Saturation and Growth Over Time: When Demand for Minerals Peaks*

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Prisme N°34

November 2016

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* This text acknowledges funding through the SINCERE project (funded through ESRC ES/L015838/1 and research councils from China, France, Germany and the Netherlands), as well as through the EU-funded POLFREE project (Grant Agreement no. 308371). The authors are grateful for discussions with Arkaitz Usubiaga, Florian Flachenecker, Jun Rentschler and Stijn van Ewijk. The text also greatly benefitted from discussions at the Cournot Centre seminar in Paris on 26 May 2016 and comments made by Aurélien Saussay, as well as from discussions at the SINCERE project meeting in Paris on 12 October 2016.

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Summary

Decoupling is at the core of the contemporary debate about economic growth and natural resources: will the delinking of economic growth and resource use happen at all given the dynamics in developing countries? Will it occur through an invisible hand of progress and improvements in resource efficiency? What lessons can be learned from a long-term international perspective?

This *Prisme* combines the analytical strands of resource economics and material flow analysis to answer those questions. It looks at 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 for a group of four industrialized countries (Germany, Japan, the UK and the USA) together with China, as the most pre-eminent emerging economy. In analysing a new set of per capita and gross domestic product indicators, our research confirms the relevance of a saturation effect with a number of specifications. We cautiously expect decoupling processes to occur in China over the next few decades, and most likely in other developing countries as well. Forecasts and modelling efforts should take such saturation into account.

Contents

1. Introduction

The turmoil on Chinese stock markets in early January 2016 is one recent illustration of fundamental uncertainties in growth expectations for emerging economies and the world economy as a whole. Important causes of the drag on growth rates involve commodities and the consumption of natural resources, raising the following questions: Will tomorrow's economy accelerate the use of resources? Will demand start to decouple from gross domestic product (GDP) in a more visible manner? Will the Chinese shift to a more service- and consumption-based economy accompany more resource use, or will the growth in the consumption of natural resources be more moderate? Could an absolute reduction occur? What could be the impact of circular economy strategies on the overall demand for natural resources and growth?

This discussion is often referred to as "decoupling the use of resources from GDP". The United Nations (UN) International Resource Panel calls it the "imperative of modern environmental policy" (UNEP 2016: 14). The contemporary debate, nevertheless, does not appear to pay enough attention to growth patterns of economies and their implications for natural resource use. A key issue appears to be the limitations of the current database in dealing with development trends. We propose looking at longer time series, making it possible to obtain more robust conclusions on such patterns and enabling better foresight analysis. Analysis of such development patterns will also contribute to the recently launched UN Sustainable Development Goals (SDG), in particular to SDG 12.2, pledging to achieve the sustainable management and efficient use of natural resources by the year 2030.

Our text analyses the interface between the following debates.

- The first is a broad and lively debate about decoupling that looks at (a) the decoupling of GDP from environmental impacts ("Environmental Kuznets Curve"[1]) and (b) the decoupling of GDP from resource use. Indicators are used to look at the aggregated use of natural resources

[1] The Environmental Kuznets Curve (EKC) illustrates a hypothesis on the relationship between development and environmental quality. The EKC is an inverted U curve and suggests that environmental quality decreases with development up to a given income level and then begins to improve.

based on Material Flow Analysis[2] (MFA) usually beginning with the year 1990, in other words, a relatively limited time period (see for example: UNEP 2011, 2016; Wiedmann et al. 2015).

- The second is a debate focused on the historic metabolism[3] of societies beginning with ancient agrarian civilizations towards a contemporary global perspective based on estimated data on materials and energy and a few other resources from 1750 to 2000 (see, for example, Wiedenhofer et al. 2013). This time period may be too long, however, for drawing conclusions on development patterns related to infrastructure investments and build-up of capital stock.
- The third is the debate in resource economics about single commodities and their consumption patterns across time and space (see, for example, Wårell 2014), often referred to as the "intensity-of-use hypothesis" as put forward by Wilfred Malenbaum (1978). This debate leaves aside, however, decoupling issues and build-up stocks.

We have identified a research gap between the different methods and time series, making insights on development trends and advances towards SDG 12 for the year 2030 difficult. Our text intends to address this issue by applying the MFA method to single, natural resources for selected countries in order to determine per capita consumption and saturation[4] dynamics along the development curve, that is, GDP per capita. Our analysis covers the time period of 1900 to 2013 – representing the better part of modern development in industrialized countries – and is used for steel, aluminium, cement and copper in China, the USA, Germany, Japan and the UK. The

[2] Also used in this *prisme*, the MFA is a physical accounting method to determine flows and stocks of materials within a bounded system (e.g. country). It was introduced in the 1990s and is used by the OECD and a number of statistical agencies. See our annex for more information.

[3] Social metabolism refers to the extraction, flows and transformation of materials, as well as their disposal as driven by societies. It is usually measured by material flows analysis and applied over long-term horizons.

[4] We define the saturation effect as a stage of development when the intensity in the per capita use of materials within a region or a country decreases. The causes may be manifold, be it through having established a physical infrastructure in an economy, or substitutions towards less material-intensive technologies, or structural changes between sectors, general technological change or social changes. The literature refers to it also as the "intensity-of-use hypothesis" or "materials Environmental Kuznets Curve".

choice of these materials is justified by the fact that all economies require them in order to develop – steel and cement demand is a function of infrastructure development and urbanization; copper and aluminium are multifunctional materials for housing, energy, mobility and consumer goods. Accordingly, these materials are often included in commodity market analysis.

The underlying questions are:

- Is there a saturation of consumption for materials in those developed countries?
- Is there a time gap in material consumption between developed and emerging countries, given their different stages of wealth?
- What are the development patterns of the build-up stocks?

A hybrid approach that focuses on single commodities combines the strengths of the various approaches but has inherent limitations, as possible substitutions are likely to be overlooked (for example, increased applications of plastics). Furthermore, analysing resource productivity in general requires a feedback with MFA data. The aim of this *Prisme* is thus to address the research gap in development trends by testing the usefulness of a hybrid method and by contributing to the establishment of a comprehensive database and to macroeconomic modelling efforts.

