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Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions

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Abstract: In recent decades economic growth and increased human wellbeing around the globe have come at the cost of fast growing natural resource use (including materials and energy) and carbon emissions, leading to converging pressures of declining resource security, rising and increasingly volatile natural resource prices, and climate change. We ask whether well-designed policies can reduce global material and energy use, and carbon emissions, with only minimal impacts on improvements in living standards. We use a novel approach of combined economic and environmental modelling to assess the potential for decoupling for 13 world regions and globally. We apply a production (territorial) and consumption approach to discuss regional differences in natural resource use and carbon emissions across three stylized policy outlooks: a reference case with no significant changes to environment and climate policies; a 'high efficiency' outlook involving a global carbon price rising from \$50 to \$236 (constant price) per tonne of CO_2 between 2010 and 2050 and improvements in resource efficiency (rising from 1.5% historically to between 3.5%-4.5% in the scenarios); and a 'medium efficiency' outlook midway between the 'no change' and 'high' outlooks. We find that global energy use will continue to grow rapidly under all three scenarios from 17 billion tonnes of oil equivalent (toe) in 2010 to between 30 and 36 billion toe. Carbon emissions would be considerably lower with a global carbon price, less than half the level of the reference case (29 to 37 billion tonnes of CO_2 instead of 74 billion tonnes) and also material use would grow much more slowly under a carbon price and significant investment to increase resource efficiency (95 instead of 180 billion tonnes of materials). We find that OECD economies have significant potential to reduce their material throughput and carbon emissions with little impact on economic growth, and that developing economies such as China could expand their economies at much lower environmental cost. Globally, the effects of very strong abatement and resource efficiency policies on economic growth and employment until 2050 are negligible. Our study suggests that decarbonization and

dematerialization are possible with well-designed policy settings and would not contradict efforts to raise human wellbeing and standards of living. The research demonstrates the usefulness of scenarios for unpacking environmental and economic outcomes of policy alternatives. The findings have important implications for future economic opportunities in a highly resource efficient and low carbon global economy to set human development and achieving the sustainable development goals on a more resilient path.

Introduction: Economic and human development relies on the throughput of materials and energy to support production and consumption processes, which produce waste and emissions as by-products. The notions of social metabolism (FischerKowalski and Haberl 1997) and industrial metabolism (Ayres and Simonis 1994) were introduced to refer to the fundamental character of the interactions between society, nature and natural resources which underpin human development, and their importance for the science of sustainability. Improvements in living standards in many developing countries over the past couple of decades have ratcheted up the amount of natural resources used globally and contributed to fast rising emissions. Global material use grew from 24.8 billion tonnes in 1970 to 79.4 billion tonnes in 2010. The global economy now uses three times as many resources – biomass, fossil fuels, metal ores and construction minerals – than it did four decades ago (Schandl and West 2010, Steinberger, Krausmann and Eisenmenger 2010). Similarly, world energy use roughly tripled from 224 eJ (1971) to 597 eJ (2010), while carbon dioxide emissions grew from 20.1 billion tonnes (1971) to 32.7 billion tonnes (2010) (IEA 2014, IEA 2013).

It is now widely accepted by academics, policy-makers, industry leaders and civil society that economic growth and human wellbeing need to be decoupled from escalating resource use and negative environmental impacts in order to secure long-term sustainability for humankind. The International Resource Panel of the United Nations Environment Programme (UNEP-IRP) laid out the challenges, opportunities and possible policies for such 'decoupling' in two reports (UNEP 2011a, UNEP 2014). The initial aim is to achieve economic growth while slowing the rate of increase of natural resource use and emissions (relative decoupling) and finally for environmental impacts to decrease in absolute terms (absolute decoupling). While for developing countries relative decoupling will be the main objective for OECD countries absolute decoupling and perhaps refocussing from economic growth to quality of growth and de-growth (Martinez-Alier et al. 2010) will need be achieved. Targets for decoupling are also being discussed as part of the ongoing deliberations for the new Sustainable Development Goals (SDGs) (Bizikova et al. 2014).

Natural resources are unequally distributed among nations. They depend on geomorphology, the location of reserves and past resource exploitation. International trade of primary materials supplies centres of demand with natural resources that are essential for production and consumption in those places. The increasingly global character of supply chains has resulted in trade in primary resources being the fastest growing component of global resource use (Schaffartzik et al. 2014, Dittrich and Bringezu 2010, Dittrich, Bringezu and Schutz 2012a), and as a consequence the separation of resource extraction and demand has also grown rapidly. Reflecting the separation of consumption and production and the burden shifting that goes hand in hand with such a process, a body of literature has emerged recently and has established the differences between territorial resource use and emissions and material, energy and carbon footprints of consumption (Hoekstra and Wiedmann 2014, Moran et al. 2013, Steen-Olsen et al. 2012, Hertwich and Peters 2009, Tukker et al. 2014). One important finding was that wealthy OECD countries have outsourced a large part of their material intensive production to developing countries with the economic benefit occurring in OECD countries and the environmental and social burden occurring in resource supplying countries (Muradian, Walter and Martinez-Alier 2012, Wiedmann et al. 2013).

While research on historical material and energy use has grown over the past couple of decades we know comparatively little about the future trajectories of material and energy use and carbon emissions. So far, a small number of studies have looked at possible trajectories of material use in Europe (Giljum et al. 2008) and globally (Dittrich et al. 2012b). The analysis for this paper establishes, for the first time, scenarios of future material, and energy and carbon footprints for the four decades to 2050, taking into account economic drivers and biophysical pressures.

The scenario analysis is based on a novel modelling architecture employing an integrated climate and economy model (GIAM) (Gunasekera et al. 2008, Harman et al. 2008), a global, multi-regional technology-based physical stocks and flows model (MEFISTO) (Schandl and Turner 2009, Baynes et al. 2014), and a global multi-regional input-output model (Eora) (Lenzen et al. 2013, Lenzen et al. 2012). This modelling architecture allows us to evaluate scenarios of economic growth and employment from a global and holistic perspective, while accounting for the impact of a global carbon price and for improvements in the efficiency of natural resource use. The modelling framework is based on the stock turnover rates of important infrastructure and produces environmental satellite accounts for materials, energy and carbon emissions for future years that incorporate both physical and economic information. Model outputs provide estimates for resource efficiency and emissions intensity of the global economy and 13 major countries or regions (see data and methods). The analysis focuses on man-made emissions only, and does not account for potential land sector-based carbon emissions or sequestration.

We are interested to see whether decoupling of economic growth and environmental pressure is a viable pathway for the global economy and its constituent regions, and to uncover the circumstances under which this may occur. We use three scenarios for a global carbon price as a proxy for effective global environmental policy that encourages resource efficiency and low carbon development. What amount of natural resources would be used globally by 2050 in the absence of policy action? What is achievable through a medium carbon price of starting at $25 for a tonne of carbon? What would a high carbon price starting at $50 per tonne of carbon and rising to $236.50 (constant prices) per tonne of carbon in 2050 mean in terms of decoupling human wellbeing from environmental pressure?

Data and Methods

Data

Historical data (1990–2010) for global and regional material use were sourced from the CSIRO Global Material Flow Database (West and Schandl 2013) which accounts for all relevant material use for each country, applying internationally agreed compilation guidelines (Eurostat 2012). Data for energy use were sourced from the International Energy Agency database (IEA 2014, IEA 2013) and data on carbon dioxide emissions came from the Emissions Database for Global Atmospheric Research (EDGAR). Economic data was sourced from the United Nations Statistical Division.

