbonization.

(ii) How do final demand and discard of products in the different case studies develop over time under the assumption that the entire world will eventually build up the same in-use stocks as currently observed in industrialized countries? How do demand and discard change once different climate change mitigation strategies are implemented?

The evolution of in-use stocks over time determines the long-term trends in final consumption. From the studies of transportation in China and the steel cycle I found that stock growth in the developing world will lead to substantial increases in final demand. In regions with maturing stocks, consumption remains on a high level or may even decline in some cases. Together with the product lifetime distribution, the stock pattern determines the future amount of discarded products and thereby the potential for material recycling and product re-use. This correlation can be used for estimating future waste flows and scrap supply, for long-term planning of investments in primary and secondary production assets, and for forecasting the demand for primary mineral resources.

Figures 13-16 show that many strategies to reduce emissions heavily impact the output of the manufacturing industries, the waste management industries, and the material suppliers, e.g., the steel industry.

Increased energy efficiency in the steel industry does not alter the demand baseline, but implementing the material efficiency strategies would significantly reduce final steel demand. For buildings, construction or renovation activities will rise significantly when the existing dwelling stock is upgraded to passive house standard. In the transportation sector, lifestyle changes could reduce the number of passenger cars produced by up to one third.

Next to the service and emissions layer, the models contain information on stocks and flows of products, materials, and energy. They may enable policy makers and other stakeholders to anticipate the consequences of different emission abatement strategies on the supplying industries. The model results may point out the need for incentives for development or re-structuring in certain industrial sectors.

(i) How can dynamic stock models be extended to include both direct and indirect energy consumption and carbon emissions, and what are the critical assumptions and variables?

How can emissions reductions in different countries and sectors be benchmarked against the 2°C target and other global climate targets?

The model developed in section 2 allows us to estimate energy demand and carbon emissions resulting from building up, maintaining, and using stocks of goods and products that provide service to people. It allows us to estimate the emissions savings from strategies that decouple service provision from material and energy throughput.

The model has several limitations and underlying assumptions that one needs to be aware of. I now list and explain the main limitations of my approach, and discuss how they could be overcome.

The interplay between foreground and background system: Through a combination of dynamic stock models, MFA foreground models, and background inventories, the carbon footprint of a sector or country can be tracked over time, emissions savings from material recycling can be considered, and different upstream emissions can be included as well. The way this approach was implemented in the different case studies has several limitations and potential inconsistencies:

(1) The foreground system may overlap with the background process chain, which may lead to double-counting. The model of the steel cycle, for example, comprises the entire anthropogenic use of this material. At the same time, the steel contained in power plants, the electricity grid, and coke ovens may already have been accounted for as capital investment in the background inventory for this study. A detailed breakdown of

steel use into different industrial activities could give information on the size of steel stocks in the background system, and would allow us to estimate the magnitude of double-counting in this case. Constructing, renovating, and operating residential buildings represent final consumer demand, which is not part of life cycle inventories of industrial activities. Hence, there is no overlap in the case study on buildings.

In future models, a filter, which sets all flows in the background system that are already part of the foreground system to zero, might be applied to the upstream inventories to systematically eliminate double-counting. This requires that the upstream flows are tagged or categorized to facilitate the application of the filter.

(2) When quantifying indirect emissions associated with the MFA foreground system it is tempting to use readily available data from the literature. However, the inventories used in different studies are often based on different system boundaries, have different geographical coverage, background systems, use different databases, or refer to different years. When compiling the background impacts one must therefore be aware of this limitation and conduct a critical examination of the eligible inventories. Whenever possible, congruent background systems should be used, e.g., by referring to a single LCA or I/O database. For the Norwegian dwelling stock I refer to a single LCA study on the upstream impact of new construction. This study uses EcoInvent v2.2 as background system, and I apply the same database to determine the inventory of renovation activities and the different energy carriers. Only for district heating, a study with a Norway-specific background system was used. For the steel cycle I assisted with the compilation of an inventory of all processes in the MFA foreground system, and the compilation of a common demand vector for the different energy carriers. The upstream impacts of this demand vector were determined by referring to global average figures provided by the International Energy Agency and the WorldSteel Association.