The text is organized as follows. The next section briefly reviews the debate on intensity-of-use, decoupling, and metabolism in the broader context of growth and resources. Section 3 introduces the analytical framework used and key saturation indicators. The subsequent sections present results and discuss findings. The final section draws conclusions towards our research aims, with a cautious outlook on implications for future infrastructure investments in emerging economies. Parts of the methodology (MFA analysis and data treatment) are explained in the Annex.

2. A short review on growth and resources

A series of growth theories emerged beginning in the 1950s. Among those, Walt Rostow (1960) developed a theory with stages of development, according to which economies undergo a series of transformations from early take-off, to industrialization, eventually developing into mature economies where services and consumption are the dominant patterns. Although this proposition was contested by other growth theoreticians, it reappeared in the 1970's debate about limits to growth along with the unprecedented price peaks for energy and other commodities at that time. Rostow himself argued against any evidence of scarcity for raw materials and pointed at innovation, as well as at the decline in the rate of raw-material use in relation to increases in real income in the more advanced industrialized nations (Rostow 1978: 616).

The intensity-of-use hypothesis was developed by Wilfred Malenbaum (1978), and further elaborated by John Tilton (1985) and Richard Auty (1985), all adding empirical evidence for a number of materials across countries and time. The overall findings on whether or not the materials intensity of GDP declines with economic maturity nevertheless remained ambiguous at that time. The basic concept was seen as vaguely defined; the data and measurement efforts had a number of limitations and did not yield unequivocal results; and the underlying drivers remained poorly understood. With emerging input-output data, it was concluded that future research should be based on better and more comprehensive data (Auty, 1985). Looking back now, we see that the debate never took off. Only a couple of contemporary publications exist. Tilton and Guzman (2016) provide an excellent textbook on mineral economics and policy, yet it does not provide analysis on the issues discussed here. Warell (2014) revisits the intensity-of-use hypothesis for steel with data for 61 countries over 42 years, concluding that it is valid for the middle-income group of countries.

In parallel, the broader debate on growth and development has changed significantly since the 1980s, adding human capital, innovation, and new opportunities for developing countries via the so-called endogenous growth theory that developed throughout the 1990s. During those years, raw material prices were heading downwards, and the attention on scarcity issues disappeared. Patterns of economic growth shifted to formerly developing countries such as China. A multi-polar growth world has since emerged with increasing economic ties among developing and middle-income countries (see the recent attempts to formulate a "unified growth theory"; Galor, 2011).

The more recent debate, started in the 2000s, often refers to a "decoupling" of resource use through, for example, the Organisation for Economic Co-operation and Development (OECD) Environmental Strategy (2001) and the Sixth Environment Action Programme of the European Community 2002–2012[5]. It is rooted in concepts such as Factor Four (Weizsäcker, 1997) and Factor 10 (Schmidt-Bleek, 2009)[6] with numerous examples, as well as in the debate about an "Environmental Kuznets Curve" on pollutants and GDP growth. Decoupling of resource use is based on the method of material flow analysis that has emerged since the 1990s (see, for example, Adriaanse et al., 1997; Matthews et al. 2000). The United Nations Environment Programme's (UNEP) International Resource Panel has contributed key documents to the decoupling debate (UNEP 2011; 2016), while much ongoing research looks at countries and regions and at drivers for decoupling (West et al., 2014; Schandl and West, 2010; Bringezu et al., 2004; Steger and Bleischwitz, 2011). In addition, there is a lively debate about indicators for decoupling that analyses system boundaries, international trade and environmental impacts of different decoupling indicators (Hoekstra and Wiedmann, 2014; Wiedmann et al., 2015; Giljum et al., 2014; Tukker et al. 2014; UNEP, 2010; Nansai et al., 2015; Saurat and Ritthoff, 2013). The points to make here are that (a) all this valuable research grapples with MFA data restrictions, and the usual start year is 1990 or later – much later than the take-off of most developed nations; and (b) it hasn't yet explicitly dealt with stages of development or the intensity-of-use hypothesis. Steinberger et al. (2013) arrive at useful conclusions about an autonomous rate of technological progress and a peak income for any dematerialization based on a panel analysis of 39 countries and MFA/DMC[7] data from 1970 onwards. Their time series, however, appears too limited, and the saturation effect is not explicitly referred to.

In contrast, the academic debate about a social or industrial metabolism takes a historic perspective beginning with "hunting and gathering" as well as agrarian "regimes" that were present long before the industrial revolution emerged in the 18th

[5] http://ec.europa.eu/environment/archives/action-programme/intro.htm

[6] "Factor Four" introduced a "doubling wealth, halving resource use" approach. "Factor Ten" refers to similar thoughts but on a broader scale and more long-term. Both have been the subject of popular books written by eminent academics (see Weizsacker et al., 1998 and Angrick et al., 2014).

[7] Domestic Material Consumption; see the Annex for an analysis, also covering the indicator Material Footprint (MF), defined as the global allocation of used raw material extraction to the final demand of an economy.

and 19th centuries (Ayres, 1989; Fischer-Kowalski and Haberl, 2007; Wrigley, 2013; Sieferle, 2001). This research has provided insights into the great transformations, such as the beginning of the use of fossil fuels on a large scale. Wiedenhofer et al. (2013) have characterized the flattening of many resource-related indicators as the "1970s syndrome". This strand of research, however, appears fairly descriptive, driven by statistical analysis and without an explicit debate about intensity-of-use and economic development stages.

Ongoing research provides other interesting features about, for example, the shape of the growth curve, that is, whether decoupling occurs at all, or whether data suggest rather a "re-coupling" (Bringezu and Bleischwitz, 2009: 76f). Others include estimating the anthropogenic stocks in societies (Rauch, 2009; Gordon et al., 2006; Pauliuk et al., 2013), examining the criticality of materials[8] (Graedel et al., 2012), and studying single commodities (Allwood 2013; Crowson 2007; Wårell 2014).