Scenario settings

Three scenarios were constructed to discuss global and regional differences in environmental pressures (material and energy use, carbon emissions) across three stylized policy outlooks: a reference case with no significant changes to environment and climate policies (termed ‘BS’); a ‘high efficiency’ outlook involving a global carbon price rising from $50 per tonne of CO_2 and improvements in resource efficiency (‘T50’), and a ‘medium efficiency’ outlook, involving a global carbon price rising from $25, midway between the ‘no change’ and ‘high’ outlooks (‘T25’). The carbon price increase by 4% per year reaching $236.50 in constant 2007 price by 2050. This assumption is based on Hotelling who established that the real price for non-renewable natural resources should increase at the real interest rate in order to maximise the present value of the resources over the extraction period (Hotelling 1931) also known as the 4% rule. (Edmonds et al. 2008) discuss the application of this rule to policy that aims to constrain global GHG concentration and mitigate global warming in the long term. Our approach mimics the expected behaviour of an efficient international emissions market that allows for banking and borrowing of emissions rights, exploiting the benefits of the so called 'where, what and when flexibility'(Gurney, Ahammad and Ford 2009). We follow (Garnaut 2008) and use a rate of increase of 4% per year (a 2% riskless real interest rate plus a 2% risk premium) to define the Hotelling price path.

The resource efficiency path is driven by the carbon price and has been separately implemented assuming that best available technologies are utilized in key sectors including heavy industry (iron and steel and cement production), manufacturing, construction and performance of buildings, transport and mobility, and agriculture and food. Potential efficiency gains are taken from the literature (Von Weizsaecker et al. 2009) but no technologies were considered that do not already exist today (i.e. we made very conservative assumptions regarding the development of new technologies). The very large efficiency potential of up to 80% for some activities is offset by population growth and growing final consumption. Cost savings that occur due to material and energy efficiency improvements are largely offset by the increasing carbon price and growing investments into resource efficiency which reduce the rebound effect (Binswanger 2001) in our model. (Giljum et al. 2008) and (UNEP 2011a) argue that additional measures on the company (product) and macro-economy level would need to be taken to avoid unintended consumption growth enabled by efficiency gains. Finally, we used a medium population outlook of the United Nations (UN 2013) for all three scenarios.

Models

The quantitative evaluation of scenarios was accomplished by using three separate global models in sequential order, using outputs from one model as inputs to another in an iterative fashion. The economic scenarios of gross world product, employment, consumption and investment were developed and analysed using CSIRO's (Commonwealth Scientific and Industrial Research Organisation) current version of the Global Integrated Assessment Model (GIAM) (Newth et al. 2011, Sealey et al. 2012). GIAM is an integrated assessment model originally developed jointly between CSIRO and the Australian Bureau of Agricultural and Resource Economics (Garnaut 2008, Harman et al. 2008, Gunasekera et al. 2008).

GIAM is a coupled climate-economic model. The economic component of GIAM is a long-run version of the Global Trade and Environment Model (GTEM), a dynamic recursive, multi-regional and multi-sectoral general equilibrium model of the global economy (Pant 2007, Clarke et al. 2009, Gurney et al. 2009). The economic module allows projections for the major human-induced factors influencing climatic conditions (such as greenhouse gas emissions) to be developed after accounting for regional and global production and consumption decisions and international trade. The economic module of GIAM used in this paper currently allows for analysis across 13 regions, 21 industries, four primary factors and six greenhouse gas emissions (see Table 1). Base year data are taken from the GTAP 8 database (Badri, Aguiar and McDougall 2012).

Table 1 Economic module components of GIAM

Regions	Industries	Primary factors	Greenhouse gases
United States	Coal	Capital	Carbon dioxide
EU-25	Oil	Land	Methane

China	Gas	Labour	Nitrous oxide
Former Soviet Union	Fossil fuel products	Natural resources (energy)	Hydrofluorcarbons
Japan	Electricity		Perfluorcarbons
India	Iron and Steel		Sulphur hexafluoride
Canada	Non-ferrous metals		
Australia	Chemical, rubber, plastics		
Indonesia	Other mining		
South Africa	Non-metallic minerals		
Other Asia	Manufacturing		
OPEC	Water transport		
Rest of the World	Air transport		
	Other transport		
	Wheat		
	Rice		
	Coarse grains		
	Other crops		
	Forestry, fishing		
	Processed food		
	Services		

The climate module of GIAM is a non-linear model for global CO_2, other greenhouse gases and global temperature, commonly known as the Simple Carbon Climate Model (SCCM) (Raupach et al. 2011). This is a globally averaged or 'box' model of the carbon–climate system, using well established formulations. The model includes non-linearity in the response of terrestrial assimilation to CO_2, buffering of CO_2 in the ocean mixed layer, temperature responses of land–air and ocean–air CO_2 exchanges, and the response of radiative forcing to gas concentrations (Raupach et al. 2011).

In the GIAM analytical framework, the GTEM module projects greenhouse gas emissions based on economic activities. These emissions are then fed into the SCCM module. The SCCM module converts the emissions into CO_2 concentration levels and then into changes in temperature. In the current version of the GIAM model, changes in temperature are fed into a 'climate–economy response function'. This response function analyses the interactions between changes in regional temperature and total factor productivity (see Harman et al. 2008).

To explore the material implications of alternative emissions pathways, we develop alternative emission price paths. Each price path increases in real terms over time, rising at an average of 4.5% per annum over the period 2015 to 2050, made up of a 2% riskless real return on capital and risk premium that begins at 4% per year and declines to 2% as climate policy and carbon markets mature globally (see Garnaut 2008). One advantage of this approach is that it mimics the expected behaviour of an efficient international emissions market that allows for banking and borrowing of emission rights.

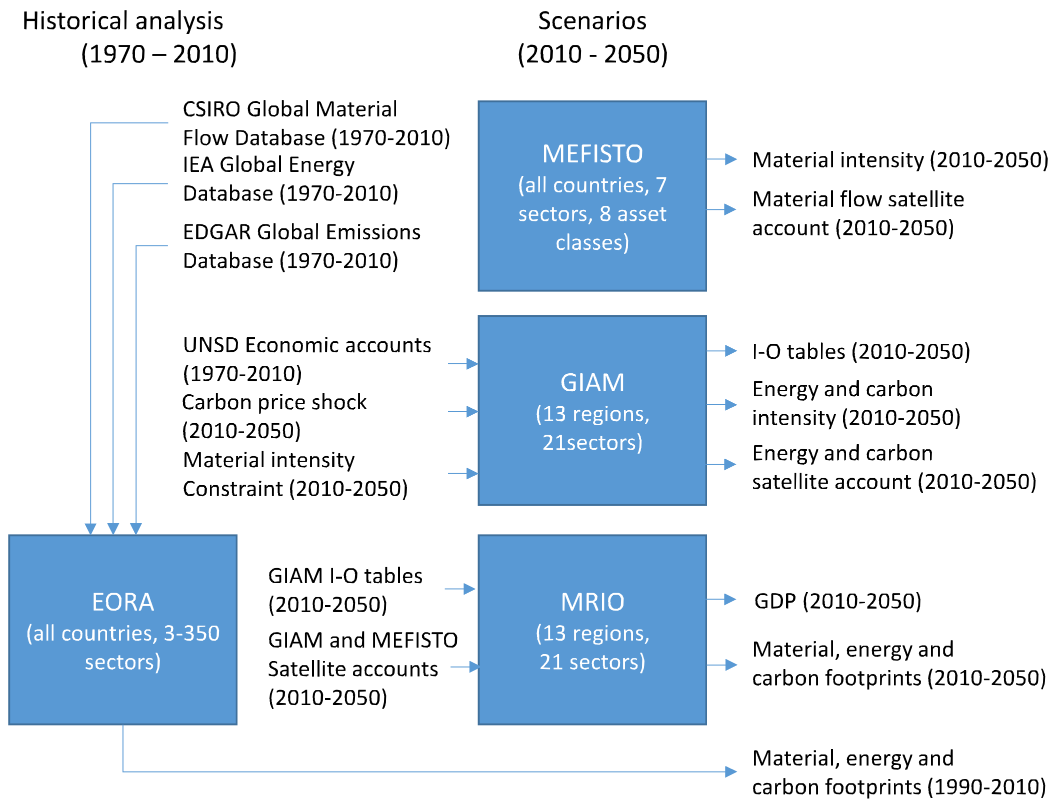
We produced GDP, employment and investment data for the 13 regions for three scenarios as well as related energy use and carbon emissions data for each scenario covering the four decades from 2010 to 2050.