(3) The upstream inventories only represent snapshots of the production processes in a given year, but the foreground system is dynamic and may extend several decades into the future. This mismatch may be the most severe limitation of the model approach as the implementation of new energy technologies, efficiency gains in industrial processes, or recycling, may significantly change the carbon intensity of energy and material supply over time. In the case study on the Norwegian dwelling stock I assumed a constant carbon intensity of the energy supply. This number may change, however, not

only due to technical changes in the supply system, but also due to changes in system boundary. Although hydroelectricity accounts for the largest part of the actual electricity consumption in Norway today, a higher level of integration of the Norwegian grid into the European grid may change this situation. I anticipated this development by assuming the Nordic electricity mix instead of the Norwegian electricity mix in the case study. For the global steel cycle, different rates of electricity decarbonization are already part of the energy efficiency scenarios.

Several existing integrated assessment models include a changing carbon intensity of the energy supply over time (Weyant et al. 2006). A combination of dynamic stock models with these methods may allow for a more accurate and more comprehensive assessment of the future impacts of human activities. This combination would form a new type of integrated assessment model, where affluence is measured in terms of service provided by in-use stocks rather than in terms of economic output.

(4) Material recycling and scrap diversion reduce industry's energy consumption and carbon emissions. By including the respective material flows in the MFA foreground system, the sector- or country-wide recycling potential can be quantified. This opportunity needs to be considered when determining the split between the model parts B and C in future applications.

Stocks as measure of service: Alternative affluence measures may help to shift the focus away from economic throughput and may therefore represent an important tool to achieve lifestyle changes within society (Goossens et al. 2007). We postulated that stocks of cars, square meters of dwelling space, and tons of steel in use are suitable physical affluence measures. However, the service-providing products and materials are in turn only means to support human activities. Cars are a means of transport, and transport in turn is a means of accessibility. Buildings are a means of shelter and representation. Steel is a material used in many different services and activities due to a large number of physical properties such as stability, stiffness, tensile strength, ferromagnetism, etc. In-use stocks can therefore be considered as intermediaries between human needs and the physical world. They are not an end by themselves, though the products and materials that serve us may start a life on their own. Products may become symbols of identification and status and the desire for having them is sometimes larger than the practical demand for their services (Özcan 2003).

Some of the reduction strategies, such as light-weighting or more intense use of steel-containing products, actually decouple stocks from the service they provide. Using affluence measures that are based on services provided by stocks rather than based on the stocks themselves may help to develop, communicate, and implement strategies that decouple stocks from services.

Saturation: I assumed that eventually, all countries will develop in-use stocks comparable to those in the developed world and that there will be some form of stock saturation on a per capita basis in all sectors. In the case studies, I found historic evidence for saturation of passenger cars per capita, dwelling area per person, and steel stocks per capita, and I postulated that eventually, in-use stocks in the entire world will saturate on the levels I found. But there is no mechanism that enforces saturation in other regions or sectors. The example of aluminum and cement, where a possible saturation has not been observed yet, was discussed in section 4.2. The time when in-use stocks reach a possible saturation is also not certain; it is coupled to the economic development of a country. When applying the model to other end-use sectors, the saturation hypothesis may have to be replaced by other assumptions on the future development of in-use stocks.

Interdependent model parameters and the interface to social sciences (I): In all three case studies, the model parameters were treated as independent of each other. In practice however, this may not be the case. Consider, for example, an increase in fuel efficiency, which reduces the price of a kilometer driven. This price drop can lead to rebound effects (Hertwich 2005), for example, an increase in annual kilometrage. The mechanisms behind these interdependencies are not of technical nature, they lie beyond the system of social metabolism. Still, they may play a vital role in determining the actual emissions reductions that result from the implementation of the different decoupling strategies. Connecting physical models to approaches from behavioral science may enable us to study the rebound effects related to individual strategies. This connection may further open up the possibility to *design* the portfolio of decoupling strategies in way that the expected rebound effects are minimal.

Product lifetime: The lifetime of products in use determines the turnover of the stock; it determines the need for replacement and the potential for recycling and re-use. While the lifetime distribution of passenger vehicles is well-known from several case studies in different countries and years, there is much less reliable information on the lifetime of buildings and infrastructure. Next to saturation level and saturation time, product lifetimes are the main source of uncertainty in the model of the global steel cycle. For the case study on buildings in Norway, I chose to replace the lifetime by turnover rates that are derived from a specific exogenous target.

A more rapid turnover of the in-use stock by shortening the product lifetime allows new or more efficient technologies to penetrate faster. There is a controversial discussion on whether such a shortening leads to emissions reductions for the entire sector. While governments and the car industry justified the recent scrapping premiums for 'clunkers' with their expected environmental benefit (Bolton 2009) (Paper I), such a benefit was not found by studies that consider the whole life cycle of passenger cars (Kagawa et al. 2011; Suh 2010)[12]. In the case study on the steel cycle, lifetime *extension* is one of the material efficiency strategies to lower emissions from material production. The relationship between emissions savings, the efficiency improvement rate, and product lifetime extension is discussed in detail in Skelton and Allwood (2013). For buildings, a so-called onion-skin-design may help to separate structure from function and allow for extending the lifetime of the materials in the building core (Allwood et al. 2012).

