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Extrapolation or saturation – Revisiting growth patterns, development stages and decoupling

Raimund Bleischwitz[a,*], Victor Nechifor[a], Matthew Winning[a], Beijia Huang[b], Yong Geng[c]

[a] University College London, Institute for Sustainable Resources, Central House, 14 Upper Woburn Place, London WC1H 0NN, United Kingdom
[b] University of Shanghai for Science and Technology (USST), Department of Environmental Engineering, China
[c] Shanghai Jiao Tong University, Department of Environmental Science, Environment Science Building, 800 Dongchuan Rd, Minhang District, Shanghai 200240, China

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ABSTRACT

The contemporary debate considering the use of natural resources in economic growth centres around the concept of 'decoupling' driven through improvements in resource efficiency. Many studies extrapolate future demand from a short time series of previous years. However, we believe there should be greater attention on the underlying demand assumptions and the possibility of long-term changes. Accordingly, this paper is concerned with a potential saturation in material use as a result of countries moving through stages of development over decades from early industrialisation, over mass production and into a mature stage. An observation of such saturation is relevant for global environmental change as future demand for resources could be lower than currently expected, leading to less associated environmental pressures. In particular, emerging economies are undergoing changing growth patterns, and their future resource use may be significantly lower than contemporary analysis suggests.

This paper combines the analytical strands of resource economics and material flow analysis. It investigates both material-specific demand and stock build-up trends over an extended time horizon of a century. Four materials (steel, cement, aluminium and copper) are analysed applying an indicator called 'Apparent Domestic Consumption' (ADC) and using international trade data for four industrialised countries (Germany, Japan, UK, USA) together with China as the most preeminent emerging economy.

Our results confirm the occurrence of a saturation effect for most materials considered. While the evidence is strong for the per capita apparent consumption of steel, copper and cement in the four industrialised countries, it is somewhat weaker for aluminium. Also, such saturation in material use can start at different income levels, with the saturation beginning to occur relatively early for steel and cement ($12,000 GDP/capita) and later for copper ($20,000 GDP/capita). The results suggest a time gap of around thirty+ years from the take-off of large-scale adoption of one type of material and any saturation occurring. We also shed light on the build-up of stocks in the economy, where our findings suggest there is a delayed saturation of at least twenty years compared to apparent consumption depending on the lifetimes of capital goods.

With regard to China, a demand saturation for steel and copper has already started to occur, and our analysis suggests such saturation will soon take place for cement. These findings provide a more moderate outlook on China's future material demand compared to an extrapolation of recent dynamics.

Our new insights on the nexus between economic growth, development stages and the use of natural resources have implications for the decoupling debate and for investments into commodities. From a wider environmental policy perspective, one may expect China and other emerging economies to achieve a saturation effect soon and therefore also peak their industrial emissions of greenhouse gases, supporting the nationally determined contribution (NDC) to the Paris Agreement on Climate Change.

1. Introduction

The turmoil encountered in Chinese stock markets during 2015–2016 can be viewed as part of a broader picture about fundamental uncertainties related with growth expectations for emerging economies and the world economy as a whole. Although changes in growth rates are due to a number of factors, one important driver relates to commodities and the consumption of natural resources. There

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[*] Corresponding author.
E-mail address: r.bleischwitz@ucl.ac.uk (R. Bleischwitz).

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is an interest in understanding how different future socio-economic pathways may accelerate the use of resources as well as how resource prices may feedback on to growth rates. Recent studies suggest the world economy could double the amount of global extraction by 2050 compared to 2015 (UNEP, 2016: 10;Schandl et al., 2016), or a tripling compared to 2010 (UNEP, 2011: 28f), although with a great level of uncertainty.

One fundamental issue is whether the Chinese economy will shift toward a more service- and consumption-based economy. If so, Chinese production may well increase its resource use at a slower rate compared to previous increases, or perhaps even experience an absolute reduction at a certain stage. There appears to be a clear acknowledgement that, in policy terms, the implications of development stages for resource futures require further attention. It is therefore pertinent to ascertain what the impacts of changes in growth and materials use and stocks will be on the overall demand for natural resources and the wider economy?

This transition in a country's structure is often referred to as decoupling the use of resources from GDP. The International Resource Panel calls it the "imperative of modern environmental policy" (UNEP, 2017: 14). With a view to emerging economies such as China, however, it appears that the contemporary debate has to reconnect with nuanced analysis on a saturation effect, i.e. a deeper understanding of development stages and the intensity of material use over time as put forward by Malenbaum (1978) and summarised by Cleveland and Ruth (1998). Insights into a saturation effect are relevant for global environmental change as the future demand for resources may be considerably lower than expected, leading to less associated environmental pressures. In particular, emerging economies are changing their growth patterns, and their future resource use may be significantly different from what the contemporary analysis suggests.

A key issue is to adopt a long-term view. Any analysis which is looking ahead to 2030 – when the SDGs ought to be delivered − or 2050 and beyond requires analysis of previous decades to understand how countries have already developed. Such analysis should include the period after WWII when growth rates in most industrialised countries were remarkably high and, if possible, the entire last century to account for the build-up of infrastructures. Research should not adopt a year such as 1990 as a starting point for decoupling analysis or for extrapolations (which is the base year of the UNFCCC and some databases e.g. Wiedmann et al., 2015) as limitations for analysing structural changes and foresight are obvious.

Under such a circumstance, this study aims to identify the levels in economic development after which the use of key materials saturates or even declines. Our article analyses the use of four refined materials (steel, cement, aluminium and copper) in four industrialised countries (USA, UK, Germany, and Japan) and China over the 1900–2013 timeframe. In order to include the embodied imports in semi-finished and finished goods, we move away from a focus on production towards one on 'Apparent Domestic Consumption' (ADC) by including the material intensities of key product groups and internationally traded commodities. Adopting a conventional production view on those materials would imply that countries which rely on net physical imports to cater for their domestic demand appeared to perform well in terms of decoupling, while in reality they are simply shifting elements of their production base abroad. Our indicator 'Apparent Domestic Consumption' (ADC) is able to give a more nuanced view where such bias is minimised. We also use this method to estimate the build-up of stocks. The underlying questions are:

- Is there a trend in those developed countries toward a saturation of demand for materials and can a value for such saturation levels be estimated? What are the trends for China? What are the development patterns of the build-up stocks in industrialised countries and is there evidence of a material-specific stock saturation?
- How can the projections of material consumption in emerging economies be informed by a potential stock saturation in developed economies? What evidence can be given for a time gap of material consumption between developed and emerging countries given their heterogeneous development stages?

In order to answer such questions, an integrated approach that combines the strengths of different methods should be adopted. We follow an international life-cycle perspective of using materials that is specific to Material Flow Analysis (MFA) and industrial ecology. However, considering our focus on refined materials and not on raw materials (e.g. iron ore, bauxite), we adopt the 'Apparent Domestic Consumption' (ADC) indicator employed in other cross-country steel use studies (Wårell, 2014; Pauliuk et al., 2013) and apply it to four materials in five countries. Terms and methodological differences are explained below. We also consider income per capita over time measured in real terms as we intend to gain insights for future research on modelling socio-economic pathways. The authors acknowledge some inherent limitations, as possible substitutions are likely to be overlooked (e.g. increased applications of plastics), and analysing resource productivity in general requires the inclusion of feedback effects using more comprehensive data and relevant issues such as the rebound effect. Future research will be able to use our approach and fill those gaps. The wider picture of shedding light on future demand of emerging economies for macro-economic modelling purposes, and the delivery of the SDGs (in particular SDG 12 on sustainable resource management) encourages such a study.