To conclude, the decoupling debate has not sufficiently addressed the relation between resources and growth in industrialized countries for key decades due to MFA data restrictions. Furthermore, the intensity-of-use analysis appears too fragmented and selective to draw general conclusions on decoupling and the SDG 12 towards the year 2030. This text therefore aligns physical data on material flows and stocks with analysis about growth patterns and resource use across economies over time.

3. Saturation analysis framework

We introduce two indicators expressed in relation to GDP per capita: Apparent Domestic Consumption (ADC)[9] per capita and stocks per capita. These metrics are relevant for addressing the dimension of international trade and the built environment.[10] The lack of both, partly due to data gaps, has been a major

[8] The criticality of minerals is defined as a function of two variables: importance of uses and availability.

[9] Apparent Domestic Consumption is similar to Domestic Material Consumption but includes main indirect flows of materials through the international trade of goods.

[10] The built environment describes the material resources contained within the buildings, infrastructures or products of an economy at a specific time. It is a level variable as opposed to material flows (which are rate variables). Similar terms being used are "anthropogenic stocks" or "in-use stocks". See also the Annex for further information.

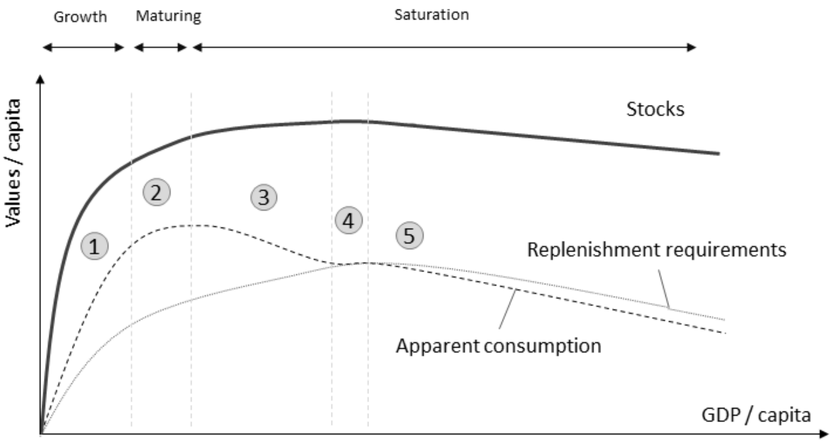
shortcoming in earlier debates. The two indicators are calculated through the MFA method described in the Annex and are used to determine the extent to which industrialized economies have reached material-specific saturation. They also help to assess the trajectory China has taken on its path toward becoming a high-income economy. Once the annual stocks are derived from ADC levels based on the aforementioned methodology, we can then delve into identifying the stage the use of each considered material is at in each country. We propose grouping the dynamics across the economic development curve into the following three stages.

- The first is a "growth" stage in which demand per capita grows at a rapid pace, leading to a pronounced stock accumulation. This is the stage where an important share of the GDP is dedicated towards the build-up of essential infrastructure and capital stock formation.
- The second is a "maturing" stage where ADC per capita starts to flatten. ADC, however, settles at a level that is much higher than the volumes required to replace the end-of-life products. This leads to a further increase in stocks per capita, although at a lower speed compared to the "growth" stage.
- The third is a "saturation" stage in which ADC per capita converges towards levels that allow for stock replenishment, therefore leading in the longer run to stock per capita saturation and even decline.

This sequencing of stages can be made operational using Table 1 below, which gives an indication of how ADC and stocks per capita are moving at each stage. Note that the "saturation" stage can be made up of different dynamics as a region moves further along the development curve (Figure 1). "Saturation" is initiated once there is a sustained decline in ADC per capita. This decline causes ADC to reach a level close to the stock replenishment requirements. At this point, stocks saturate, and there may be a period where both ADC and saturation fluctuate around a central value. This "constant ADC and stock" phase may not last for long. It may not even be visible at all, as other structural factors may influence ADC, such as material-use efficiency gains, triggering a further decline in both metrics.

Table 1: 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)



Source: *own compilation*

Figure 1: Apparent consumption and stocks of materials along the development curve

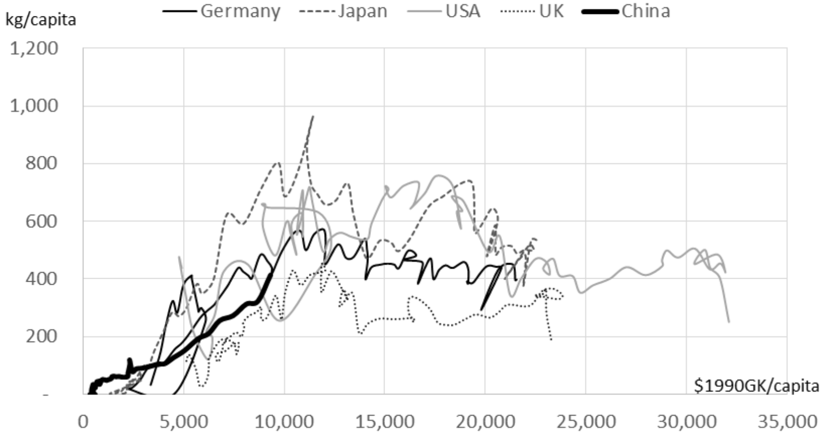
4. Results of our method

4.1 ADC and stocks per capita from a development perspective

We present the results obtained through the application of the single-material MFA method as described in the Annex. The analysis refers to the 1900–2013 time period and covers four materials (steel, cement, aluminium and copper) and five countries (Germany, Japan, the USA and China). To relate material use to economic development, the dynamics of the two key indicators (ADC per capita and stocks per capita) are related to the evolution of GDP per capita in the countries considered.