Benchmarking reductions on the country level in relation to global climate targets: I refer to section 4.4.2 for a detailed discussion.

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[12] Note that our case-study on transportation yields slightly lower total emissions from shorter vehicle lifetime (paper I). This is because we only consider direct emissions.

Targeting emissions levels in 2050 vs. accumulated emissions: There are different trajectories of how to reach a certain emissions level in 2050 and some of them involve higher *accumulated* emissions than others. One reason is that in order to achieve substantial reductions in 2050, large upstream impacts in the years before may be necessary, e.g., in the scenario B-Transform-Demolition. Such strategies may have a lower net contribution to climate change mitigation than the 2050 emissions level suggests, and I therefore recommend calculating the accumulated emissions reduction for each strategy to perform an additional check. There is an increasing interest in accumulated emissions (Anderson et al. 2008; WBGU 2009; Meinshausen et al. 2009) in the literature. The models I used calculate both sectoral emissions over time and accumulated emissions, and the latter are reported in the supplementary material of paper I as well as in papers II and V.

Another potential problem of focusing on a single target year is the build-up of a maintenance or replacement backlog in the in-use stocks. In order to stabilize the Earth's surface temperature in the long run, emission must remain stable on a low level after the benchmark year 2050 (IPCC 2007b). This means that the quality of the in-use stocks should be kept at a certain level so that large needs for replacement and associated emissions in the years after 2050 can be avoided. Modeling the dynamics and monitoring the quality of in-use stocks may help to identify the creation of such a maintenance backlog at an early stage.

Economic dimension: The models I used are purely physical. An economic layer was not required, because I only account for the total service level in a certain society, and not for how it is distributed within society. The scenarios depict the aggregate development in a certain sector and country in the long run. But in order to achieve significant emissions reductions over the next decades, the trajectory to a low-carbon regime must diverge from the business as usual path at some point before 2020 (IEA 2012). To achieve that divide, a set of new products, services, incentives, and short-term regulations must be implemented. Adding an economic dimension to the models could facilitate the development of an interface to general equilibrium or other market models. This combination could be applied to derive or at least to test short-term emission abatement strategies that affect only parts of a sector or different market segments.

Hybrid solutions and the interface to social sciences (II): At present, much effort is being put into refining emission abatement models by adding more detail on the technological side. Examples include more detailed production process routes, different building types and cohorts, or specific new energy technologies. While this makes sense from a scientific and engineering point of view it may not always serve the purpose of identifying viable options for future development. In all three case studies I saw that hybrid solutions, which are mitigation strategies with direct impact on the end-user and its lifestyle, had a substantial, and in the case of steel, the largest effect on the sectoral carbon footprint. For the housing sector the energy demand from hot water generation and appliances may account for about two thirds of the sectoral energy demand in 2050, and reducing this demand may require people to change their consumption habits.

The mechanisms that determine the demand for services such as accessibility, shelter, or representation in different societies need to be better understood. This could be achieved by enlarging the system boundaries beyond the techno-sphere and opening up for interdisciplinary concepts. A model framework that includes concepts from social sciences that shows how the users can change their behavior may be more useful than a model that adds more refinement on the technical side. Agent-based modeling may be such an option; it has recently been applied to material flow analysis of metals (Bollinger et al. 2012). Another option is to investigate how the effects of choice architecture (Thaler and Sunstein 2008) could be modeled on the sectoral scale.

4.4 Connecting my findings to some underlying challenges related to sustainable development

There are several underlying and recurrent problem fields related to sustainable development. Below, I describe the challenges in more detail and explain how my findings relate to them (question v).

1) The first one is related to the main strategies to mitigate climate change: new energy technologies and demand reduction by lifestyle changes. Both are based on different views on the potential and risks of technology and the likelihood of changes in currently prevailing business models and social norms.

2) The second one relates to the difference between industrialized and non-industrialized countries regarding economic development and level of in-use stocks and their different preconditions for emission abatement.

3) The third issue concerns the duality between global targets and local solutions, and how to reconcile global constraints on carbon emissions with development and prosperity on the local scale.