On important limitation of our approach is that bio-fuels are not represented in the model, but only a minor amount (2% of total power generation) of biomass-based power generation. As a result, in all the scenarios, the model mostly captures the substitution from conventional fossil fuels to electricity that can be produced from carbon-free technologies. The pressure of land competition between bio-feedstock production and the rest of the economy is therefore negligible.

Regarding the modelling of renewable electricity we assumed the inputs of "fixed factors" which could be understood as "location of wind mill, sun shine, rivers, approval for construction site of nuclear" that are constraints to the renewable. They can be substituted by the use of capital (such as the installation of solar trackers, upgrades to water turbines, upgrading of generation technology), but with diminishing returns.

The second model is a technology-based physical stock and flows representation of the global economy and the 13 regions based on the MEFISTO model (Baynes et al. 2014). It was used to assess the speed and scale at which improvements in material efficiency could be achieved, and generated three material flow satellite datasets on for each scenario. MEFISTO provides data for material, energy and carbon intensity of stock for seven broad economic sectors and a number of asset categories such as buildings, transport infrastructure, electricity generation, water and sewerage, and communication. It models the speed at which innovation can penetrate through the physical asset base of an economy based on age cohorts of assets and depreciation time. In principle, asset formation or replacement can be linked with investment flows provided by GIAM. For this research, which has focused on relating GIAM to the MRIO framework, such a link between GIAM and MEFISTO has not been established. This means that the material efficiency measures have been derived purely following the logic of a physical economy and in the absence of economic considerations such as the level of investment and changes in price. Linking the two models and bringing economic dynamics into the picture will need to be a focus in follow-up research.

Figure 1.Model interactions between GIAM, MEFISTO and EORA for historical and scenario analysis



Finally, we calculated material, energy and carbon footprints by multiplying final demand for goods and services (including capital investment) for the 13 world regions (countries) with multipliers representing all upstream global material, energy and emission requirements associated with one unit

(US$) of product. The multipliers were established using environmentally extended input-output (I-O) analysis and applying Leontief's standard I-O calculus (Leontief 1970). For the period 1990 to 2010, the underlying model was the Eora database (Lenzen et al. 2013, Lenzen et al. 2012). Eora is a high resolution global multi-regional input-output database containing domestic and international monetary transactions among 15,909 industry sectors across 186 countries, supplemented with material, energy and emissions satellite data. For this study, Eora was aggregated to the regional and sectoral classification of GIAM: 13 global regions and 21 sectors within each region.

Footprints for 2011 to 2050 were calculated using time series of year by year input-output tables generated by GIAM. A separate time series was generated for each of the three scenarios. The input-output tables of all three time series were given using the same classification: 13 world regions and 21 sectors per region, which is also identical to the classification that Eora was aggregated to. Hence, all input-output tables used in this study were given in the same classification.

A satellite account for domestic material extraction for the 13 regions was established for different material intensity assumptions of the global economy and within regions. Satellite accounts for energy and carbon emissions were established using GIAM.

After the quantification of future annual time series data for carbon dioxide emissions, population, gross domestic product (GDP), material and energy use, we analysed trends in emissions globally and for key economies and unpacked their demographic, economic and technological drivers employing the Kaya identity (Waggoner and Ausubel 2002, Raupach et al. 2007) . The Kaya identity expresses emissions as a product of four driving factors (see equation 1):

(Eq. 1) $CF = P * GDP/P * EF/GDP * CF/EF$

where CF is the carbon footprint of consumption (CO_2 only), P is population, GDP/cap indicates the level of wealth (or national income), EF is the energy footprint of consumption, EF/GDP is the energy intensity of economic activity, and CF/EF refers to the carbon intensity of the energy footprint.

We also applied a second Kaya equation for carbon emissions and materials to reflect the fact that many materials such as fossil fuels, agricultural products, iron, steel and cement in a modern society's metabolism are carbon intensive (see equation 2). Because of the carbon intensity of material use, improvements in resource efficiency of key sectors and processes may lead to preferential outcomes with regard to carbon emissions beyond the energy and electricity generation system.

The Kaya identity for carbon emissions and materials is given by:

(Eq. 2) $CF = P * GDP/P * MF/GDP * CF/MF$

where CF is the carbon footprint of consumption, P is population, GDP/cap indicates the level of wealth (or national income), MF is the material footprint of consumption, MF/GDP is the material intensity of economic activity, and CF/MF refers to the carbon intensity of the material footprint.

Results for both relationships – carbon and energy as well as carbon and materials – are provided below for the global economy and for four major economies, namely the United States, Japan, China and the EU-25.

Results

Global results

Our research shows that while some relative decoupling can be achieved in some scenarios, none would lead to an absolute reduction in energy or materials footprint, while carbon footprint could be reduced in absolute terms.

Interestingly, strong carbon abatement policies with a global carbon price starting at $50 per tonne and rising to 236$ per tonne in 2050 and achieving very high improvements in material efficiency (a doubling of current yearly efficiency gains) of the global economy would have a negligible impact on the growth of global GDP. Global inflation adjusted GDP, according to our modelling, is expected to grow strongly over the next four decades from 58 trillion US$ (at 2007 prices) in 2010 to about 190 trillion US$ (at 2007 prices) in 2050 in all three scenarios. Strong abatement policies and high investment in resource efficiency technologies would see global wealth grow by US$3 trillion less than they would otherwise, equivalent to a loss of only1.6% of global output over 40 years. (Direct impacts of climate change on economic growth are smaller than the impacts of abatement policies before 2050). Our GDP trajectory sits in the middle of the range of estimates that is reviewed by (Rogelj, Meinshausen and Knutti 2012) and it is close to the underlying economic assumption of representative concentration pathway (RCP) 8.5.

Global energy use continues on a strong growth trajectory under all three scenarios and in alignment with economic growth. Figure 2 shows that even strong carbon abatement and large investment into resource efficiency would see global energy use growing from 14,253 million toe (416 eJ) in 2010 to 26,932 million toe (1,128 eJ) in 2050. This would mean an energy saving over the base case scenario of 4,392 million toe (184 eJ). However, energy use continues to be strongly coupled with economic activity in all three scenarios and the elasticity of energy use and GDP remains very high. Energy efficiency grows at a yearly rate of 1.5% under the most favourable scenario.

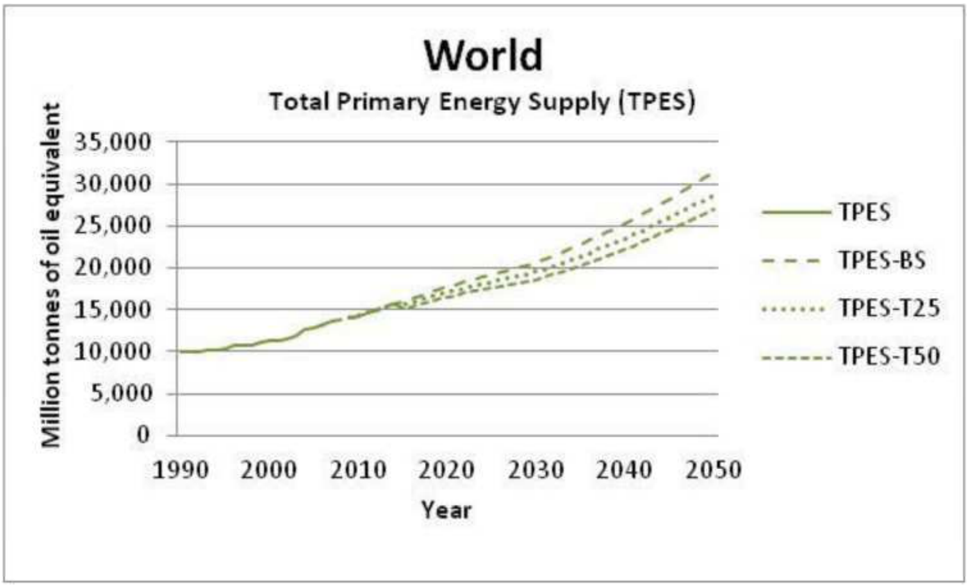


Figure 2 Global total primary energy supply (TPES, in Mtoe), 1990 to 2050; historical data and three scenario projections

Despite small differences in economic growth and strong growth in energy use in all three scenarios, our model suggests that a global price on carbon would drive large shifts in the energy sector to renewable and low carbon technologies. Figure 3 shows that global carbon emissions would more than double over the next four decades from around 32.7 billion tonnes in 2010 to 74.1 billion tonnes in 2050. Strong abatement policies would see global energy use stabilizing at around 36.7 billion tonnes by 2050, which is only slightly higher than the 2010 level and is consistent with the world having a good chance of limiting global warming to 2 degrees or less, relative to preindustrial levels. As discussed below, the modelling currently understates the potential for reducing CO_2 emissions from transport and industrial heat processes. Better representation of this potential would be expected to see much greater potential to decouple energy use from CO_2 emissions.