(a) Steel

i. Steel –ADC/capita



ii. Steel – stocks/capita

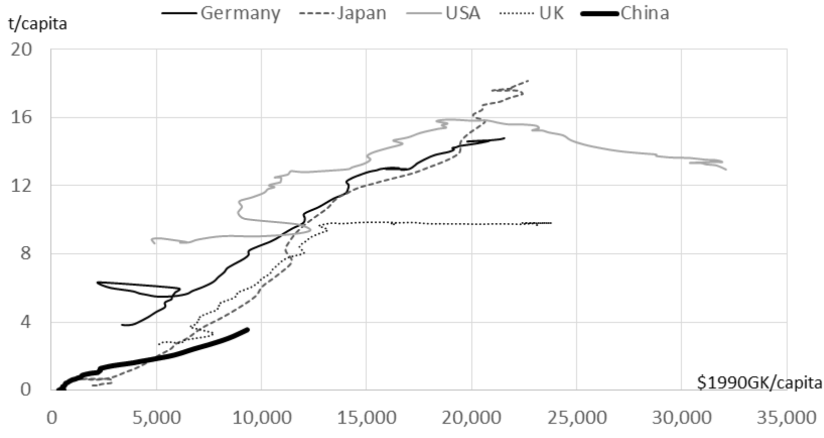


Figure 2 - Steel ADC (i) and stocks per capita (ii)

Industrialized countries

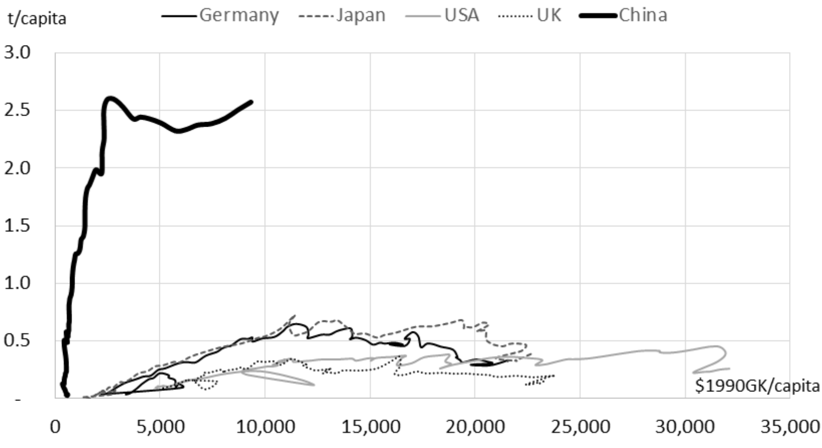
In all countries, steel ADC/capita seems to saturate at a level of 0.5–0.8 tons per capita once a $12,000[11] GDP/capita threshold is passed (Figure 2). Nevertheless, these saturation ADC levels still contribute to a further increase in stocks. The US case suggests that after $16,000, the ADC per capita starts to decline towards levels that determine a decrease in stocks per capita. Germany appears to confirm the same trend with a slowing down of stocks/capita growth after $20,000 GDP/capita.

China

Growth patterns for steel in China are in line with past trends obtained for industrialized countries. ADC per capita levels are increasing towards the saturation levels obtained in the other regions as the country goes beyond the $10,000 GDP/capita level. Stock levels have had an uninterrupted increase with signs of acceleration in the later part of the development curve.

(b) Cement

i. Cement – apparent consumption/capita



[11] All income/capita values are expressed in purchasing power parity (PPP) terms by using 1990 Geary-Khamis US dollars.

ii. Cement – stocks/capita

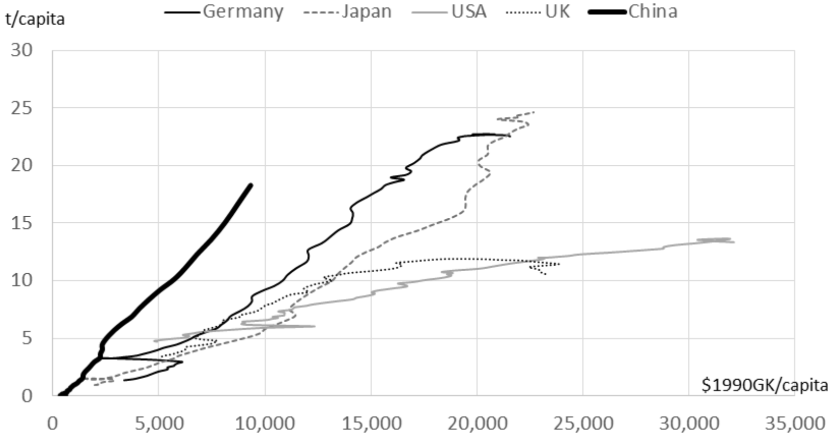


Figure 3 - Cement ADC (i) and stocks per capita (ii)

Industrialized countries

A change in consumption dynamics for cement is observed for the same $12,000 GDP/capita threshold at a level of about 0.4–0.7 tons per capita (Figure 3). The US is the only country to continue to increase its per capita consumption beyond this income level. Although occurring at a slow rate, the estimated levels remain below those of other countries (Germany and Japan) along much of the development curve. Saturation of consumption in Japan at high per capita values continues to increase the stocks significantly, this being slowed down only in the latter part of the country's development.

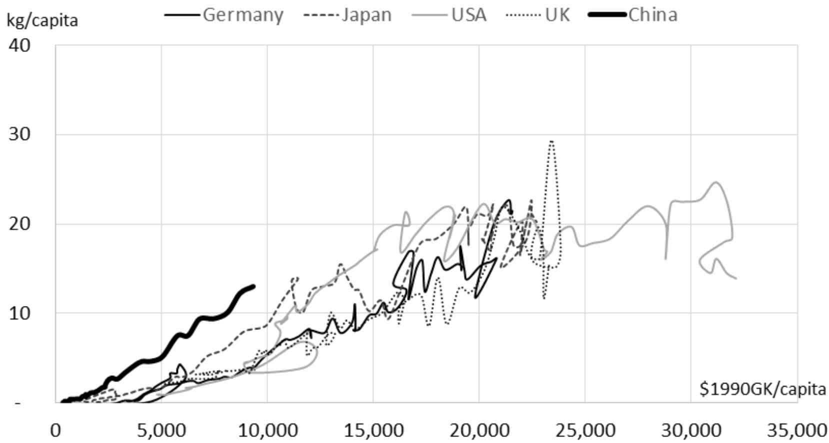
Overall, in industrialized countries, the saturation of stocks per capita is less visible for cement than for steel, with clear indications of plateauing over a longer development phase for the UK and Germany, and only some incipient signs for the US and Japan.