4.4.1 Demand reduction vs. new energy technologies

I found that the currently deployable portfolio of energy efficiency is not sufficient to reach the range of the 2°C benchmarks. Thus, effective climate change mitigation needs to go far beyond the typical spectrum of energy efficiency, and there are two main directions of development to achieve further emissions reductions.

1) **New energy technologies** can lead to a decarbonization of the energy supply by shifting from coal and oil-based energy to natural gas, renewable energies, or nuclear power, and by implementing carbon capture and storage. The current state of energy decarbonization and the apparent difficulties with its implementation on the large scale were discussed in section 1.3.2.
2) **Demand reduction** lowers energy and material consumption by decoupling service from throughput. Its potential contribution to emissions reductions and the challenges and barriers related to its implementation are explored in the thesis at hand.

The knowledge gained in the course of this work allows us to make some comments about these directions and the specific challenges associated with them:

(a) By studying hybrid solutions, moderate lifestyle changes, and material efficiency I showed that the solution space for global warming can be extended. The mitigation potential of these measures is so large that the 2°C benchmark could be reached in two out of three cases studies. A broader portfolio of mitigation options increases the flexibility and the likelihood of eventual success in fighting global warming. The set of decoupling strategies examined here may represent an alternative to the potentially most risky or most expensive supply-side measures such as nuclear power or carbon capture and storage.

(b) Impact assessment modeling on the sectoral scale as shown here enables us to scale up different mitigation strategies from the product level to the society level. These models can estimate the overall emissions reductions of different strategies, which may give valuable insight to policy makers.

(c) The strategies of both directions have significant trade-offs, risks, barriers, and potential drawbacks. Whereas for new energy technologies the drawbacks seem to lie more on the environmental side and in the long-term, demand reduction requires short-term changes in economic paradigms and the way how societies perceive material and energy consumption.

The impacts of new energy technologies on resources, the environment, and society may be many: potential scarcity of specialty materials; decreasing ore grades and subsequently increasing energy demand for primary material production; land use change and food crises due to biofuels production; decreasing overall efficiency; increasing energy prices. Moreover, many new energy and geoengineering technologies bear the risk of accidents or leakage. A sole focus on technology as remedy to global warming may therefore bear consequences that are in conflict with other environmental aspects of sustainable development or that are not acceptable to society. For example, power stations equipped with carbon capture and storage emit less carbon to the atmosphere per kWh delivered but lead to severe increases in eco-toxicity (Singh et al. 2011), and may bear other, more severe risks such as leakage or ground water pollution (Wilson et al. 2007). Demand reduction through more efficient use, light-weighting, or lifetime extension automatically leads to lower environmental impacts in all categories.

However, large economic and social challenges are likely to be related to the lifestyle changes I discuss. Some of the strategies discussed require businesses to extend the responsibility for their products beyond the use phase and call for more communication and interaction between previously separated businesses to improve overall material efficiency in the cycle. User behavior should be integrated in the process of designing specific decoupling strategies. Decoupling requires a new perspective on the social metabolism that focuses on preserving stocks rather than increasing throughput, as originally envisioned by Boulding (1966).

4.4.2 Industrialized countries and the developing world

The second paradigm concerns the difference between industrialized and industrializing countries and their difference in income and present levels of in-use stocks, which both result in different challenges and opportunities for emission abatement.

The decoupling of environmental impacts from economic development in some OECD countries as demonstrated for example by Jackson (2009) can partly be understood from a stock perspective. *Building up* infrastructure networks, residential buildings, industry assets, and later consumer products in an industrialized society requires large amounts of materials, which have to be sourced from primary resources. Once major parts of the built environment are in place and stocks of different materials in use become mature, demand for primary production drops and recycling via secondary production can take over to *maintain* the in-use stock. The phenomenon of saturating steel stocks coincided with the *steel crisis* in many western countries ((Tarr 1988; Müller et al. 2011), Paper III) and is an important example for decoupling that occurred after a sufficient stock level was reached. Countries with developing economies are not endowed with mature material stocks and therefore they have a double disadvantage regarding climate change mitigation: a) They first need to build up material stocks and b) they cannot access urban mines for secondary production to lower emissions from material production.

Paper V shows a possibility for how this dilemma could be resolved on a global scale. By implementing the different material efficiency strategies the stock levels required for high human development can be lowered. This leads to excess scrap supply in the developed world, which can be fed into the growing stocks in developed countries. This way, the amount of primary steel needed can be reduced significantly, which would substantially reduce the carbon footprint of the steel sector.