The structure of the paper is as follows. After this introduction section, Section 2 briefly reviews the debates on intensity-of-use, decoupling, and metabolism in the broader context of growth and resources. Section 3 describes our research methodology. Section 4 presents our research results and Section 5 discusses these findings. Finally, Section 6 draws research conclusions and provides policy implications for future infrastructure investments in emerging economies. Additional information on the material intensity data and a sensitivity analysis is given in the Supplementary information files.

2. A short review on growth and resources

A number of growth theories emerged from the 1950s. Among them Rostow (1960) developed a growth theory covering different development stages which posits that all economies experienced various transformations from early take-off to industrialisation and then move towards mature economies where services and consumption are the dominant patterns. Although this proposition was contested by other development and growth theories, it reappeared in the 1970s, with a focus on 'limits to growth' (Meadows et al., 1972) along with the unprecedented price peaks for energy and other commodities. Rostow also argued against any evidences of scarcity for raw materials and pointed at innovation as well as at the decline of the rate of raw materials use in relation to increases in real income in the more advanced industrialised nations (Rostow, 1978: 616).

An 'intensity use' hypothesis was developed by Malenbaum (1978), and further elaborated by Tilton (1985) and Auty (1985), adding empirical evidences for a number of materials across different countries and time periods. However, the overall findings on whether materials intensity per GDP declines with economic maturity remained ambiguous at that time. The basic concept was seen as vaguely defined because the data and measurement efforts had several limitations which did not yield unequivocal results, and the underlying drivers were still unclear. Later, with emerging input-output data, it was concluded that future research should be based on better and more comprehensive data (Auty, 1985). Cleveland and Ruth (1998) conducted a further survey on the state of this debate. However, research progress has been limited, with few contemporary publications explicitly referring to a saturation level. Although Tilton and Guzmán (2016) published a textbook on mineral economics and policy, they did not conduct any analysis on such issues. Wårell (2014) investigated the intensity-of-use hypothesis for steel with data from 61 countries, covering over 42 years. They concluded that the hypothesis is valid for the middle-income countries. Finally, a steel analysis was conducted for China by Yin and Chen (2013).

In parallel, the broader debates on growth and development have changed significantly since the 1980s, adding human capital, innovations, and new opportunities for developing countries via the so-called endogeneous growth theory throughout the 1990s (Barro, Romer, Aghion, Tirole et al.). During those years, raw material prices had declined, leading to less attention for scarcity issues. Patterns of economic growth shifted to formerly developing countries such as China and a multi-polar growth world emerged, with increasing economic ties among developing and middle-income countries (see the recent attempts to formulate a 'unified growth theory' in Galor 2013).

The more recent debates often refer to a "decoupling" of resource use from GDP. These began in the 2000s e.g. through the OECD Environmental Strategy 2001 and the Sixth Environment Action Programme of the European Community (2002). The decoupling analysis forms part of wider discussions on global environmental change and especially considers (a) a decoupling of GDP from environmental impacts, and (b) a decoupling of GDP from resource use, i.e. indicators looking at the aggregated use of natural resources based on MFA.

The "decoupling" debate was also rooted in concepts such as Factor Four (von Weizsäcker et al., 1998) and Factor 10 (Schmidt-Bleek, 2009) with numerous examples as well as in the debate about an 'Environmental Kuznets Curve' on pollutants and GDP growth. Decoupling of resource use was based on MFA that emerged in the 1990s (e.g. (Adriaanse et al., 1997; Matthews et al., 2000). UNEP's International Resource Panel has contributed key documents to the decoupling debate (UNEP, 2011, 2014, 2017), while many ongoing research projects focus on countries and regions and also decoupling drivers (West et al., 2014; Schandl and West, 2010; Bringezu et al., 2004; Steger and Bleischwitz, 2011).

In addition, another debate on decoupling indicators exists that analyses system boundaries, international trade, and environmental impacts (Hoekstra and Wiedmann, 2014; Giljum et al., 2014; Tukker et al., 2014; Hertwich et al., 2010; Nansai et al., 2015; Saurat and Ritthoff 2013).

Unfortunately, these studies suffer from data restrictions as the initial data year is often 1990 (Wiedmann et al., 2015) or even later, which is after the take-off of most currently developed nations. For Domestic Material Consumption (DMC), the OECD (2015) applies data from 1980 onwards, and data are now available from 1970 onwards (UNEP, 2017). However, even those base years are much later than the period for the resource-intensive early stage in most industrialised countries. Also, these studies did not explicitly take a development view nor did these engage with the intensity-of-use hypothesis.

In contrast, the academic debate about societal or industrial metabolism takes a historical perspective beginning with what is called hunting and gathering as well as agrarian 'regimes' that were present long before the industrial revolution emerged in the 18th − 19th century (Ayres, 1989; Fischer-Kowalski and Haberl, 2007; Wrigley, 2013; Sieferle, 2001). This debate partly refers to Perez (2010) and other historians with much broader interests in the overall economic development, providing policy-relevant insights into the great transformations such as the beginning of using fossil fuels at a large scale. Wiedenhofer et al. (2013) characterised the pattern of many resource-related indicators as the "70 s syndrome". In general, this strand of research appears relatively descriptive, driven by statistical analysis and without an explicit debate about material use intensity and economic development stages.

The existing studies have other interesting features such as: the shape of the growth curve i.e. whether a decoupling occurs at all, whether data suggests a "re-coupling" (Bringezu and Bleischwitz, 2009: 76f), about the estimation of the anthropogenic stocks in societies (Rauch, 2009; Gordon et al., 2006; Pauliuk et al., n.d.; Mueller et al., 2011), about criticality of materials (Graedel et al., 2012), and also about single commodities (Allwood, 2013; Crowson, 2007; Wårell, 2014).

In conclusion, two main research gaps exist:

(a) the decoupling debate has not yet sufficiently addressed the relationship between resource use, development stages and economic growth, most likely due to MFA data restrictions;
(b) the intensity-of-use analysis appears too fragmented and selective to draw general conclusions with regards to decoupling and the SDG 12 towards the year 2030. What is required is an interdisciplinary approach, aligning physical data on material flows and stocks with socio-economic analysis about growth patterns and resource use across economies over time.

3. Methods and data

3.1. Material flow analysis and apparent domestic consumption

This study follows the general principles of MFA. A core method of industrial ecology and social metabolism, MFA quantifies flows and stocks of materials on different spatial and temporal scales. It is based on systems thinking and the mass balance approach in which matter cannot disappear or be created spontaneously. Matter that enters a system boundary either stays within the system or leaves this at the end of the considered period. The MFA framework can be employed to determine economy-wide metrics which bundle all material use within a region (SERI database, http://www.materialflows.net, or EORA MRIO database, http://worldmrio.com) or it can capture the use of single materials (Wårell, 2014; Pauliuk et al., 2013).

This article applies MFA principles to four key refined materials (steel, cement, aluminium and copper) in five countries (United States, United Kingdom, Germany, Japan and China) using production and trade data for the 1900–2013 period. The selection of these materials is justified by the fact that all countries require these in order to develop their economy. For instance, steel and cement demand is a function of infrastructure development and urbanisation, while copper and aluminium are multifunctional materials for housing, energy, mobility and consumer goods. Accordingly, these materials are usually the top materials for commodity markets analysis. We selected these five countries as they represent the largest economies in the world. UK and USA are two countries with early industrialisation patterns. Germany and Japan are two followers, and China is the most eminent emerging economy.

Our representation of the four considered system topologies (one for each key material) is simplified to a few nodes (see Fig. 1): production and trade of materials in primary form, manufacturing & construction, international trade of finished goods and stock build-up. These nodes are sufficient to determine the two metrics of interest calculated for each selected material − Apparent Domestic Consumption (ADC) and in-use stocks.