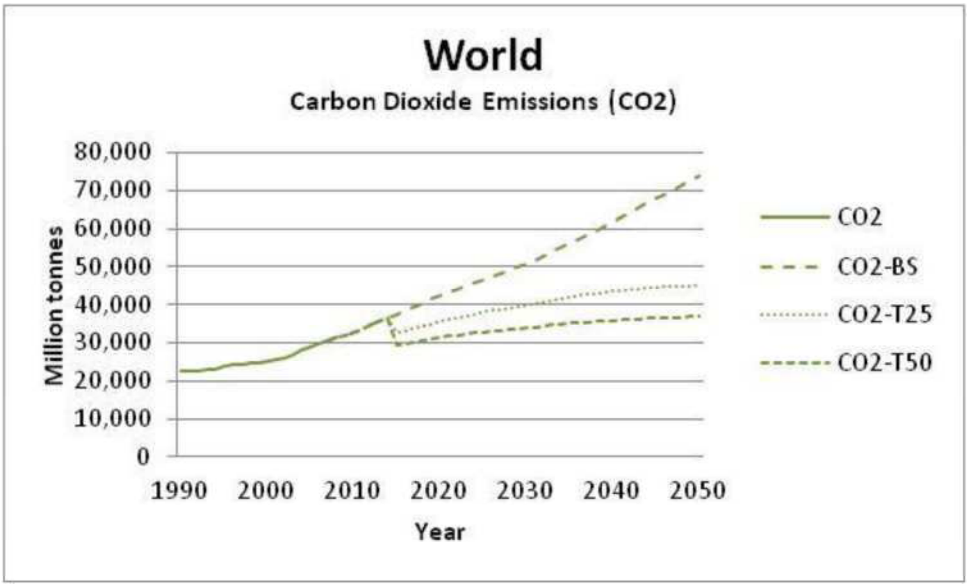


Figure 3 Global carbon emissions, 1990 to 2050, history and three scenarios, in million tonnes

The relatively sharp decline of carbon emissions in the year after the introduction of the carbon price shock is somewhat unrealistic and driven by changes in energy generation that in the real world would need a longer transition period. The imposition of a carbon price that is as high as $50, and the uptake of low-hanging-fruit technologies, as mimic by GTEM’s mechanism of endogenous technology growth in reducing carbon intensity in industries and household consumption causes this rapid decline. Our estimate of carbon mitigation is, however, consistent but slightly more conservative than the recent work of (McKibbin, Morris and Wilcoxen 2014) for the USA, which predicts a similar drop of US CO_2 emissions from baseline due to a carbon price that starts at $23 in 2013.

Global material extraction, shown in figure 4, would grow strongly in a business as usual world from 79.4 billion tonnes of extraction of biomass, fossil fuels, metal ores and minerals to 182.8 billion tonnes of extraction. A global carbon price in concert with technological change resulting in a doubling of material efficiency would allow stabilization of material extraction at 95.2 billion tonnes by 2050. Even the moderate scenario would see a reprieve in global material use, which would be at 129.8 billion tonnes by 2050 more than a third lower than in the business as usual scenario.

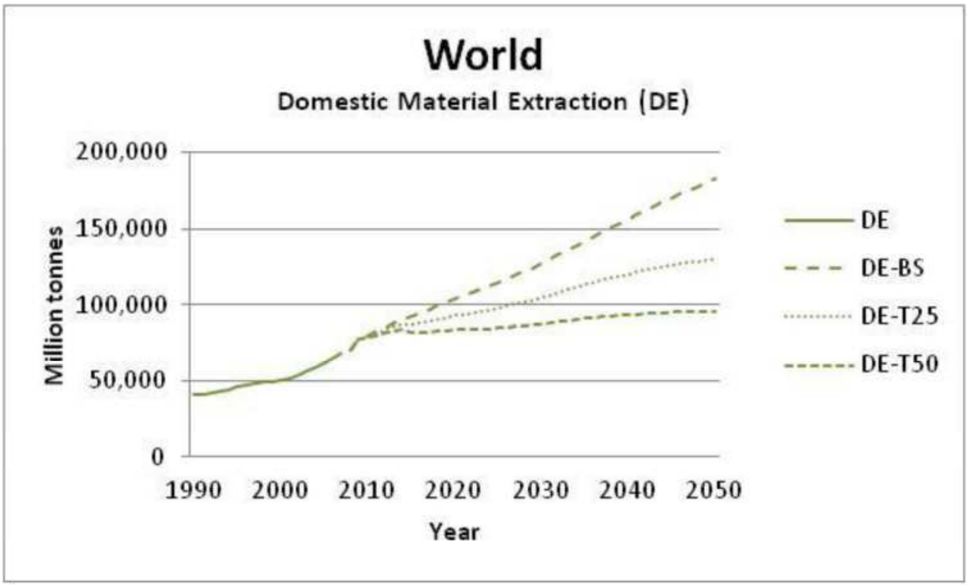


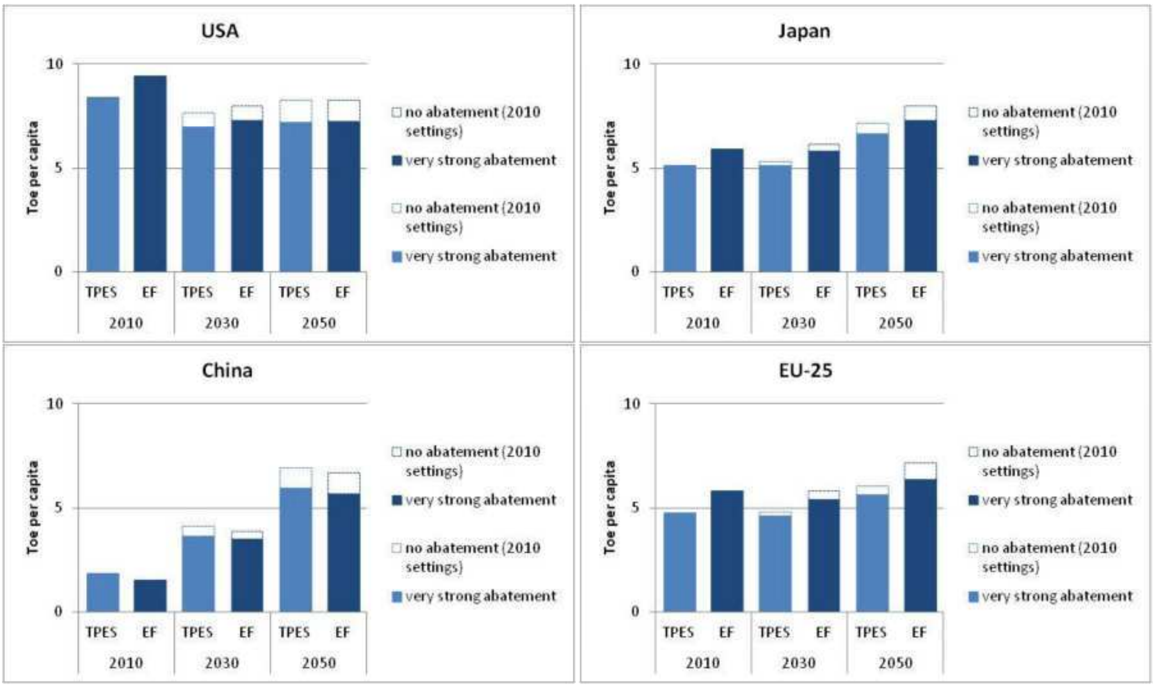
Figure 4 Global material extraction, 1990 to 2050, history and three scenarios, in million tonnes

Regional results

Our model allows a detailed analysis of 13 world regions covering important economies such as the United States, China, Japan, and the European Union. When we compare the world economy of 2010 with 2050 we see a shift of economic activity away from the United States, the European Union and Japan towards China. In 2010, China has a share of 8.4% of global output which will rise to 22.6% by 2050. The United States, by contrast, produced one quarter of total global output in 2010, which will fall to 14.6% in 2050. The European Union will experience a similar reduction in the share of global economic activity, down to 16.5% by 2050 from initially 28% in 2010. The United States, Europe and Japan would profit marginally from very strong abatement policies and a global carbon price in terms of their share of global GDP while the same effect, for instance, on the former Soviet Union would be slightly more negative.