Developing countries have a major advantage. Since a large part of the built environment is not yet in place, it can be designed and planned to facilitate a lower carbon footprint of its future inhabitants. Leapfrogging, that means to skip certain transition stages of infrastructure development (Dalkmann 2006), is another strategy to develop the built environment in a targeted way. An example is the deployment of passive house technologies, which is easier to achieve for new construction than for existing buildings.

Since 2006, more than 50% of the world's population lives in cities (United Nations 2011). Changing urban density and applying different land-use planning strategies may reduce commuting distances, make public transport more attractive, and lead to a lower car ownership rate. The correlation between city density and car ownership is well documented (Broca 2012; Kenworthy and Laube 1999). Offering attractive urban structures may make it easier for people to change their demand for transportation.

When establishing the benchmarks, I assumed a uniform per capita allocation of emissions all over the globe. One can expect that by 2050, some parts of the developing world will not have reached the transition stage that e.g., China is in now. The surplus emissions quotas of these countries could be re-allocated to those parts of the world that emit more than the average reduction target in a given year. This re-allocation could be compensated for in monetary terms. Richer countries could pay off the poorer part of the world that does not seize 'their' emissions quota to allow these countries to speed up economic development.

4.4.3 Global targets and local actions

To successfully curb global warming, the myriad of consumer decisions all over the world that are made every day must be in line with the long-term emissions reduction targets. However, the sphere of action of individuals and businesses is very small compared to the global scale. Current microeconomic theory considers both as price takers that aim at maximizing their individual utility with a given set of market prices.

Successful mitigation of global warming requires that peoples' values and preferences (the utility side) or the market prices (regulatory side) change in a way to allow for significant reductions of mankind's carbon footprint.

The models and scenarios I developed are purely physical and thus they do not allow us to address utility and price issues. However, they allow us to estimate which stocks levels can be built up and maintained in a carbon-constrained world. They give an idea of the service that can be provided to people depending on the mitigation strategies implemented. This information can be used to establish specific targets for development in different economic and end-use sectors, and I identified several ways of how the model framework presented here may help to bridge the gap between individual products on the micro scale and global environmental constraints:

Impact assessment on the large scale: The impact of a very large number of individual products on the material cycles and the energy supply cannot be fully understood from a single product perspective. Not the individual products, but the interplay of the multitude of different products in different end-use sectors drives changes in industry and material and energy supply, and determines resource depletion and the potential for recycling. A model that comprises the entire metabolism within a certain sector may therefore complement life cycle assessments of single products. Both modeling approaches could strengthen each other by using common process inventories and feeding back their specific insights on e.g., material recycling into each other.

Sector-specific targets: A breakdown of the global emissions reduction targets into different countries assigns a specific responsibility to individual governments. A parallel breakdown into different sectors assigns responsibility to individual industries and consumers.

Over-achieving the assigned reduction target in some sectors may give room for higher emissions in other sectors. The IPCC AR4 finds different emission abatement potentials for the different sectors (IPCC 2007b). However, Allwood et al. (2010) demonstrate that if only one sector misses the average reduction benchmark, the additional reductions required in the other sectors expressed in percent would have to be substantial (Table 1 in Allwood et al. (2010)). I found that in none of the sectors studied, not even the building sector, the 2°C benchmark could be met without some kind of lifestyle changes. However, a changing carbon intensity of the energy supply over time may alter the picture.

As long as emissions in all sectors continue rising, the question whether the sectors should have different emissions reduction targets may not be the most urgent one to answer. To us it seems more important to develop and implement a set of short- and mid-term strategies that can change the trend in each individual sector. The models developed here may help to assess these strategies in relation to the long-term climate targets and the way they impact the stocks and the service level in the different sectors.

Links between sectors: Including the industry background into the definition of a sector inevitably leads to overlapping sectoral boundaries, because the material- and energy-supplying industries are connected to all other sectors. Some decoupling strategies can contribute to emissions reductions in several sectors at the same time. Light-weighting of cars, for example, may reduce the demand for primary steel and may lead to lower specific fuel consumption in the use phase of the cars (Kim et al. 2010). Higher upstream emissions may be acceptable if they are compensated for by savings in the use phase, as in the example of using aluminum to produce lighter cars with lower specific fuel consumption (Kim et al. 2010).