China

Chinese per capita consumption for cement dwarfs the levels determined for industrialized countries. Whilst a stabilization of consumption is observed from about $2,500 GDP/capita, it is questionable whether the current 2.5t/capita consumption level will be maintained for longer as current stocks per capita are already comparable to those in industrialized countries at their current development stage: the determined values are higher than those of the UK and the US and slightly lower than those of Germany and Japan.

(c) Aluminium

i. Aluminium – apparent consumption/capita



ii. Aluminium – stocks/capita

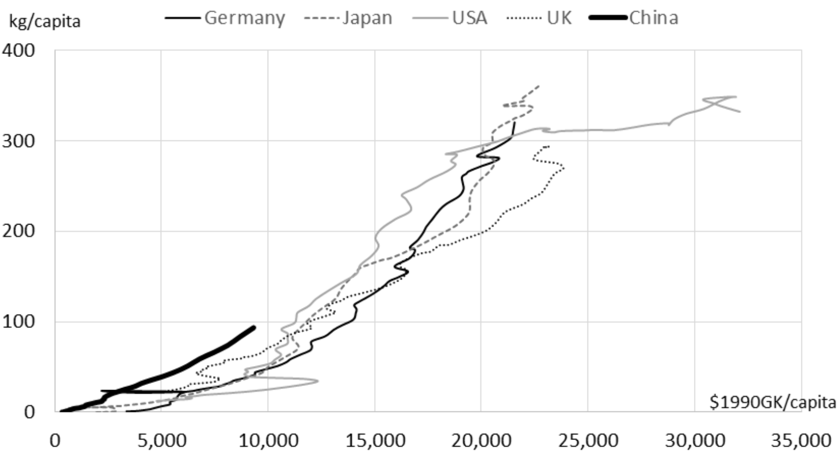


Figure 4 - Aluminium ADC (i) and stocks per capita (ii)

Industrialized countries

Saturation in per capita consumption for aluminium starts to be observed at the $17,000 income threshold in the case of the US. The other industrialized countries face a change in dynamics beyond the $20,000 threshold when the apparent consumption continues to increase, but at a slower pace. The 20–25 kg per capita saturation consumption is much lower than that of steel, thus reflecting the more advanced applications of aluminium, preponderant in medium-to-high-income economies.

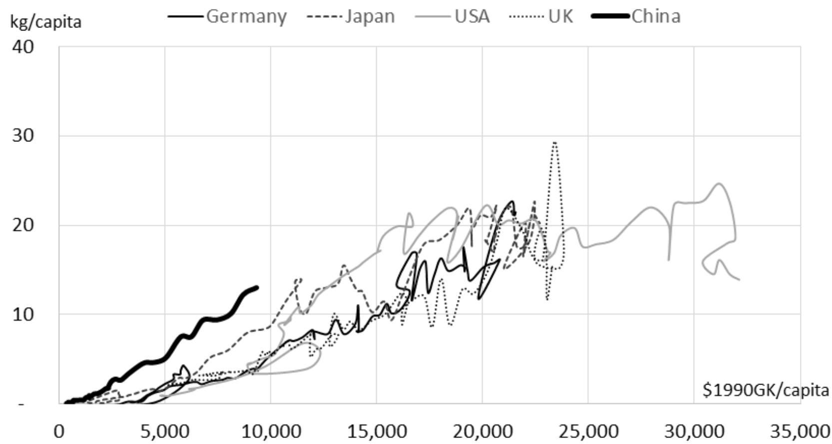
Except for the US, where stocks per capita stabilize after the $20,000 GDP-per-capita level, stocks in the group of industrialized countries do not indicate any sign of saturation.

China

China's use of aluminium outpaces consumption and stocks per capita levels for comparable income levels in the other countries of this study, indicating a lower efficiency of use in contrast to the findings for the other metals. As a consequence of the high ADC levels, stocks are building up at a faster rate than in industrialized countries.

(d) Copper

i. Copper – ADC/capita



ii. Copper – stocks/capita

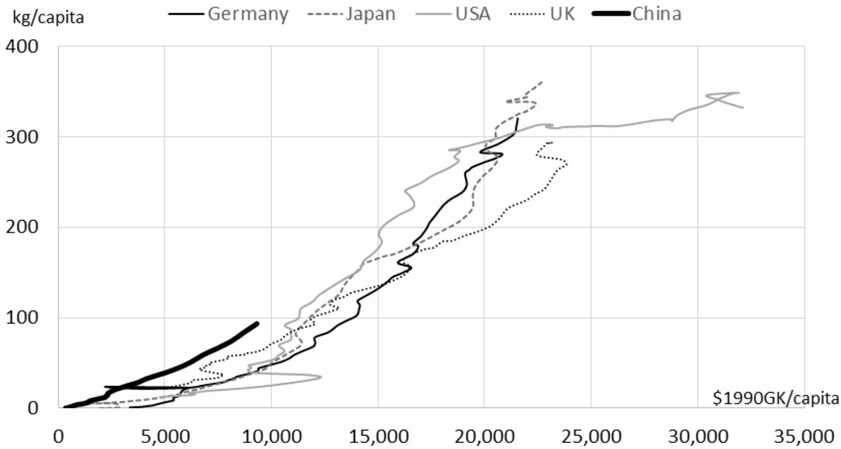


Figure 5: Copper ADC (i) and stocks per capita (ii)