At the regional level, beyond GDP, we distinguish direct (i.e. territorial/domestic) material and energy use and carbon emissions from material, energy and carbon footprints of consumption (depicted in two different shadings in Figures 5-7a-d).

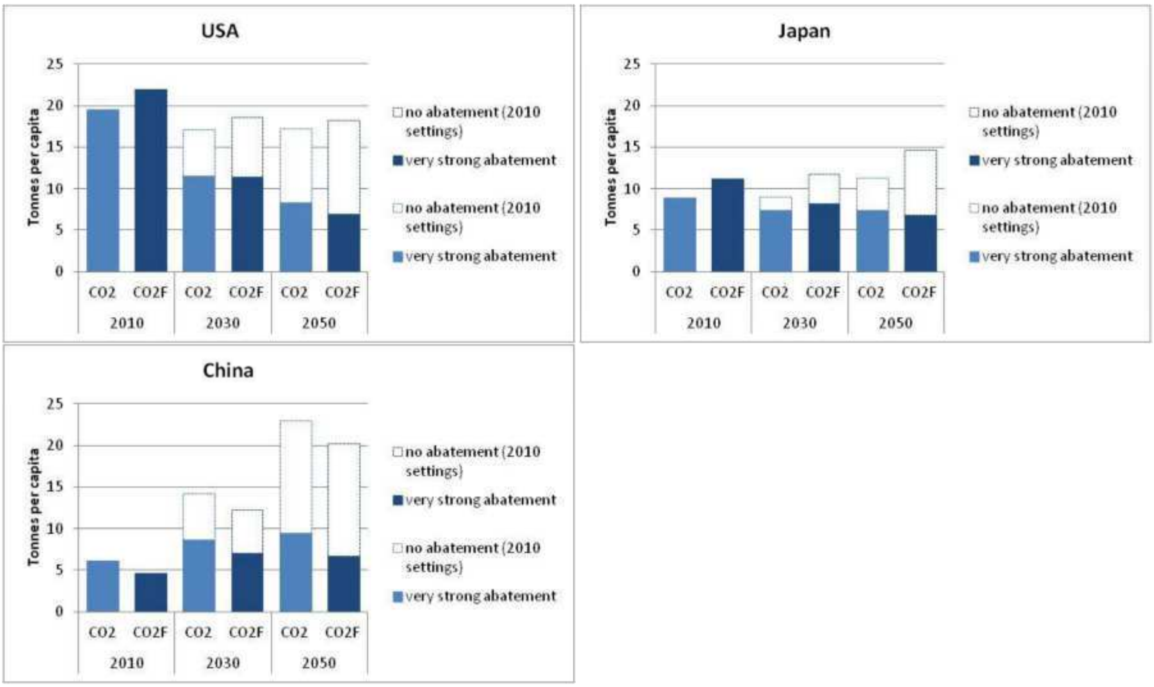
The base case scenario sees energy use decreasing in the United States, growing in Japan and growing strongly in China (Figures 5a-d). Strong abatement and resource efficiency policies would have the largest impact in China but would be negligible in Japan. By 2050, per capita energy use in China would be at 6.0 tonnes of oil equivalent, close to the Japanese levels at 6.6 tonnes of oil equivalent per capita but somewhat lower than the US at 7.2 tonnes of oil equivalent per capita. In Japan, the energy footprint would remain higher than territorial energy use with the US and China showing very similar levels of territorial energy use and footprint mainly because most of the economic interactions in the two largest economies occur internally and trade plays a relatively smaller role than it does in Japan.



Figures 5a to 5d Territorial energy use and energy footprint United States, Japan, China and EU-25 in 2010, 2030, 2050; two scenarios (BS and T50), toe/cap

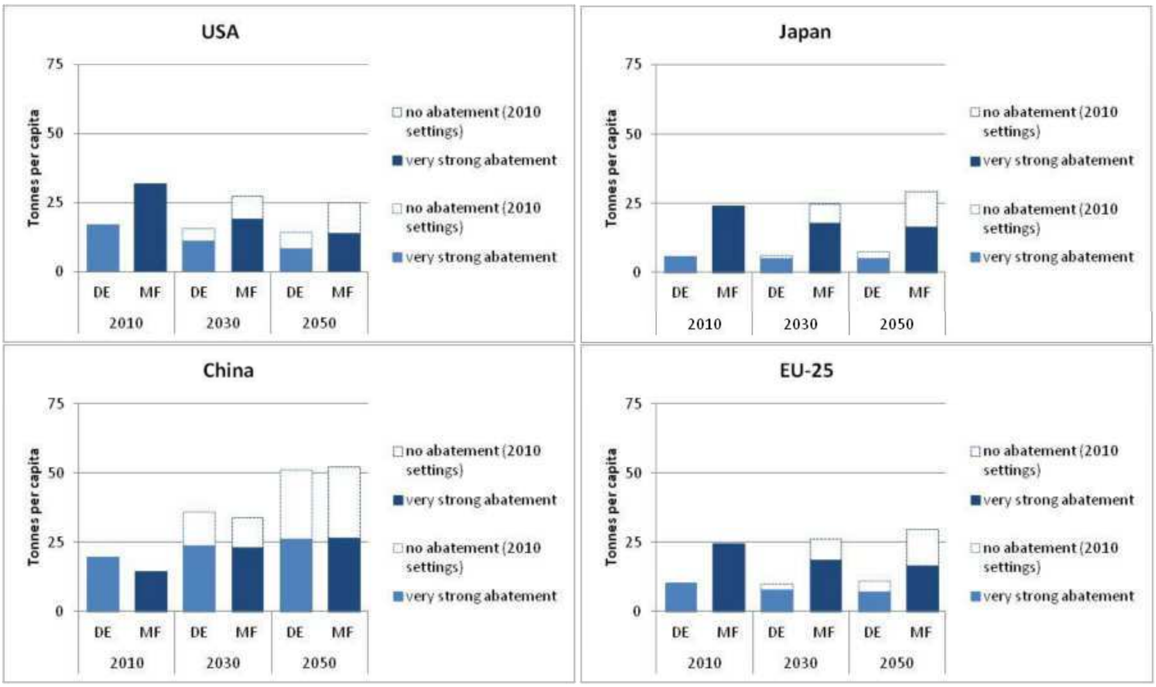
The European Union (25 member States) has a similar per-capita energy use and consumption as Japan but growth is slightly lower until 2050 in all scenarios. Over the 4 decades until 2050 the EU-25 continues to rely on embodied energy of trade.

Figures 6a-d demonstrate that in a business as usual world China's per capita carbon footprint would surpass that of the United States by 2050 and would reach 20 tonnes per capita. Very strong abatement would make an enormous difference in future per capita carbon emission in China and would reduce the per capita carbon footprint by two thirds. There is similarly large savings potential for US per capita carbon emissions, which would be reduced from around 18 tonnes per capita to less than 7 tonnes per capita by 2050. Even in Japan the difference between business as usual and very strong abatement would be around a 50% reduction in per capita carbon emissions. Strong abatement efforts expressed in a $50 per tonne carbon price at the start would mean that the per capita carbon footprint of the three most important economies would converge at around 7 tonnes per capita by 2050 despite strong continuing economic growth. The EU-25 has a similar saving potential for both direct and embodied carbon emissions to Japan and follows a similar trajectory.