Overlapping sectoral definitions, such as ‘metal production’ and ‘transportation’, allow for viewing the global warming challenge from different angles. From a product or end-use perspective, the inclusion of upstream impacts that can be associated with the end-use sector studied allows for determining trade-offs between increases in the upstream impacts and savings in the use phase. This approach is widely used in life cycle assessment (Kim et al. 2010; Hawkins et al. 2012). In addition to the product perspective, a material perspective across different end-use sectors allows for estimating the total demand for the different materials and the opportunities for recycling over time. The total final material demand and the recycling potential can be used to estimate the demand for mineral resources and to identify possible geo-political dependencies related to the location of these resources.

Overlapping sectoral boundaries may decrease the risk that some industries or end-use sectors fall ‘under the radar’. Steel, for example, is first accounted for in cars and buildings and then for the second time in the steel cycle. The material costs for steel typically account for not more than 4-6% of the costs of cars or buildings (Figs. 6.3-6.5 in Allwood et al. (2012)), and hence, the incentive for reducing this small cost fraction by light-weight design or use of secondary material may be small. Still, when taking all these small fractions from all products together, one finds an industry which accounts for 9% of all energy- and process-related carbon emissions, which has its own dynamics, and for which significant carbon emissions reductions represent a major challenge.

4.5 Conclusion

The main contributions to the existing knowledge are listed below and some general concluding statements follow.

- A new type of dynamic stock model that allows for splitting individual cohorts into different types, materials, or drive technologies, was developed and implemented in three case studies. The model links the service provided by in-use stocks to products, materials, direct energy demand, and carbon emissions.
- An interface between dynamic stock models, material and energy flow analysis, and life cycle assessment was developed to assess indirect emissions and impacts of in-use stocks.
- A detailed dynamic model of the global steel cycle was developed together with Rachel Waugh from the University of Cambridge. It covers production, use, and recycling of steel for the period 1700-2100. It includes iron flows and carbon emissions and allows us to assess the emissions mitigation potential of novel strategies such as new iron making technologies or material efficiency.
- The three case studies on passenger cars in China, residential buildings in Norway, and the global steel cycle provide independent evidence that the IPCC's 2°C target is unlikely to be reached by pursuing energy efficiency improvements alone.
- The work presented here is documented in five journal papers, four of them being first-author papers, and their respective supplementary material. All five papers have been published in international journals.

In-use stocks link physical services, such as shelter or mobility, to economic activity. With the parameter values I chose for the scenario analysis, decoupling material and energy throughput from stocks and service could yield emissions savings that are sufficient to limit global warming to 2°C in the case studies on buildings and steel, and 3°C in the case of personal transportation. At the same time, the entire world could reach a service level comparable to the one presently seen in industrialized countries. Material and energy efficiency, hybrid solutions, and lifestyle changes extend the toolbox of climate change mitigation strategies, which may increase the probability of eventual success in fighting global warming. These strategies may represent an alternative to the potentially most risky or most expensive supply-side measures such as nuclear power or carbon capture and storage.

Implementing the decoupling strategies on the large scale, however, may require a paradigm shift similar to the transition from the Cowboy Economy to the Spaceman Economy that Kenneth E. Boulding envisioned in 1966. It would possibly require a shift in our *consumer culture*, which brings us back to the initial quotation taken from the book “Sustainability by Design” by John R. Ehrenfeld (2008): “*Sustainability is a cultural phenomenon.*” Ehrenfeld argues that the only way to achieve a sustainable regime is to create cultural change “deliberately by designed interventions”. Human culture, although not part of the system of social metabolism, appeared in the discussion several times. I found that many decoupling strategies directly affect the behavior and the expectations of the end-user, thus, their consumer culture. Maybe more important, it is the human culture that has to create the condition for sustainable development to happen.

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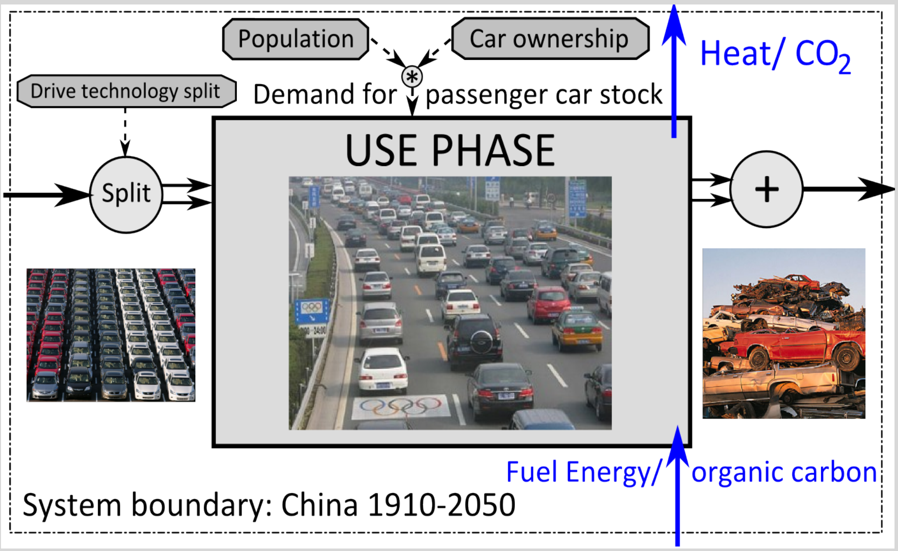
Paper I