The ADC metric is an estimation of the total annual quantities of one type of material that are used within the system boundaries and

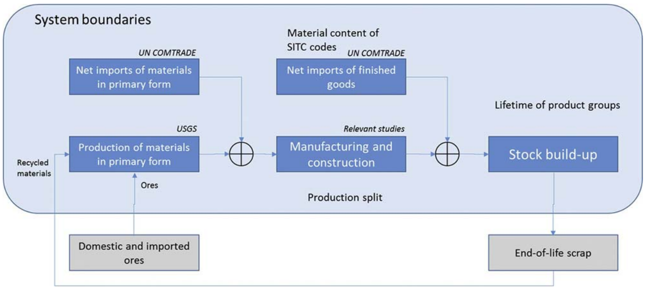


Fig. 1. System overview of the simplified MFA design.
Source: the authors' own compilation

gradually transformed into final demand goods (durable and non-durable consumer goods, capital, infrastructure etc.); ADC is therefore different from the Net Additions to Stocks (NAS) metric by including goods with a short lifetime, e.g. aluminium in packaging. ADC is determined by adding up country-level primary production with net imports of materials in their primary form *and* as embedded parts of products along supply chains until goods delivered to final consumers. ADC does not account for annual changes in inventories. However, given the long time horizon of the analysis, it was considered that any inventory addition occurring in one given year has eventually been employed at a later point. Thus, inventories would not appear as separate accounts; the main limitation to this assumption is that losses due to dissipation or landfilling applicable to materials in primary form are not included.

We consider anthropogenic stocks in order to also gain an understanding of materials potentially becoming available for secondary use after a certain time. Using the term ‘stocks’ we follow UNEP’s International Resource Panel defining a stock as the quantity (e.g. mass) of a chosen material that exists within a given system boundary at a specific time; see also e.g. Rauch (2009). In terms of measurement units, stock is a level variable (i.e. it is measured in kg) as opposed to material flows (which are rate variables). Stocks are determined based on the distribution of each material to a representative set of product groups and on the corresponding lifetime of these groups. The calculation of stocks for each year is thus derived from that of annual ADCs, by summing up all annual material consumption values attributed to products that are expected to be still in-use in that particular year.

The ADC indicator implies similarities and differences to the ones often applied in MFA, namely Domestic Material Consumption (DMC) and Raw Material Consumption (RMC)/Material Footprint (MF). According to a definition provided by OECD (2008), DMC measures the total amount of material directly used in an economy (i.e. the direct apparent consumption of materials, excluding indirect flows). DMC thus is a measure of direct physical material use within an economy; it does not consider the indirect “hidden flows” associated to resource extraction and transformation taking place outside of the focal economy. Hence, analyses based on DMC would overlook much of the shifting of resource use and associated environmental pressures among countries. This metric is generally associated to the use of raw materials and is employed in the resource-productivity oriented studies of the recent years (OECD, 2015). In comparison, RMC/MF is defined as a consumption-oriented indicator (Eurostat, 2001) based on Raw Material Equivalents (RMEs) in that it reflects the total material use associated with final domestic demand by including both direct and indirect flows of the associated resource extraction. In line with Wiedmann et al. (2015, see also the excellent Supporting information), RMC can complement those other footprint indicators that prominently feature in the areas of water and carbon; however, a broader ‘footprint debate’ is beyond the scope of our article.

Thus, the ADC metric used in this article is not aimed to consider these indirect flows. Instead, we change the focus from raw materials to refined materials as done for steel in Wårell (2014) and Pauliuk et al. (2013), and from a resource productivity view to the angle of the material use saturation induced by economic development. We thus propose that our indicator can provide valuable insights on ‘off-shoring’ of material-intensive production via trade while more studies should be initiated to capture the full range of problem shifting via indirect flows of waste and pollution abroad.

3.2. Data sources and treatment

Our article tracks the four materials for a considerable time span, much beyond the timeframe being applied so far for the decoupling debate, which is relevant and necessary to analyse saturation levels in a growing economy. Production information for all four materials was obtained through the USGS Mineral Yearbooks with the starting year of 1928 for steel, 1931 for cement and 1932 for aluminium and copper. Steel and cement are considered to have begun industrial scale production from 1850 onwards, and 1900 for aluminium and copper. Therefore, production figures before 1928 for all materials were estimated with a linear production increase. Since copper refining data are absent in the USGS Yearbooks before 1976, refined copper production was estimated using USGS smelting data as a proxy − a country-specific smelting-to-refining conversion ratio.

Table 1
Data sources for material intensity of internationally traded goods

Material	Data source
Steel	Pauliuk et al. (2013)
Cement	*Not applicable*
Copper	Ruhrberg (2006)
Aluminium	Authors’ estimates

The international trade component of the ADC was introduced through the Physical Trade Balance of each country derived from UN Comtrade database. For steel, copper and aluminium, the relevant SITC trade codes were selected and the material intensity of goods traded was determined either from existing literature or estimated by the authors (see Table 1). The material intensities of each trade code are available in the Supplementary information spreadsheet. For cement, only the international trade of its primary form (Portland cement) was considered. The cement quantities contained in transformed goods were assessed to be negligible relative to both apparent demand and Portland cement traded quantities, and are also relatively difficult to identify in any international trade codification.

3.3. Material flow accounting

For each year t, the total demand for each material m in its primary form $D_{pf,m}$ was calculated by adding production $P_{pf,m}$ and physical trade balance $PTBP_{pf,m}$ of materials in primary form (Eq. (1)). These figures were then distributed as inputs $D_{tr,m}$ to the manufacturing of main product groups tr (Eq. (2)) using production split shares $\delta_{\mathrm{tr,m}}$ derived from other studies (Table 2). This approach takes product categories directly from trade data and means that we do not need to apply MFA data and allocate them back to product groups. The split shares are assumed to be constant throughout the analysed period for steel and cement due to the lack of a longer time series showing a change in the structure of demand of primary materials. For aluminium, extended time series were available through the Global Aluminium Model whilst the USGS copper end-use statistics (USGS, 2015) are employed for copper.

Intermediate material losses in the transformative industries tr were considered to be negligible − most “new scrap” (the excess material resulted from production processes) would be recycled and returned as secondary materials to the production of primary forms, thus remaining within the system boundaries. Hence, material input amounts $D_{tr,m}$ would be equal to the materials embedded in the output of the transformative sectors.

The ADC values was calculated for each country by adding materials from net traded finished goods $PTB_{fg,m}$ and the output of the transformative industries (equation 4). Materials embedded in the internationally traded goods were determined by applying material intensities $\theta_{fg,m}$ (Eq. (3)) specific to each SITC trade code fg.

Demand for materials in primary form $$D^t_{pf,m} = P^t_{pf,m} + PTB^t_{pf,m} \qquad (1)$$

Distribution of materials to transformative sectors $$D^t_{tr,m} = \delta^t_{tr,m} * D^t_{pf,m} \qquad (2)$$

Net imports from finished goods $$F^t_{tr,m} = \sum_{fg,tr} \theta^t_{fg,m} * PTB^t_{fg,m} \qquad (3)$$

Apparent domestic consumption $$ADC^t_m = \sum_{tr} (D^t_{tr,m} + F^t_{tr,m}) \qquad (4)$$

Table 2
Product groups associated with steel, cement, aluminium and copper.