Figures 6a to 6d Territorial carbon emissions and carbon footprint for United States, Japan, China and EU-25, 2010, 2030, 2050; two scenarios (BS and T50), t/cap

Strong policy efforts in increasing resource efficiency in major material intensive sectors including construction and buildings, transport and mobility, agriculture and food (through larger investment into eco-efficiency of production and use) and energy generation (through the carbon price) would have a considerable positive impact on material consumption in all three leading economies (see Figures 7a-d). China would see its current material footprint of about 14.6 tonnes per capita grow to 26.7 tonnes per capita by 2050. Most of the growth dynamic of material footprint in China would have occurred by 2030 at which time a saturation of material growth would have happened. Material footprint in the US would decrease even under business as usual assumptions because of stock saturation but even more so if strong investments into resource efficiency are taken into account and the US could halve its material footprint by 2050 over 2010 levels. Japan shows a similar saving potential for natural resources and so does the EU-25. By 2050, the US, Japan and the EU-25 show a level of material footprint per capita of around 15 tonnes. Levels in China are quite a bit higher, 25 tonnes per capita of material footprint, which is caused by the fact that investment into new buildings and transport infrastructure in China will remain strong until the middle of the century while most of the required infrastructure is already in place in Japan and the US and therefore the material demand for buildings and roads will mostly involve maintaining existing assets. A material consumption of 50 tonnes per capita in China by 2050 is somewhat unrealistic and most be interpreted as a modelling artefact.

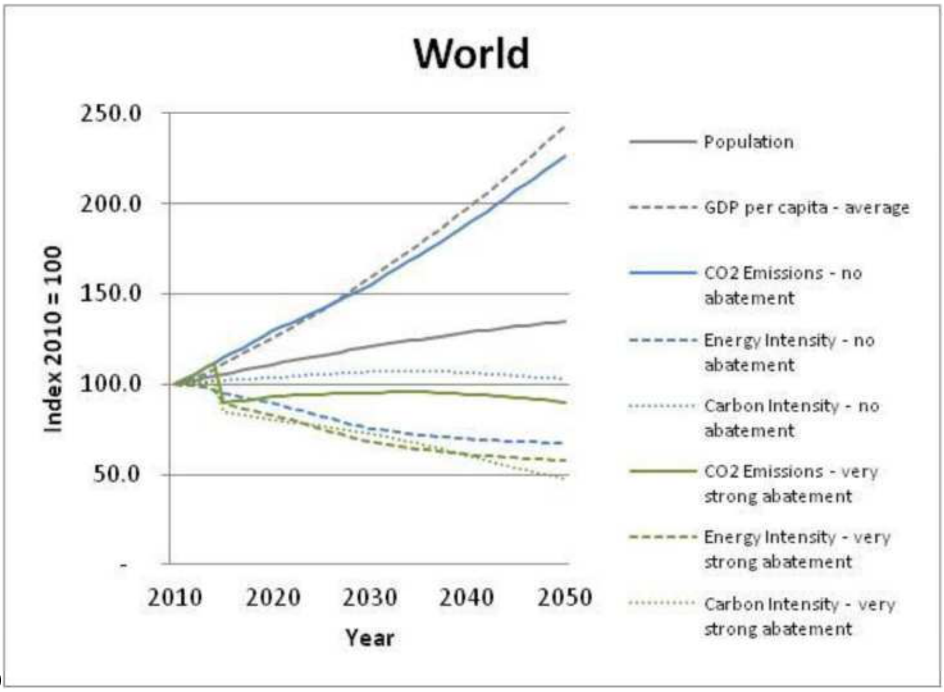


Figures 7a to 7d Domestic material extraction and material footprint for United States, Japan, China and EU-25 in 2010, 2030, 2050; two scenarios (BS and T50), t/cap

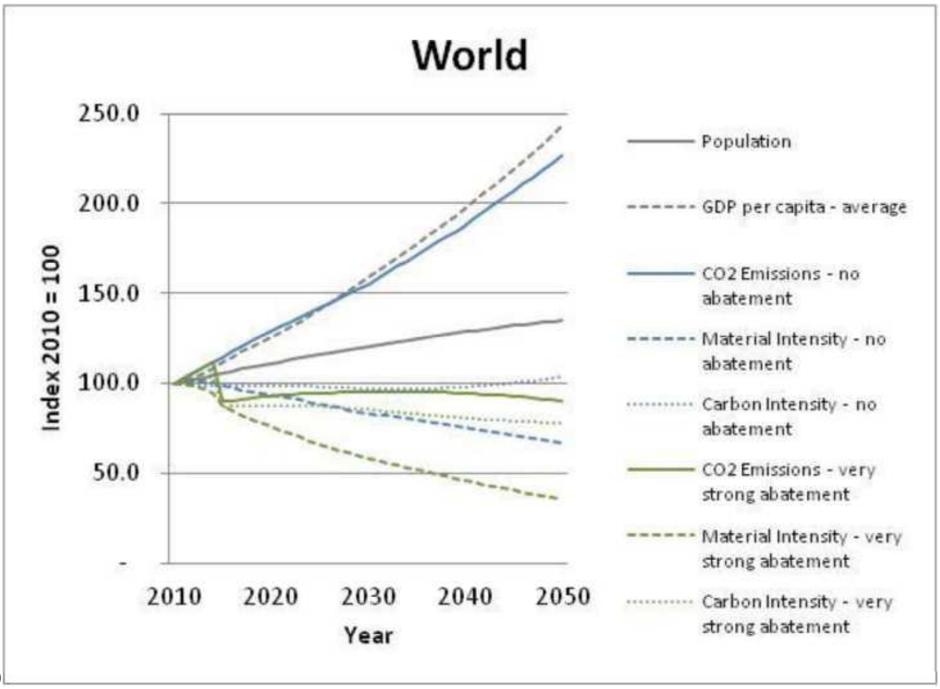
To further explore the relationship between the driving forces of a growing industrial metabolism (energy and material flows) and climate change we employ the Kaya identity introduced in the methods section. In our context the Kaya decomposition reveals the extent to which carbon footprints are related to energy and material footprints of consumption.

At the global level, business as usual – i.e. no global carbon price (scenario BS) – would see carbon emissions grow in parallel with GDP growth more than twofold over 2010 levels by 2050, despite some improvements in energy intensity especially from 2030 onwards. Very strong abatement (T50) would allow a substantial slowdown in emissions growth enabled by large reductions in the carbon intensity of energy generation and some further improvements in the energy intensity of the economy over business as usual (Fig. 8a).

Improvements in material intensity of the overall world economy would have a strong mediating effect on carbon emissions and would be more important than the carbon intensity of material use, which also contributes to reducing emissions in the strong abatement scenario but to a lesser extent (Fig. 8b).



a)