“Reconciling Sectoral Abatement Strategies with Global Climate Targets: The Case of the Chinese Passenger Vehicle Fleet”

Stefan Pauliuk, Ni Made Arya Dhaniati, Daniel B. Müller, Environmental Science and Technology 2012, 46(1) pp. 140-147.



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Paper II

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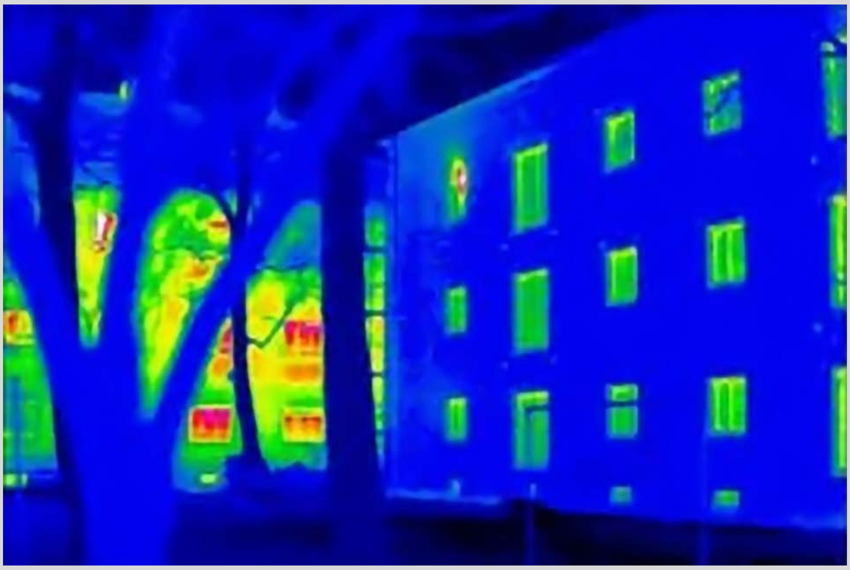
Stefan Pauliuk, Karin Sjöstrand, Daniel B. Müller, Journal of Industrial Ecology 2013.



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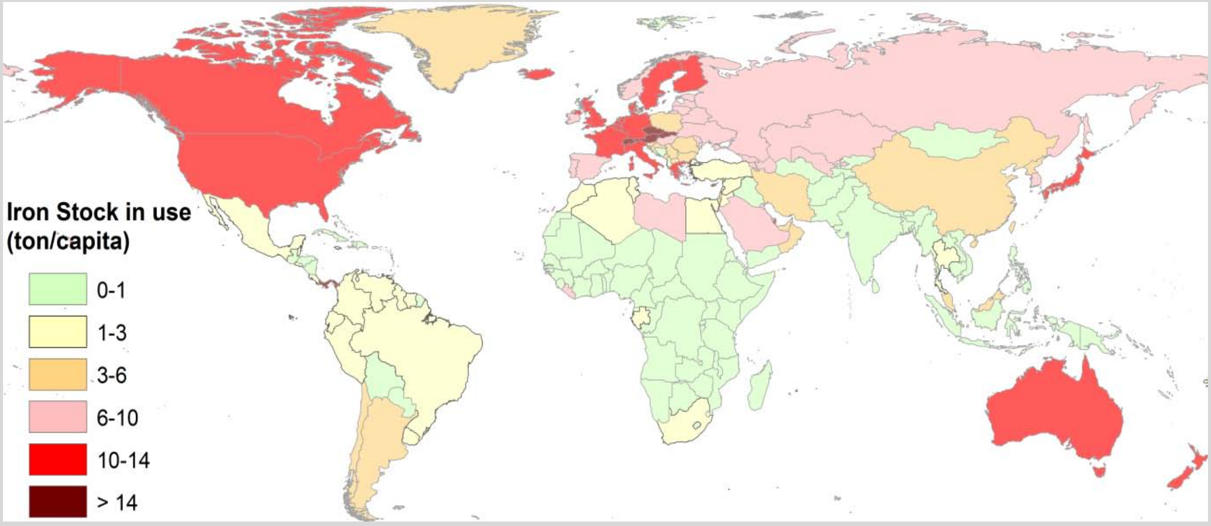
Paper III

"Steel all over the world: Estimating in-use stocks of iron for 200 countries"

Stefan Pauliuk, Tao Wang, Daniel B. Müller, Resources Conservation and Recycling 2013, 71(February 2013) pp. 22-30.