Material	Product groups (life-time)	Relevant study for production split shares
Steel	Transport (13 years) Machinery (30 years) Construction (50 years) Small consumer products (15 years)	Pauliuk et al., 2013
Cement	Roads (45 years) Residential buildings (50 years) Commercial buildings (50 years) Public buildings (50 years) Farms (50 years) Water distribution (60 years) Utilities (60 years) Other (45 years)	US Portland Cement Association
Aluminium	Transport (13 years) Machinery (30 years) Construction (50 years) Small consumer products (15 years) Packaging (1 year)	Aluminium Association – Global Aluminium Model (GAM)
Copper	Transport (13 years) Machinery non-electrical (30 years) Electrical equipment (15 years) Construction (50 years) Small consumer products (15 years)	USGS Copper End-Use Statistics

Finally, stocks were calculated using different product group lifetime assumptions in line with mean values found in previous studies (Table 2). For simplicity, the calculation of stocks does not take into account any uncertainty related to these lifetime values and thus an implicit deterministic probability distribution was employed. For lifetime assumptions, a sample sensitivity analysis is provided for steel in the Supplementary information.

3.4. Saturation analysis

We introduce two indicators which are both expressed in relation to GDP per capita – ADC per capita and stocks per capita. These indicators are employed to determine the extent to which industrialised economies reach material-specific saturation. They also assist in assessing the trajectory. China has taken on its pathway toward a high-income economy. For the indicator representation, GDP per capita is expressed in PPP terms using Geary–Khamis 1990 international dollars with time series data taken from the Maddison Project database (Bolt and van Zanden, 2014).

Once the annual stocks are derived from ADC levels based on the method above, we can then delve into identifying the stage of each considered material within a specific country. We propose grouping the dynamics across the economic development curve into the following three stages:

- A "growth" stage: in which per capita demand grows at a rapid pace leading to a pronounced stock accumulation. Here an important share of the GDP is dedicated toward the build-up of essential infrastructure and capital stock formation.
- A "maturing" stage: where per capita ADC starts to be stable. However, ADC settles at a level that is higher than the volumes required to replace the end-of-life products. This leads to a further increase in per capita stocks, although at a lower speed compared to the "growth" stage.
- A "saturation" stage: in which per capita ADC is converging towards levels that allow for stock replenishment, therefore leading to per capita stock saturation and even decline in the long run.

Table 3
Material saturation stages.

Stage	ADC	Stocks	Description
Growth	↗	↗↗	Rapid accumulation of stocks (1)
Maturing	→	↗	ADC slowdown (2)
Saturation	↘	→	Start of stock saturation (3)
	→	→	Steady-state (4)
	↘	↘	Material use efficiency adjustments (5)

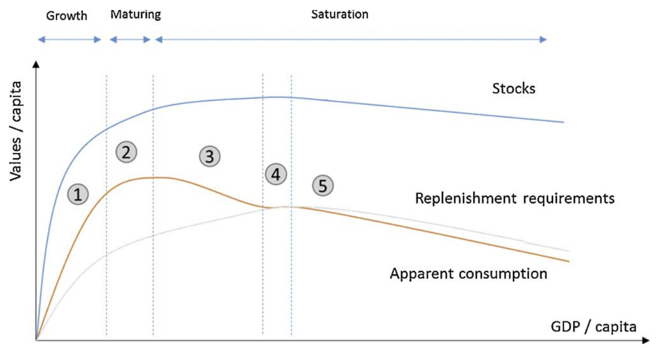


Fig. 2. Stylised apparent consumption and stocks of materials along the development curve.

The three development stages can be operationalised using Table 3 which comprises an indication of how per capita ADC and stocks are evolving at all stages. An interesting note is that the 'saturation' stage can be categorised into different sub-stages with different dynamics as a region moves further on the development curve (Fig. 2 phases 3–5). 'Saturation' is initiated once there is a sustained decline in per capita ADC. This decline causes ADC to reach a level close to the stock replenishment requirements and at this level, stocks start saturating. There may then be a period where both ADC and saturation fluctuate around a central value. A 'constant ADC and stock' phase may not last long, or may not be visible at all, as other structural factors may influence ADC such as material use efficiency gains which trigger a further decline in both indicators. Clearly, testing such a stylised model is beyond the scope of our article, in particular as we expect any saturation of stocks to have started rather recently, but we use it as a heuristic device for our analysis.

4. Results

4.1. Per capita ADC and stocks

(a) Steel

Industrialised countries

For all studied countries, per capita steel ADC appears to saturate at a level of 0.5-0.8 tonnes per capita once a threshold of $12,000 GDP/capita is passed (Fig. 3). Nevertheless, these saturation ADC levels still contribute to a further increase in stocks. The USA case suggests that only after $16,000 GDP/capita does the ADC start to decline towards levels that determine a decrease in stocks per capita. Germany experienced the same trend with a current slowing down of stocks/capita growth after $20,000 GDP/capita.

China

Growth patterns for steel in China follow the past trends of those industrialised countries. Per capita ADC levels are increasing toward the saturation levels obtained in other regions as the country goes beyond the $10,000 GDP/capita level. Stock levels have had an

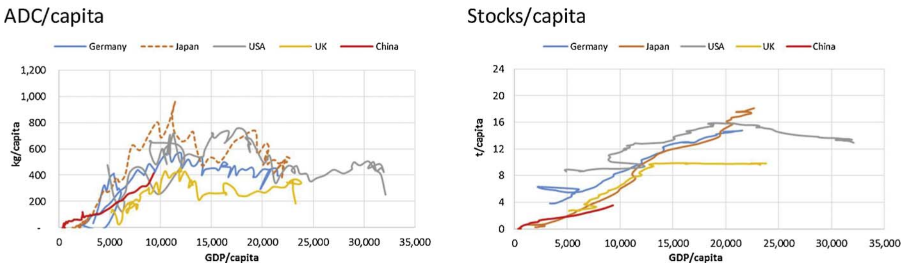


Fig. 3. Steel ADC and stocks per capita.

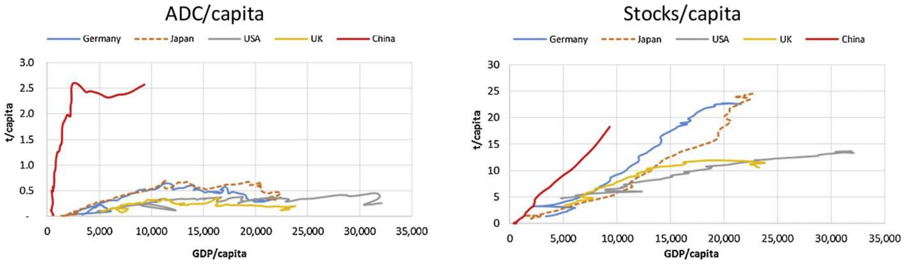


Fig. 4. Cement ADC and stocks per capita.

uninterrupted increase with signs of acceleration in the later part of the development curve.

(b) Cement

Industrialised countries

A change in consumption dynamics is observed for the same $12,000 GDP/capita threshold at a level of about 0.4-0.7 t per capita (Fig. 4). The USA is the only country to continue to increase its per capita consumption beyond this income level although at a slow rate. This phenomenon took place whilst the estimated levels remained below those of other countries (Germany and Japan) along much of the development curve. Consumption saturation in Japan at high per capita values continues to increase the stocks significantly, slowing down only in the latter part of the country's development.

Overall, the saturation of per capita stocks in industrialised countries is less visible for cement than for steel, with clear indications of plateauing over a longer development phase for the UK and Germany and only some incipient signs for the US and Japan.

China

China's cement per capita consumption dwarfs the levels determined in the industrialised countries. Whilst consumption stabilisation is observed, it is questionable whether the current 2.5t/capita consumption level will be maintained for a longer period as current per capita stocks are already comparable to those in industrialised countries at their current development stage. The determined values are higher than those of UK and US, and slightly lower than those of Germany and Japan.