Industrialized countries

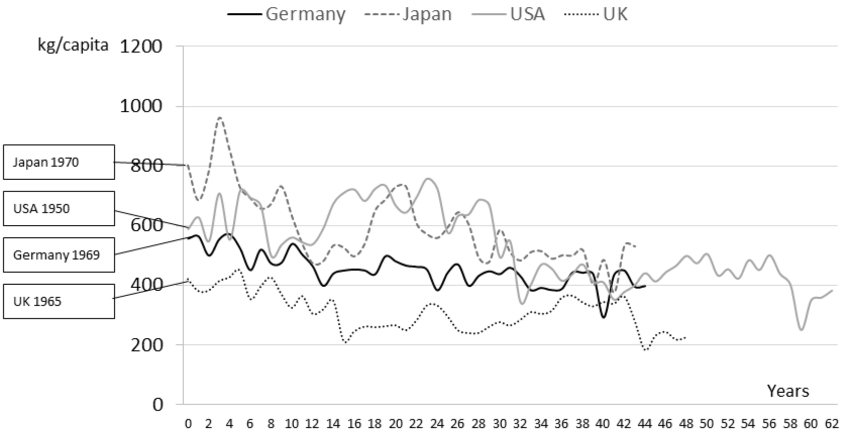
For copper, there seems to be a change in regime of per capita consumption observable in the $15,000–$20,000 income range. Consumption at this point stagnates at a level of about 10kg per capita or even starts to decline. As the most developed economy in the group, the US faces similar dynamics for copper as for aluminium – a fluctuating consumption per capita around a central value beyond the $17,000 income level and a steady growth of stocks per capita with hints of saturation towards the end of the development curve.

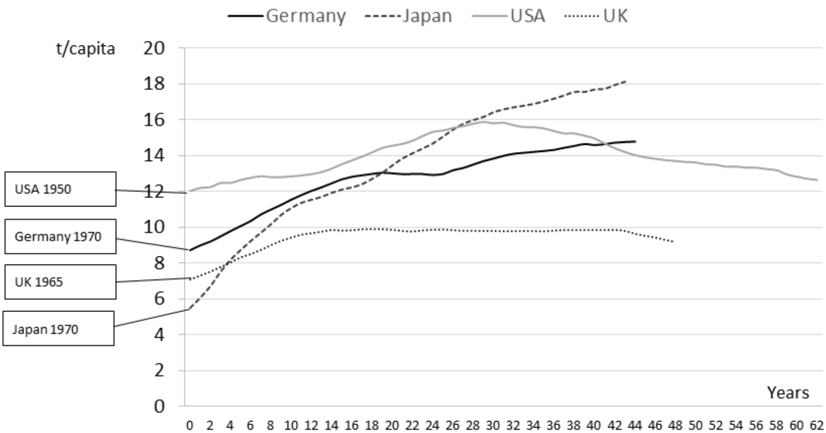
China

As opposed to aluminium, copper consumption per capita trends in China are more in line with those observed in industrialized countries for similar growth stages. For stocks, Chinese per capita values are on the lower end of the range compared to the other economies, whose dynamics are consistently similar to those determined for Japan.

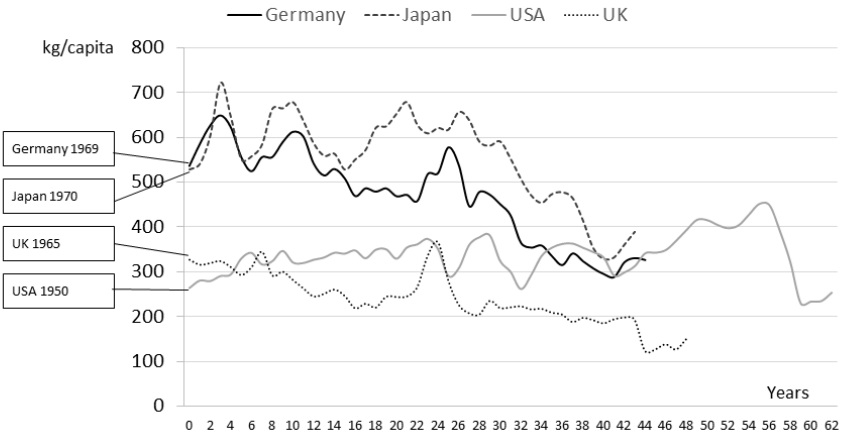
4.2 Time lags between ADC and stock saturation

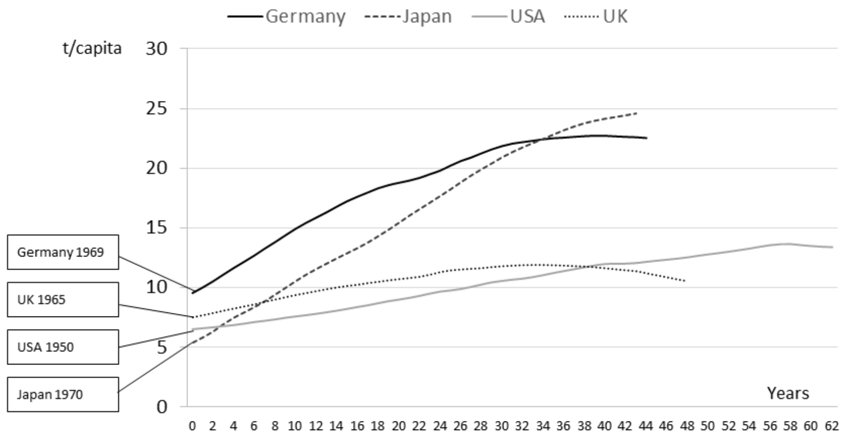
i. Steel





ii. 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

Figure 6: Historic evolution of ADC and stocks – steel (i) and cement (ii)

Figure 6 offers a time-series view on the evolution of ADC and stocks for 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 the 1970s for the industrialized countries, stocks continued to grow even 40 years later in some cases (Japan and Germany for steel, and Japan and the US for cement). Nevertheless, the observation that stock per capita saturation does occur in a subset of countries may lead to the following insights: a) the saturation of stocks is possible as a country becomes wealthier; and b) this informs material consumption outlooks with expectations of continued declines in ADC per capita from current levels.