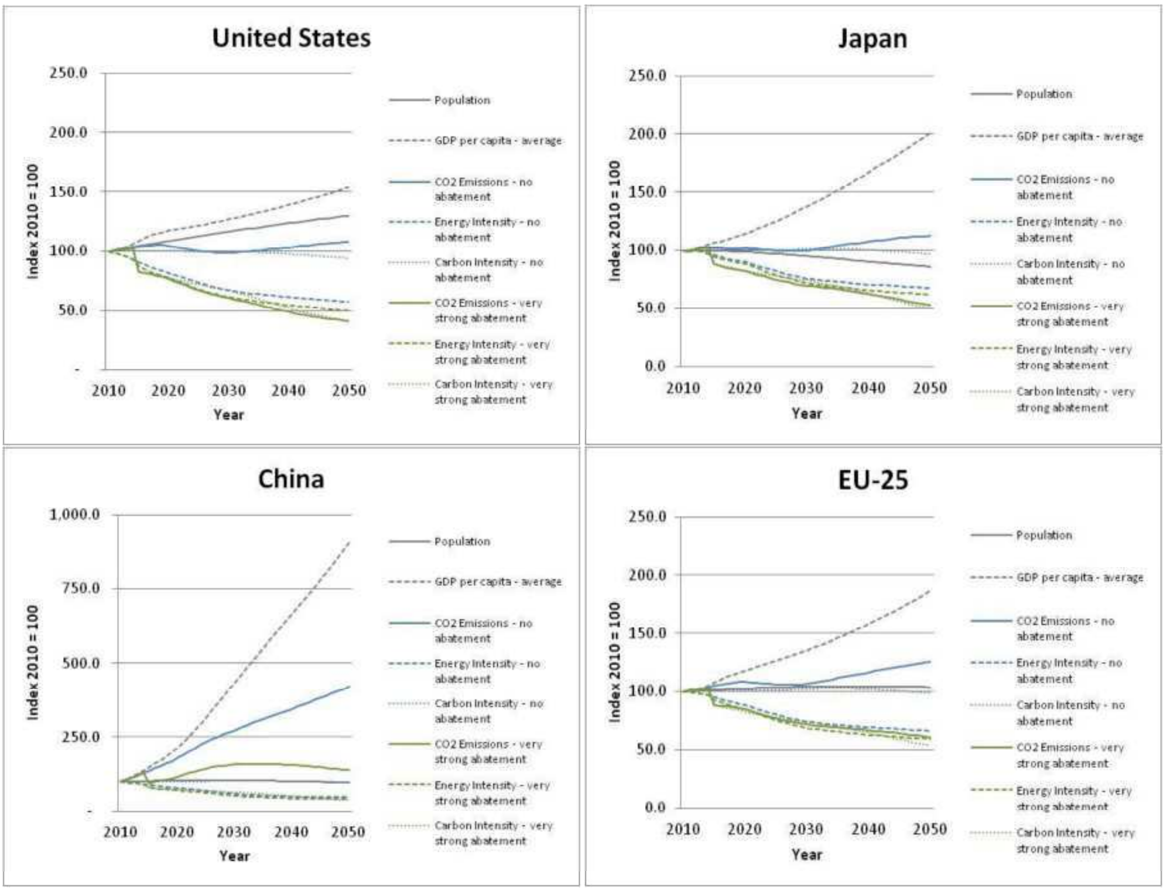


b)

Figures 8a and 8b Global drivers of carbon emissions, 2010 to 2050, index 2010 = 100. Panel a) shows the Kaya decomposition for the carbon and energy footprint and the carbon intensity of energy, Panel b) for the carbon and material footprint and the carbon intensity of material use.

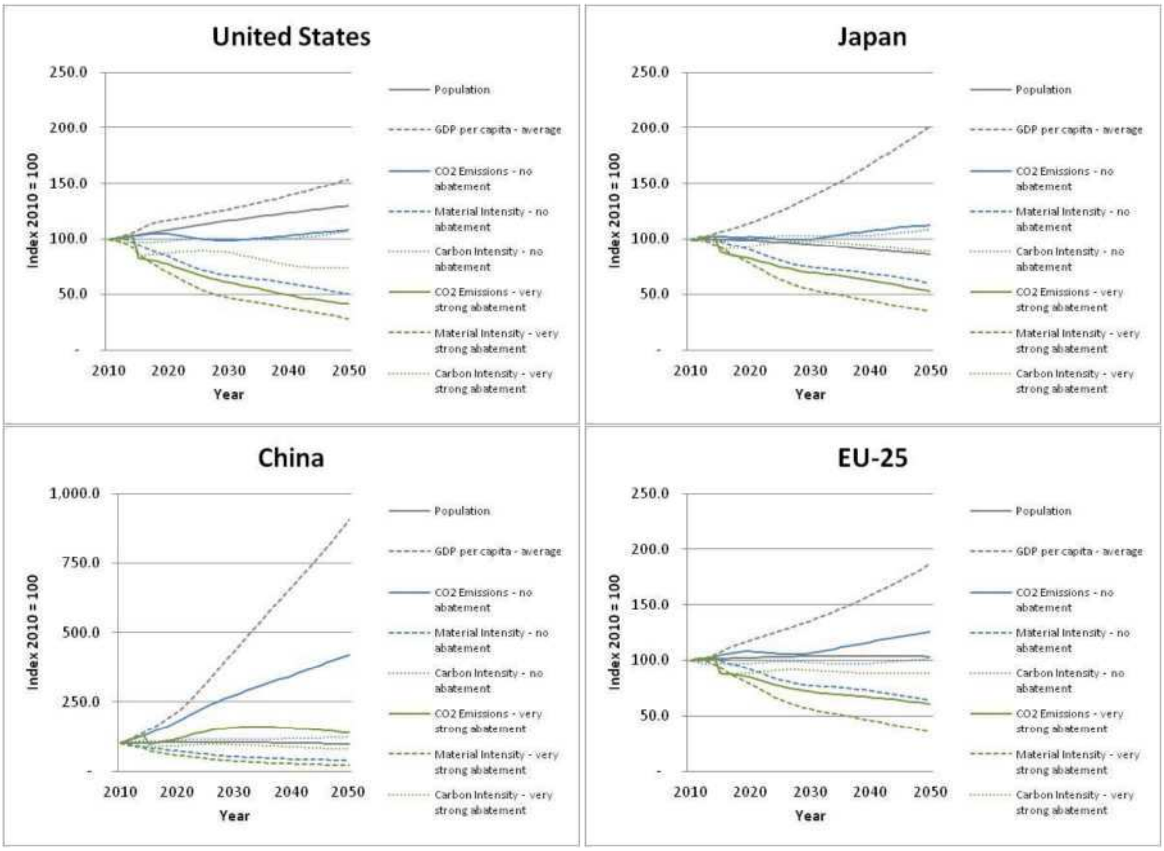
In the US, direct emissions would grow slowly over the next four decades, despite substantial growth in GDP and population growth enabled by increases in energy efficiency. Carbon emissions, however, could be markedly reduced with a $50 carbon price which would help reduce the carbon intensity of the US energy footprint, particularly by removing coal for electricity generation at a large scale. This will not occur without ancillary costs. Removing coal for electricity generation at a large scale will require a significant investment in clean power technologies, redeployment and reskilling of labour, and redevelopment of a smart-grid network. However, the large investment for clean technologies will also become an impetus to the economy, creating new market demand and job opportunities. Our model predicts that the positive impact of investment in new technologies will almost completely offset the negative cost impacts of removing coal in the power sector. In a sense, our estimate is rather optimistic, but it is consistent with empirical findings by (Ohler and Fetters 2014) that development of renewable energy can positively impact GDP.

In China, economic growth far outpaces carbon emissions; however, a similar level of wealth could occur even at much lower levels of emissions with energy intensity and carbon intensity being of similar importance for achievable reductions. Japan and Europe will see GDP doubling without emissions growing initially. Carbon emissions will, however, start to grow from 2040 onwards in a situation where population stabilizes in Europe and declines in Japan. Europe and Japan have some potential to reduce their carbon emissions if policy settings drive change towards reducing the carbon intensity of the energy system and especially of electricity generation (Figures 9a-d).



Figures 9a to 9d Drivers of carbon emissions (CO_2 and energy use), United States, Japan, China and EU-25, 2010 to 2050, two scenarios, indexed 2010 = 100

Improvements in the material intensity of the economy are very strong contributors to reducing carbon emissions both in the business as usual scenario but even more so in the strong abatement and resource efficiency scenario. Using fewer resources would help reduce energy use and using fewer carbon intensive materials – especially reducing coal and iron and steel use – would further assist in reducing carbon emissions. The carbon intensity of material use is of much lesser importance, especially in China which will continue to expand its economic assets and infrastructure over the decades to come and hence continues to use carbon intensive materials (Figures 10a-d).