(c) Aluminium

Industrialised countries

Saturation in per capita consumption for aluminium starts at the $17,000 income threshold in the case of the US (Fig. 5). Other industrialised countries face a dynamic change beyond the $20,000 threshold when the apparent consumption continues to increase but at a slower rate. There are indications for consumption saturation at levels of 20–25 kg per capita. Altogether one has to consider the wide range of aluminium applications in medium to high-income economies, e.g. for packaging. Except for the USA, where per capita stocks stabilise after the $20,000 GDP/capita level, stocks in other industrialised countries do not indicate any sign of saturation as yet.

China

China's aluminium consumption outpaces the per capita consumption and stocks of other countries, indicating a lower use efficiency than other metals. Also, consequent to the high ADC levels, aluminium stocks are increasing at a somewhat faster rate than the industrialised countries. More explanations are provided in the discussion section.

(d) Copper

Industrialised countries

The per capita copper consumption in the selected industrialised countries appears to have experienced variations during the $15,000-$20,000 income range. From then on, copper consumption stagnated at a level of about 10 kg per capita or even started to decline. As the most developed economy, the USA faces similar dynamics for copper as for aluminium – a fluctuating consumption per capita around a central value beyond the $17,000 income level and a steady growth of per capita stocks with hints of saturation toward the end of the development curve. Germany appears to have had a copper-intensive period during certain development stages, perhaps as a result of the economic recovery after WWII; this deserves a further investigation (Fig. 6).

China

The trend of per capita copper consumption in China is similar to those industrialised countries, which indicates copper is somewhat different from the experience of aluminium. For stocks, the per capita values in China are lower than those in the other economies.

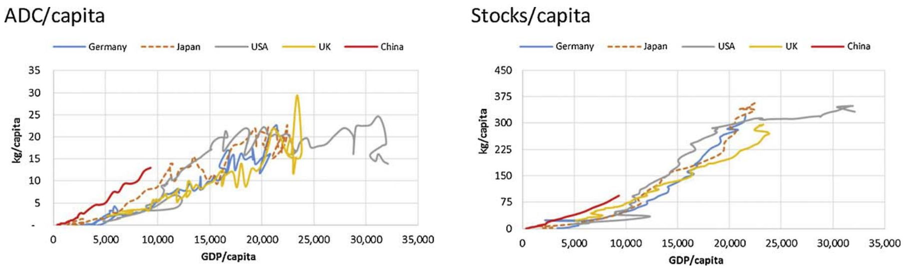
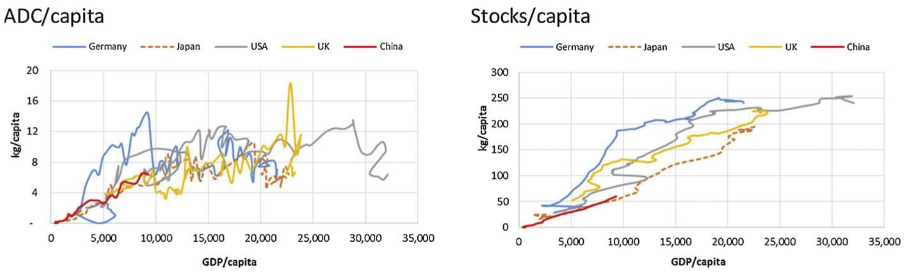


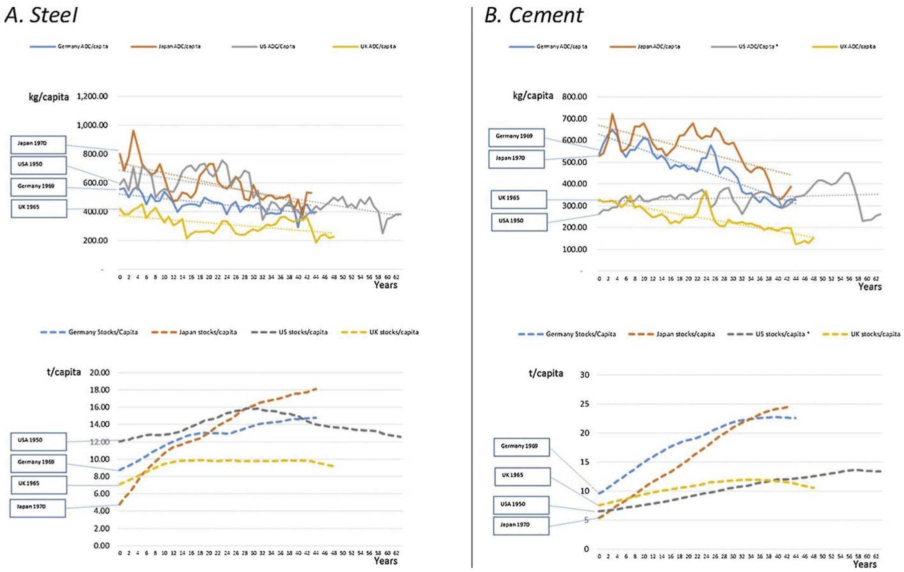
Fig. 5. Aluminium ADC and stocks per capita.



ADC/capita

Stocks/capita

Fig. 6. Copper ADC and stocks per capita.



A. Steel

B. Cement

Fig. 7. Historical evolution of ADC and stocks – steel and cement.

*cement: although the US does not show signs of ADC saturation, the time series have the same start year as that for steel for comparative reasons.

Source: own calculations

4.2. Time lags between ADC and stocks saturation

Fig. 7 illustrates a time series view on the evolution of ADC and stocks for two materials, steel and cement, with the base year marking the start of ADC saturation. Whilst ADC/capita appears to have peaked for the two materials, in the 1950s for the US and 1970s for the other industrialised countries, stocks continue to grow even forty years later in some cases (Japan and Germany for steel, and Japan and the US for cement). Nevertheless, per capita stock saturation does occur in several countries, leading to the following insights: a) saturation of stocks is possible when one country becomes wealthier; b) this informs material consumption outlooks with expectations of continued declines in per capita ADC from current levels.

Therefore, the consumption dimension suggests an earlier and a more pronounced saturation stage in industrialised countries. However, it does not reveal the broader picture of an increasing societal reliance on materials. An important finding of our analysis suggests that there is a considerable delay between the saturation of consumption and that of stocks. For materials where stock saturation can be captured, the time lag involved can last several decades. For instance, the USA takes around 30 years to begin saturating steel stocks and 40 years for cement. Nevertheless, such a lag in stock saturation is dependent upon the income growth rate, product group lifetime, evolution of consumption structure, and the speed of ADC decline.

5. Discussion

Our general findings confirm a remarkable variety across developed countries using steel, cement, aluminium and copper, and the build-up of stocks at different rates, probably due to their very specific national circumstances such as standards for buildings and other products, institutions and policies, and growth dynamics in general (see Section 2). In this section, more perspectives will be discussed so that valuable policy insights can be obtained.

5.1. Saturation overview for industrialised countries

The results of this analysis suggest an overall material use reduction in the industrialised countries (see also Fig. 2). The dynamics across the considered time horizon in this group of economies includes three stages:

- A growth stage of demand and stocks over both per capita and GDP dimensions. Regions accumulating wealth allocate an important share of their GDP toward infrastructure build-up − early for the US, followed by the UK and Germany prior to the 1970s, and Japan − with a delay of one decade. These material use dynamics confirm the existence of a “1970s syndrome” as described by Wiedenhofer et al. (2013) for developed countries, while adding a differentiation for the USA, in line with the growth theories referred to above (Section 2). Again, a database beginning in 1990 appears inappropriate for analysis of long-term growth patterns, and even a start year of 1970 requires corrections toward earlier years.
- A “maturing” stage of stable demand measured in ADC occurred when a shift toward diversified economic growth took place (1970–1980s). During this stage wealth growth rates were less pronounced. However, material stocks were still accumulating, as suggested by the stocks/capita indicator. Such a finding confirms the need for infrastructure and capital stock maintenance, and the different dynamics on the consumption side, such as more spacious housing patterns.
- A saturation stage where material demand is declining toward a steady-state level that allows for a replacement of the infrastructure reaching the end of its lifetime which is suggested by the constant

> per capita in-use stocks. At this stage a relative decoupling of economic growth from infrastructure build-up can be observed through the demand/GDP and stocks/GDP indicators, accompanied by a selective absolute decoupling of demand from economic growth (apparent for steel in Japan and the US; cement in UK, Germany, Japan; Copper in Germany since the 60s, US since the 70s, Japan since the 90s). Such an absolute decoupling is relevant for global environmental change as it suggests lower levels of resource consumption for future worldwide pathways than often expected.