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Paper IV

"The Steel Scrap Age"

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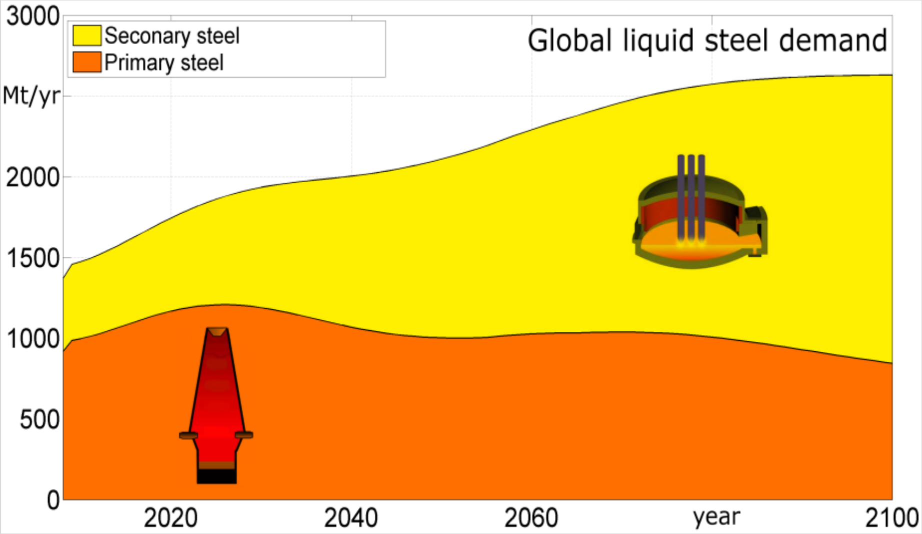

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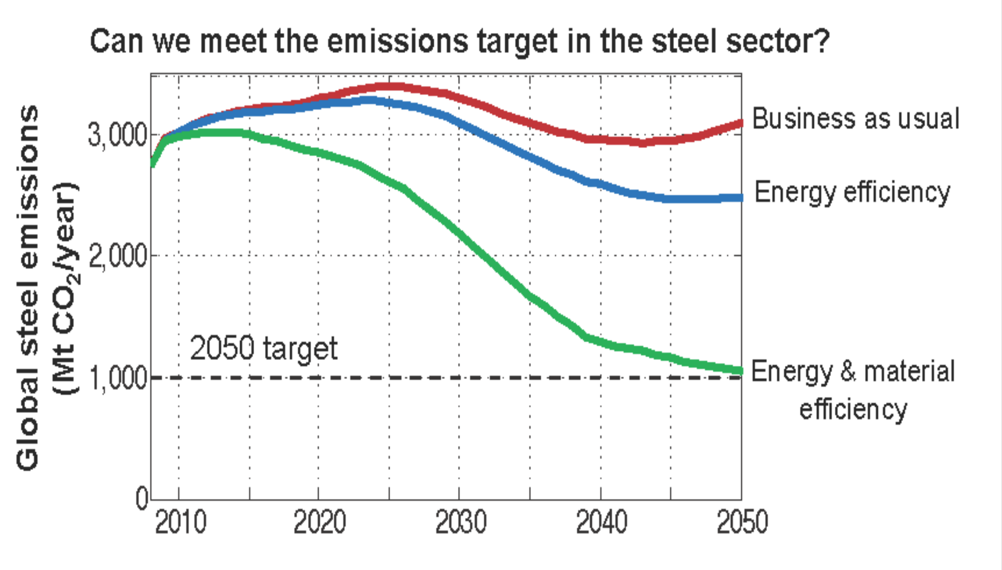
Paper V

"The Roles of Energy and Material Efficiency in Meeting Steel Industry CO_2 Targets"

Rachel L. Milford, Stefan Pauliuk, Julian M. Allwood, Daniel B. Müller, Environmental Science and Technology 2013.



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