Therefore, the consumption dimension alone suggests an earlier and a more pronounced stage of saturation in industrialized countries. It does not, however, reveal the broader picture of an increasing social reliance on materials for much longer along the development curve. The 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 amount to several decades. This lag depends on the income growth rate, the product group lifetime, the evolution of the consumption structure and the speed of ADC decline.

5. Discussion

5.1 Saturation overview for industrialized countries

The results of this analysis suggest an overall slowing down of material use in industrialized countries (see also Figure 1). The dynamics across the considered time horizon in this group of economies broadly comprise three stages.

- The first is a growth stage of demand and stocks over both the per capita and GDP dimensions. Regions becoming wealthier allocate an important share of their GDP towards infrastructure build-up: early for the US, followed by the UK and Germany prior to the 1970s, and Japan, with a delay of a decade.
- The second is a "maturing" stage of flat demand occurring as the shift towards diversified economic growth takes place (1970–1980s). At this stage, however, wealth growth rates are less pronounced (and this may come as a surprise) and material stocks are still building up as suggested by the stocks/capita metric.
- The last is a saturation stage where demand for materials is generally declining towards a "cruising" level that allows for a replacement of the

infrastructure reaching the end of its lifetime. This is suggested by the constant in-use stocks per capita. At this stage, relative decoupling of economic growth from infrastructure build-up can be observed through the demand/GDP and stocks/GDP metrics, accompanied by a selective absolute decoupling of demand from economic growth (apparent for steel in Japan and the US; cement in the UK, Germany and Japan; copper in Germany since the 1960s, the US since the 1970s, and Japan since the 1990s).

Nevertheless, a general saturation across all four materials considered cannot be confirmed just yet. Referring to the analysis framework outlined in Section 3, the ADC and stocks-per-capita indicators suggest that the saturation phase has been reached for a subset of materials (cement, steel and copper), but not for all industrialized countries considered, notably for Japan where stocks per capita continue to increase across all four material types.

For steel and cement, there is a factor two or three difference between the lowest and highest country value across the two considered indicators (Table 2). These differences probably reflect the heterogeneity in terms of infrastructure intensity, consumption basket and technological choices among developed countries. Interestingly, the UK has maintained its steel stocks/capita levels at a constant level for much of its development curve. Despite the increase in absolute stocks, the growing population acts as a countering effect here. Early industrialization in the UK could also be a factor leading to its quick stock saturation. The recent significant drop in ADC/capita in Japan may indicate that a similar stocks per capita saturation may occur in the near future. The high ADC and stock levels in Japan, the US and Germany may find an explanation in the significant scale of their siderurgy, which may have trickle-down effects on domestic demand and the steel intensity of consumption. Another factor may be the size of their manufacturing sectors, which translates into significant capital stock requirements.

Table 2: ADC and stocks per capita values in the industrialized countries and China

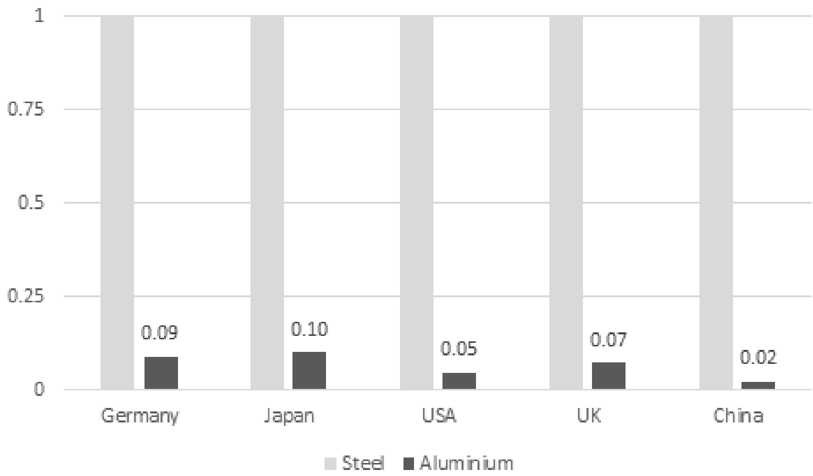
Material	Consumption			Stocks		
	ADC/capita saturation (kg)	2013 values (kg)		Stocks/capita saturation	2013 values	
		Industrial.	China		Industrial.	China
Steel	400-850	227-530	543	9.8t (UK), 15.9 t (US)	9.2-18.1 t	5.3t
Cement	350-720	150 – 390	1770	11.9t (UK), 22.1t (DE)	10.6-24.6 t	18.3t
Aluminium	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

It is noteworthy that cement consumption per capita is lower than that of steel for all the industrialized countries in the group. This can be attributed to the higher versatility of steel, which has implications for 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; transportation and consumer goods need to be replenished more frequently. Furthermore, 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 mainly goes into the construction sector, and hence stocks continue to accumulate.

Interestingly, the gap in consumption and stocks within the group of industrialized countries appears to be lower for aluminium and copper than 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, such as construction.

Our findings also suggest a divide between two groups of materials: one is essential to infrastructure build-up (cement and steel) and the other is specific to more advanced applications (aluminium and copper). For the first group, a saturation point for consumption is observed around the $12,000 GDP/capita threshold followed by stagnation or even a decline in ADC per capita thereafter. For the second, changes in dynamics of ADC per capita are visible only past the $17,000 GDP/capita threshold, thus indicating that the use of these materials becomes more intense in medium-to-high-income economies.