However, these trends are neither linear nor give evidences to an ‘inverted U-curve’ as the saturation stage is rather flat. Plus, a general saturation covering all four materials cannot be confirmed. In reference to the analysis framework outlined in Section 3, the per capita ADC and stocks indicators suggest that the saturation phase has been reached for a subset of materials (cement, steel and copper) and not for all the industrialised countries. Particularly, per capita stocks in Japan continue to increase across all four types of material. Referring back to Fig. 2 on the ‘stylised apparent consumption and stocks of materials along the development curve’ we find solid evidences for steel in the USA, but not for other materials and other countries. As expressed above, variety is a dominant feature. While we acknowledge merits of such stylised figure, one should be cautious to expect a simple application in reality. As stocks seem to have reached saturation rather recently, further studies should be conducted in this area in future years.

For steel and cement, there is a factor of two or three difference between the lowest and highest country values across the two considered indicators (Table 4). These differences reflect the heterogeneity regarding infrastructure intensity, consumption patterns and technological choices among developed countries. It is interesting to note that the two ‘follower’ countries, Germany and Japan, have higher steel consumption compared to the UK and USA, whose industrialisation took place in earlier decades.

Interestingly, the UK have maintained steel stock/capita levels at a constant level for much of its development curve − despite the absolute increasing stocks, the growing population acts as a countering effect here. Early industrialisation in the UK may be a factor leading to such a rapid stock saturation. A significant drop in recent ADC/capita levels in Japan may indicate that a similar stocks/capita saturation may occur in the near future. The high ADC and stock levels in Japan, USA and Germany can be explained by the significant scale of their steel industries which may have knock-on effects on domestic demand and steel consumption intensity. Another significant factor may be the scale of manufacturing sectors which translate into significant capital stock requirements.

The per capita values obtained for in-use stocks in industrialised countries are consistent with other relevant calculations. The steel estimates reviewed in Pauliuk et al. (2013) indicate the same spread of stock values between high-use (Japan) and low-use (UK) countries with an 8–14t/capita range circa 2005. The levels obtained for copper in this article are in the middle of the 140–300 kg/capita range from UNEP (2010) whereas for aluminium the obtained results are closer to the lower end of the reported estimates − 350–500 kg/capita in UNEP (2010) compared to 296–361 kg/capita in this study. For cement in 2008, Müller et al. (2013) identified a 13.7-25.2 t/capita span for these countries. Similarly, stocks per capita in Japan and Germany are double those in the UK and the USA. Lifetime assumptions are indeed crucial, as the sensitivity analysis for steel presented in our supplement indicates.

Due to data limitations, our stock levels do not include losses which occurred during WWII. Nevertheless, any changes in stocks during 1939–1945 did not have a significant impact over the saturation trends observed; a simulations does not show a significant influence over the shape of the stock curves nor on the saturation income levels even with an extreme assumption of all stock being destructed during WWII. This low influence is explained by the largest part of stock accumulation occuring since the 1950s.

It is noteworthy that per capita cement consumption is lower than that of steel in all the industrialised countries; an observation underlining the extraordinary amount of cement consumed in China, which is roughly five times higher than the levels in industrialised countries. These steel levels can be attributed to the higher versatility of this material which has implications over the speed of stock replenishment − cement is locked in for many years in construction, whereas steel is consumed in more applications and stocks for equipment, and transportation and consumer goods need to be replenished more frequently. Also, the greater lag for cement between the start of ADC/capita decline and signs of stocks/capita saturation is a consequence of the longer lifetime of cement product groups. Cement is mainly an input of the construction sector and hence stocks continue to accumulate.

Interestingly, the gap in consumption and stocks within these four industrialised countries appears to be lower for aluminium and copper than those for steel and cement. This may be explained by the embedding of these materials in products that are more intensely traded internationally, thus lowering the impact of disparities determined by locally specified applications e.g. construction.

These trend differences between the two material groups also reflect the limitations of the approach taken in this analysis. New applications of one material (either of those included in this article or others outside i.e. plastics) could lead to a substitution effect over the other. For instance, the increased aluminium use in transportation has led to a lower steel intensity in this sector. Thus, the relative sizes of material consumption could give some further insights into how much material use could grow through substitution. Fig. 8 shows the relative intensity of aluminium use to steel for transport. The disparities between industrialised regions indicate an important growth potential in these regions and even a higher potential for China. Nevertheless, assessing the extent to which aluminium could replace steel requires more application-specific studies − see EAA (2013) for instance.

The findings also suggest a division between two groups of materials, one being essential to infrastructure build-up (cement and steel) and the other being specific to more advanced applications (aluminium and copper). For the first group, a saturation level for consumption is observed around the $12,000 GDP/capita threshold followed by a stagnation or even a decline in ADC per capita thereafter. For the second, changes in dynamics of per capita ADC are visible only past the

Table 4
ADC and stocks per capita values in the industrialised countries and China.

Material	Consumption			Stocks		
	ADC/capita saturation (kg)	2013 values (kg)		Stocks/capita saturation	2013 values	
		Industrial.	China		Industrial.	China
Steel	400–850	227–530	543	9.8 t (UK), 15.9 t (US)	9.2–18.1 t	5.3t
Cement	350–720	150–390	1770	11.9 t (UK), 22.1 t (DE)	10.6–24.6 t	18.3t
Aluminium	25 (USA)	13.9–21.5	13	n/a	296–361 kg	93.6 kg
Copper	10.5(JP), 13.5(USA)	6.4–7.1	6.4	260 kg (DE)	194–241 kg	60.2 kg

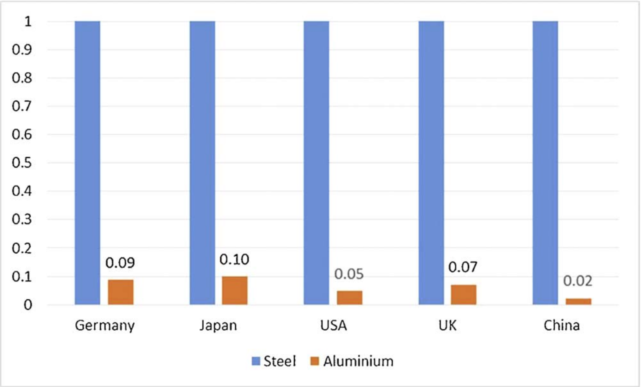


Fig. 8. Aluminium to steel relative intensity in the transport sector in 2012.
Source: own calculation from sectoral demand values

$17,000 GDP, indicating that the use of these materials becomes more intense in medium- to high- income economies.

The single-material view adopted in this article is useful in highlighting a tendency toward a saturation effect in industrialised countries and should be treated as complementary to broader metrics, such as DMC, which capture the dynamics of materials organised in functional groups. Furthermore, the RME could be used to reveal the impacts of adopting more advanced materials which are employed in lower amounts but have potentially higher environmental implications.