Figures 10a to 10d Drivers of carbon emissions (CO_2 and materials use), United States, Japan, China and EU-25, 2010 to 2050, two scenarios, indexed 2010 = 100

Discussion

Our modelling shows that a low carbon and dematerialized world economy is potentially achievable if strong and well-designed policies guide a change towards technologies and practices that support a resource efficient and low carbon economy (modelled in our case by a globally accepted carbon price of $50/t rising to $236/t by 2050 under strong abatement action in line with a two degree warming limit). The environmental and perhaps even social benefits of such change are enormous while the impact on economic growth appears to be negligible. The overall loss in GDP over the next four decades would be as low as 1.6%, even in the T50 scenario, which indicates that there is no apparent contradiction between achieving human wellbeing supported by a decent standard of living and environmental sustainability, provided appropriate policies are in place.

Imposing a global carbon price would increase the cost of energy consumption and constrain economic activities that are energy-intensive due to sluggish demand. But at the same time, in our model, this also creates incentives for nations to invest in renewable energy generation. As "investment" is an important element in the GDP accounts, the increase of investment in renewable energy industries to a large extent offsets the negative impacts of the carbon price on conventional industries. As a result, due to those shifts, our model predicts relatively low overall GDP loss.

It is important to note that no resource limitations were modelled and if strategic resources for production systems such as energy carriers, metals or biomass would face supply constraints (and related price increases) it could mean that economic growth in a business as usual world would contract and would actually be lower than in the contrasting two scenarios (BS and T50) which depend on much lesser amounts of natural resources to fuel economic activity because of the much higher efficiencies that would have been achieved.

Our scenario results for future energy use (BS, T50) coincide with the modelling of the International Energy Agency projections (IEA 2012) and with the scholarly literature suggesting a very high coupling of energy use to economic growth meaning that an increase in GDP drives a proportional increase in energy use (Steinberger et al. 2010).

Baseline projections from global integrated assessment models for energy related carbon emissions are typically characterized by fast growth in income and declining energy intensity that comes as a dividend when economies mature (Steinberger et al. 2013) but usually only a modest change in carbon intensity (IPCC 2014) which is commensurate with the results of our baseline scenario outcomes. Carbon emission reductions in our model are driven by both energy efficiency gains and large improvements in the decarbonization of the energy system which are in line with the assumptions found in the scholarly literature around reducing the carbon intensity of energy (Barcker and Crawford-Brown 2015). Decarbonization is driven by changing price relations for different energy technologies introduced through a global carbon price, which sets the global economy on a 2 degree warming path.

For global material use the business as usual scenario coincides with previous work (Dittrich et al. 2012b) that suggested 180 billion tonnes for a medium population scenario under business as usual assumptions, higher than the 140 billion tonnes suggested by the UNEP International Resource Panel (UNEP 2011a). However, our modelling suggests that the reduction potential is much less than that suggested by Dittrich et al. (2012) who assume, in the absence of economic dynamics, that global resource use could be as low as 40 billion tonnes (equivalent to 4 tonnes per capita) in 2050, which appears unrealistic according to our model results.

We find reductions in carbon footprint are mostly driven by global improvements in the carbon intensity of energy provision. This could involve moving to renewable energy technologies and energy sources that have lower carbon contents, especially by phasing out coal, which happens when other energy technologies become economically competitive because of the global carbon price. Energy efficiency supports this process but plays a subsidiary role to the decarbonization of the energy system. Material efficiency, on the other hand plays a much bigger role in reducing carbon footprint than does energy efficiency while the carbon content of materials is of much lesser importance. Improvements in material efficiency reduce carbon in several ways, through a declining need for transport services because of declining volumes and through energy saving in energy intensive heavy industries, such as the iron, steel and cement industries, again because of declining overall volumes.

There are a number of limitations to be mentioned in regard to the findings presented. First, the sectoral disaggregation of the economic model into 21 sectors is rather coarse and while it focuses on resource and emissions intensive sectors, a more detailed sectoral disaggregation would be useful for characterizing inter-industry relationships and specific technology developments. A similar caveat applies for the regional disaggregation into 13 world regions, although the most important economies have been covered.

Second, modelling of decarbonization trajectories consistent with limiting temperatures to 2 °C requires extension of the technology options modelled, including a wider range of low carbon transport solutions (including public and private passenger transport), greater attention to land use and food production trade-offs, and exploration of 'negative emission' energy options (such as biomass electricity with biochar or carbon capture and storage). In some cases these options may increase energy use (as often occurs with electrification of transport), but in general they would be expected to strengthen the decoupling results found in this paper.

Third, at this stage there were no constraints set for natural resource availability and timely supply. It may well be that the business as usual scenario, as a consequence, is somewhat unrealistic and may not occur in the way described because supply scarcity for strategic resources may slow down production which would also mean that emissions would grow much more slowly. On the other hand it appears that many natural resources will still be abundantly available over the next 40 years and may not be the main limiting factor (Randers 2012). It seems plausible that climate change and related impacts, as well as issues related to rising amounts of waste, will weigh heavier on the world economy compared to resource depletion over the next four decades.

There are also many social limits for extending raw material extraction to the levels required in the business as usual scenario, including macroeconomic pressures on countries relying vastly on their extractive industries – Dutch disease (Bruno and Sachs 1982) – as well as land use conflicts and community concern (Reeson, Measham and Hosking 2012).

Ultimately, all natural resources are limited and hence modelling resource availability as a constraint would be useful. While many resources may still be abundant in the Earth crust, the cost and effort to establish extraction infrastructure has been increasing for many primary materials and imbalances of supply and demand reflected in price volatility are to be expected. Incorporating resource supply limits would also enable a more realistic assessment of the amount of natural resources required to achieve the energy technology transition (Gibon and Hertwich 2014) that is suggested by the price dynamic in GIAM and would enable decarbonization of the energy system.

Finally, material, energy and carbon intensities driven by current and future stocks would also become more reliable if they were linked to capital investment and did not rely solely on technical and physical assumptions. Despite these limitations this research demonstrates a new approach for linking natural resource dynamics, hence industrial metabolism, to carbon dioxide emissions and climate change and presents a modelling architecture which promises to be influential in informing policy on sustainable development.

Conclusions

This research has used innovative modelling architecture to demonstrate the interrelationships between climate change (carbon emissions) and industrial metabolism (energy and material flows), now and over the next forty years. We have demonstrated that such integrated modelling involving climate, economic and physical aspects is feasible and leads to results that may become very relevant for policy making. The ongoing agreement on new sustainable development goals (SDG's) has stressed the importance of resource efficiency and low carbon development for achieving increasing living standards and reducing poverty. By employing scenario analysis at global and regional levels, we have shown that a global transition to a low carbon and resource efficient economy is not only possible – if strong and appropriate policies are put in place – but could be achieved with little or no impact on economic growth. This suggests that economic growth, per se, is not the main problem for environmental pressures and impacts but that the focus should rather be on the quality of growth. There is hence no real contradiction in achieving the economic and environmental goals of the SDG's. Investing in green economic strategies will support economic development in the future.

Policy settings including putting a price on carbon emissions and redirecting investments to infrastructure, production systems and technologies that allow products and services to be delivered at a much lower environmental cost (lower material and energy intensity), are technically achievable and economically viable options. Global initiatives such as the UN 10-year framework of programs to support sustainable consumption and production (SCP) (Akenji and Bengtsson 2014) and investment in a green economy (UNEP 2011b) in concert with initiatives by national governments can align environmental sustainability with a broader sustainable development agenda that includes reducing poverty, enhancing equitable access to natural resources and improving human wellbeing.

Our modelling suggests that a global price for carbon emissions, starting at $50 per tonne and reaching $236 by the middle of the century (at 2007 prices), would be sufficient to drive decarbonization of the energy system by increasing the share of renewable energy technologies to such an extent that would reduce the likelihood of global warming beyond 2 °C. Equally, doubling the global efforts to raise resource efficiency would mean that production and consumption processes could go ahead without the disruptive effects on the global resource base that business as usual economic development would have.

Conventional climate modelling abstracts from the broader perspective of industrial metabolism while physical economy models often neglect economic dynamics and realities and tend to ignore linkages with ecosystem functions. This research has been an attempt to bridge climate change and industrial metabolism research traditions but is clearly only to be seen as a first step. More research is needed to integrate supply constraints for strategic natural resources into the modelling and to prove the robustness and reliability of consumption-based accounting, especially in the domain of material use.

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