5.2. *Implications for China*

As the high-income countries seem to have reached saturation in the per capita consumption for three out of the four materials starting in the 1950s for the US and in the 1970s for UK, Germany, and Japan, it is interesting to see that China is now close to similar values (Table 4). The Chinese economy is unlikely to continue the same growth patterns in the use of these commodities. Following pathways of other developed countries and considering the projected stagnation or even population reduction it is possible future consumption of steel, cement and copper will be stable and may even decline in absolute terms. Our evidence is consistent with the analysis by Yin and Chen (2013) for steel in China, although it contradicts Hatfield-Dodds et al. (2017: 408) which suggests a strong increase in resource use by 2050. The consumption decline is even more likely with ongoing efforts toward a circular economy in China (McDowall et al., 2017), which will enhance process innovation and resource efficiency in manufacturing in general, recycling and the use of secondary materials (see Haas et al. (2015) for an assessment of the current status of a circular economy), as well as the development of new goods and services that should require fewer primary materials.

China's per capita ADC and stocks for steel and copper resembles much the dynamics of those industrialised countries once the development angle is adopted. Here we employ a consumption-based view, and therefore these similarities rule out most of the demand for materials related to exports. As such, China's current role as the world‘s largest manufacturer is reflected in these indicators only by the capital stock required for production processes and not by the embedded materials in exported goods.

The industrialised country to which China resembles most for at least a subset of materials is Japan. Similarities between the two economies for steel, copper and aluminium could be explained by the late industrialisation in Japan as opposed to the other countries in this study. Therefore, both countries are characterised by their high economic growths for the better part of their development relying heavily on infrastructure and capital stock build-up.

At the same time, Chinese cement consumption/capita has expanded far quicker than that of any other countries. This evolution may be attributed to the impressive number of infrastructure projects and the local specification of the construction sector. The high consumption levels from an early stage of development have determined current stocks/capita to be comparable to those currently determined in the industrialised countries. Nevertheless, more insights into how cement is being consumed in China are required in order to assess whether consumption/capita is to be sustained at current levels or whether a decline is imminent.

The aluminium trends reflect a more intense use. This suggests that China is leveraging the technological options which are increasingly reliant on aluminium (notably in construction and transportation) and which were not available for industrialised countries at this stage of development. Chinese aluminium ADC/capita is already comparable to those in high-income economies. However, stocks are three times lower, indicating that for some time high consumption levels are likely to be maintained in order for stocks to continue to accumulate. A further complicating factor is that industrialised countries do not show signs of stock saturation for aluminium, hence these cannot, at least for now, provide a reference point for the levels at which consumption and saturation may peak.

Another key finding on growth patterns and resource use is that both per capita consumption and demand per GDP are on similar trajectories for the developed countries, with a clear saturation indication beginning in the 1970s. However, this is not the case in China, where any such saturation seems to occur for demand but not yet for the intensity per GDP. Thus the Chinese economy may have a material efficiency gap compared to those developed countries; similar to what Flachenecker and Rentschler (2015) proposed for the EBRD member countries. Such a gap can be seen as a driver for the circular efforts of the Chinese economy.

6. Conclusions

Several developed countries have achieved a saturation stage in consuming the key materials assessed in this study; we determine such saturation values for Apparent Domestic Consumption at $12,000 GDP/capita for steel at a level of 400–850 kg/capita, and for cement at a level of 350–720 kg/capita. For copper, the saturation level starts a bit later, at around $20,000 GDP/capita and consumption levels of 10.5–13.5 kg/capita, reflecting the different applications in a more affluent society. Overall, the saturation evidence is strong for the per capita consumption of steel, copper and cement in the four industrialised countries (US, UK, Japan, Germany), and it is somewhat weaker for aluminium. However, with regard to China, we see early indications of a saturation effect in demand for steel and copper, and the large consumption of cement would also be expected in favour of stocks per capita coming close to a saturation effect.

Our underlying data also suggests that, for the industrialised countries investigated in our study, the build-up of stocks seems to saturate too. Depending on the product lifetimes and patterns of stock replenishment, there seems to be a delay of thirty years or more compared to the demand saturation. The implications for future projections of material consumption are probably relevant beyond the scope of our article: China is unlikely to require the same continued increase in resources in the future, and neither are the other industrialised countries investigated in our study. An extrapolation of trends taken from the last ten or twenty years should *not* be regarded as a guiding rule for future market trends and investments. Without expanding the scope of our article too far, we believe there is relevant evidence on resources being used in emerging economies in general and we suggest that such a saturation effect is likely to stabilise demand in the future. Future research should investigate the decoupling trend of GDP from resource consumption through drivers of such a saturation effect, *as well as* through resource efficiency and circular economy efforts.

Our study confirms the slightly different pathways for all four industrialised countries in the past, and variety is very likely to matter for the future too. Accounting for per-capita income might thus be more appropriate than time series based on years. However, for the use of steel, copper and cement in China, it is fairly rational for the country to expect a stable demand. Closing the efficiency gap that appears to exist between China and the industrialised countries will further contribute to such a lower demand, perhaps even a decline in absolute terms. The implications from China may provide more policy insights to other emerging economies so that these countries can find feasible pathways to achieve decoupling development.

Future research on global environmental change and policies, including the ones facilitated through UNEP's International Resource Panel, the Asian Infrastructure Investment Bank or the emerging G7 Alliance for International Resource Efficiency, should establish alternative baseline scenarios which include such a saturation effect − with clear relevance for the SDGs and their 2030 timeframe for delivery. The implications of our findings for the 2015 Paris Agreement on climate change are significant as well as they relate to energy-intensive processes in emerging economies, suggesting potential lower CO_2 emissions from such processes in the future compared to current business-as-usual scenarios. However, caution must be taken as the development of these materials in emerging regions in the future will play an important role in the trajectory of global industrial GHG emissions.

We conclude that the early findings of resource economics on the intensity of use conducted in the 1970s and 1980s can now be enriched through more sophisticated indicators coming from the MFA debate and indeed more data available through input-output datasets. Our approach considers a time period longer than available MFA data and applying this method to single commodities and a few core indicators such as ADC seems useful for the decoupling debate and should be integrated into modelling efforts. The current MFA databases should be enlarged to include decades before 1970 for key indicators, and include hidden flows associated with raw material extraction to the extent possible.

Another policy implication derived from this interaction between materials is that the analysed ADC indicator may complement other MFA indicators such as the Domestic Material Consumption (DMC) or the Material Footprint (MF). ADC could, therefore, help raise more appropriate policies on mitigating material intensity especially for industrial sectors and relevant supply chains.

Finally, this study raises the need for further comprehensive studies on the issue of material-specific saturation. Innovation and technical changes will continue to enable the industry to use materials in new product areas − thus a comprehensive perspective that captures substitution effects and systemic innovation is required. In general, our findings encourage more economic studies on decoupling, MFA, and a saturation effect from an international perspective.

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References

Adriaanse, A., et al., 1997. The Material Basis of Industrial Economies. World Resources Institute, Washington D.C.

Allwood, J.M., 2013. Transitions to material efficiency in the UK steel economy. Phil. Trans.. Series A, Math., Phys., Eng. Sci. 371 (1986), 20110577.

Auty, R., 1985. Materials intensity of GDP: Research issues on the measurement and explanation of change. Resour. Policy 11 (4), 275–283.

Ayres, R.U., 1989. Industrial metabolism. Technol. Environ. 23–49.

Bolt, J., van Zanden, J.L., 2014. The Maddison Project: collaborative research on historical national accounts. Econ. Hist. Rev. 67 (3), 627–651.

Bringezu, S., Bleischwitz, R., 2009. Sustainable Resource Management—Global Trends, Visions and Policies. Greenleaf Publishing, Sheffield, U.K.

Bringezu, S., et al., 2004. International comparison of resource use and its relation to economic growth The development of total material requirement, direct material inputs and hidden flows and the structure of TMR. Ecol. Econ. 51 (1-2), 97–124.

Cleveland, C.J., Ruth, M., 1998. Indicators of dematerialization and the materials intensity of use. J. Ind. Ecol. 2 (3), 15–50. http://dx.doi.org/10.1162/jiec.1998.2.3.15.

Crowson, P., 2007. The copper industry 1945–1975. Resour. Policy 32 (1-2), 1–18.

EAA, 2013. Aluminium in Cars − Unlocking the Light-weighting Potential, Eurostat (2001): Economy-wide Material Flow Accounts and Derived Indicators − A Methodological Guide. Methods and Nomenclature Series, Luxembourg.

Eurostat, 2001. Economy-wide Material Flow Accounts and Derived Indicators: A Methodological Guide, Methods and Nomenclature series. European Communities, Luxembourg.

Fischer-Kowalski, M., Haberl, H., 2007. Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar Publishing.

Flachenecker, F., Rentschler, J., 2015. Investments in resource efficiency – costs and benefits, investment barriers and intervention measures. In: A Report Prepared for the European Bank for Reconstruction and Development (EBRD). London : University College London.

Giljum, S., et al., 2014. Global patterns of material flows and their socio-Economic and environmental implications: a MFA study on all countries world-Wide from 1980 to 2009. Resources 3, 319–339.

Gordon, R.B., Bertram, M., Graedel, T.E., 2006. Metal stocks and sustainability. PNAS 103 (5), 1209–1214.

Graedel, T.E., et al., 2012. Methodology of metal criticality determination. Environ. Sci. Technol. 46 (2), 1063–1070.

Haas, W., et al., 2015. How circular is the global economy?: an assessment of material flows, waste production, and recycling in the european union and the world in 2005. J. Ind. Ecol. 19 (5), 765–777.

Hatfield-Dodds, S., et al., 2017. Assessing global resource use and greenhouse emissions to 2050: with ambitious resource efficiency and climate mitigation policies. J. Clean. Prod. 144, 403–414.

Hertwich, E., et al., 2010. Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials to the International Panel for Sustainable Resource Management. UNEP International Resource Panel, Nairobi.

Hoekstra, A., Wiedmann, T., 2014. Humanity's unsustainable environmental footprint. Science 344 (June (6188)).

Müller, D.B., et al., 2013. Carbon emissions of infrastructure development. Environ. Sci. Technol. 47 (20), 11739–11746. http://dx.doi.org/10.1021/es402618m.

Malenbaum, W., 1978. World Demand for Raw Materials in 1985 and 2000. National Science Foundation 75–23687, New York: McGraw Hill.

Matthews, E., Amann, C., Bringezu, S., 2000. The Weight of Nations: Material Outflows from Industrial Economies, 2000. World Resources Institute, Washington D.C.

McDowall, W., et al., 2017. Circular economy policies in China and europe. J. Ind. Ecol http://dx.doi.org/10.1111/jiec.12597.

Meadows, D.H., Goldsmith, E.I., Meadow, P., 1972. The Limits to Growth. Earth Island Limited, London.

Mueller, D., Wang, T., Duval, B., 2011. Patterns of iron use in societal evolution. Environ. Sci. Technol. 45, 182–188.

Nansai, K., et al., 2015. Global mining risk footprint of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum in Japan. Environ. Sci. Technol. 49 (4), 2022–2031.

OECD, 2008. Measuring Material Flows and Resource Productivity. OECD Publishing, Paris.

OECD, 2015. Material Resources, Productivity and the Environment, OECD Green Growth Studies. OECD, Publishing, Paris. http://dx.doi.org/10.1787/9789264190504-en.

Pauliuk, S., Wang, T., Müller, D.B., 2013. Steel all over the world: estimating in-use stocks of iron for 200 countries. Resour. Conserv. Recycl. 71, 22–30.

Perez, C., 2010. Technological revolutions and techno-economic paradigms. Camb. J. Econ. 34 (1), 185–202.

Rauch, J.N., 2009. Global mapping of Al, Cu, Fe, and Zn in-use stocks and in-ground resources. PNAS 106 (45), 18920–18925.

Rostow, W., 1960. The Stages of Economic Growth: A Non-Communist Manifesto. Cambridge University Press.

Rostow, W., 1978. The World Economy; History and Prospect. University of Texas press, Austin and London.

Ruhrberg, M., 2006. Assessing the recycling efficiency of copper from end-of-life products in Western Europe Resources. Conserv. Recycl. 48 (2), 141–165.

Saurat, M., Ritthoff, M., 2013. Calculating MIPS 2.0. Resources 2 (4), 581–607.

Schandl, H., Hatfield-Dodds, S., et al., 2016. Decoupling global environmental pressure and economic growth:scenarios for energy use, materials use and carbon emissions. J. Cleaner Prod. 132, 45–56.

Schandl, H., West, J., 2010. Resource use and resource efficiency in the Asia-Pacific region. Global Environ. Change 20 (4), 636–647.

Schmidt-Bleek, F., 2009. The Earth: Natural Resources and Human Intervention. HausPublishing Limited, London.

Sieferle, R.-P., 2001. The Subterranean Forest: Energy Systems and the Industrial Revolution. Translated from the German by Michael P. Osman. The White Horse Press, Cambridge.

Steger, S., Bleischwitz, R., 2011. Drivers for the use of materials across countries. J. Clean.

Prod. 19 (8), 816–826.
Tilton, J.E., Guzmán, J., 2016. Mineral Economics and Policy.
Tilton, J.E., 1985. Atrophy in metal demand. Earth Mineral Sci. 54 (2), 13–18.
Tukker, A., et al., 2014. The Global Resource Footprint of Nations.
UNEP, 2010. Metal stocks in society. International Panel for Sustainable Resource Management.
UNEP, 2011. Decoupling Natural Resource Use and Environmental Impacts from Economic Growth. International Resource Panel, Nairobi.
UNEP, 2014. Decoupling 2: technologies, opportunities and policy options. A Report of the Working Group on Decoupling to the International Resource Panel.
UNEP, 2017. Resource Efficiency: Potential and Economic Implications. A Report of the International Resource Panel. (Ekins, P., Hughes, N. et al.).
USGS, 2015. Copper statistics. In: Kelly, T.D., Matos, G.R., comps (Eds.), Historical Statistics for Mineral and Material Commodities in the United States: U.S. Geological Survey Data Series 140, (Available at: http://pubs.usgs.gov/ds/2005/140/).
USGS, 1928–2013. Mineral Yearbook. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/myb/.
Wårell, L., 2014. Trends and developments in long-term steel demand − The intensity-of-use hypothesis revisited. Resour. Policy 39, 134–143.
von Weizsäcker, E.U., de Larderel, J., Hargroves, K., Hudson, C., Smith, M., Rodrigues, Weizsäcker, E., Lovins, L.H., 1998. Factor Four: Doubling Wealth, Halving Resource Use. Earthscan, London and New York.
West, J., et al., 2014. Patterns of change in material use and material efficiency in the successor states of the former Soviet Union. Ecol. Econ. 105, 211–219.
Wiedenhofer, D., et al., 2013. Is there a 1970 syndrome? Analyzing structural breaks in the metabolism of industrial economies. Energy Procedia 40, 182–191.
Wiedmann, T.O., et al., 2015. The material footprint of nations. PNAS 112 (20), 6271–6276. http://dx.doi.org/10.1073/pnas.1220362110.
Wrigley, E.A., 2013. Energy and the english industrial revolution. Phil. Trans.. Series A, Math., Phys., Eng. Sci. 371 (1986), 20110568.
Yin, X., Chen, W., 2013. Trends and development of steel demand in China: a bottom-up analysis. Resour. Policy 38 (4), 407–415 (Available at: http://www.sciencedirect.com/science/article/pii/S0301420713000482).