This difference in trends between the two material groups also hints at some limitations to this analysis. New applications of one material (of those included in this article or outside, such as plastics) could lead to a substitution effect over the other. For instance, aluminium's increased uses in transportation have led to a lower steel intensity in this sector. The relative sizes of material consumption could thus give some further insight into how much the use of a material could grow through substitution. Figure 7 shows aluminium's relative intensity-of-use to that of steel for transport. The disparities between industrialized regions, but also new alloy development prospects, indicate an important growth potential for this metal in these regions, and even more so for China. Nevertheless, assessing the extent to which aluminium will be able to replace steel needs to be left to more application-specific studies (see EAA 2013, for instance).



Source: own calculation from sectoral demand values

Figure 7: Aluminium-to-steel relative intensity in the transport sector in 2012

The single-material view adopted in this text is useful for highlighting a tendency towards saturation in industrialized countries, but should be treated as complementary to broader metrics such as DMC, which capture the dynamics of materials organized in functional groups. Furthermore, the raw material equivalents (RME) could be used to reveal the impacts of adopting more advanced materials that are employed in lower quantities but have potentially greater 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 1970s, it is interesting to observe that China now comes close to similar values (Table 2). The Chinese economy is unlikely to continue the same growth patterns in the use of those commodities. Following pathways of other developed countries and considering the projected stagnation or even reduction in population, it is now more likely that future consumption for steel, cement and copper will flatten or even decline in absolute terms. Such decline in consumption is even more likely with ongoing efforts towards a circular economy in China, which will enhance process innovation and resource efficiency in manufacturing in general, recycling and the use of secondary materials,[12] as well as the development of new goods and services that should use less primary materials.

Chinese ADC and stocks per capita evolution for steel and copper greatly resembles the dynamics of industrialized countries once the development angle is adopted. Because we use a consumption-based view, these similarities rule out most of the demand for materials related to exports. Therefore, China's current role as the world's largest manufacturer is reflected in these metrics only by the capital stock required for production processes, and not by the embedded materials in exported goods.

The industrialized country that 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 industrialization of the latter as compared to the other countries considered. Therefore, both regions are characterized by high economic growth for the better part of their development, relying heavily on infrastructure and capital stock build-up.

[12] The accounting for secondary materials needs to be accurate as they are usually included in the production of materials in primary products. For an assessment of the current status of a circular economy, see Haas et al. (2015).

At the same time, Chinese cement consumption/capita has expanded far quicker than that in any other country. 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 per capita to be comparable to those currently determined in industrialized countries. Nevertheless, more insight into how cement is being employed in China is required in order to assess whether consumption per capita is to be sustained at current levels or whether a steep decline is imminent.

The aluminium trends reflect a more intense use of this material. This suggests that China is leveraging the technological options that are increasingly reliant on aluminium (notably in construction and transportation) and that were not available to industrialized countries at this stage of development. Chinese aluminium ADC per capita is already comparable to that of high-income economies. Stocks are, however, three times lower, indicating that high consumption levels will be maintained for some time into the future in order for stocks to continue to accumulate. A further complicating factor is that industrialized 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.

The analysis carried out for this text also suggests that the resource intensity (measured via the indicator "demand per GDP") of the Chinese economy has been higher for three materials compared to that of the industrialized countries with different patterns: for about 50 years for steel with high volatility, about 40 years for cement with indications of saturation, and for about 30 years for aluminium. It is interesting to see that the copper intensity of the Chinese GDP has been on the rise for the last 20 years and is now close to values measured for developed economies, thus relatively low compared to the high resource intensity visible for the Chinese economy in other areas. We may thus expect efficiency gains to win in the primary sector and subsequent industries of the Chinese economy for the years ahead. This confirms analyses made for resource efficiency patterns in general (that is, the inverse of resource intensity) – for example, by Schandl and West (2010) in the Asia-Pacific region on a timescale of 1970–2005 – and puts it into perspective for future scenarios.

As far as in-use stock per GDP is concerned, China has proven to be consistently above the levels in developed countries for cement and steel starting from the 1960s. Interestingly, the relative differences between China and the other countries seem to have remained constant over the past two decades: a factor 5 difference for cement and 1.3–2.5 for steel. While these scale differences are significant, they also reflect a possible saturation in terms of GDP in-use stock intensity for China.

Another overall observation on growth patterns and resource use is that both demand per capita and demand per GDP are on a similar trajectory for the developed countries, with a clear indication of saturation beginning in the 1970s. This is not the case for China, where saturation occurs for demand, but not yet for the intensity per GDP. Overall, the Chinese economy appears to have a material efficiency gap compared to developed countries, which is similar to what Flachenecker and Rentschler (2015) propose for the European Bank for Reconstruction and Development (EBRD) member countries. This is a result based on "apparent domestic consumption", and thus not biased through exports for other countries. Therefore, extending the circular economy in China towards materials, resource-intensive value chains and recovery from stocks would be useful.

6. Conclusions

Our text finds evidence of a saturation effect at a late development stage that seems to have been overlooked in the recent debate about the decoupling of resource use and GDP. As our analysis is based on long-term time series for apparent domestic consumption, it is not biased through patterns of international trade and shifting production sites. We thus consider it an important conclusion referring to structural changes rather than dedicated efforts of becoming more resource efficient – the latter would add to such dynamics.

While the evidence is strong for the per capita demand for steel, copper and cement in the four industrialized countries analysed (the US, the UK, Japan and Germany), it is somewhat weaker for aluminium. We observe, in addition, that the saturation point starts at different income levels: relatively early for steel and cement ($12,000 GDP/capita) and later for copper ($20,000 GDP/capita), probably reflecting the different applications and use for purposes of a more affluent society. For China, we see early indications of saturation in the demand for steel and copper. The very high numbers for cement also point in favour of stocks per capita coming close to saturation.

We conclude that a time gap of about 40 years is a relatively common pattern for those transition pathways, from take-off towards any saturation of demand. Our research thus adds more in-depth analysis in economic terms to the existence of a "1970's syndrome" as described by Wiedenhofer et al (2013) for developed countries and adds a novel element – the relevance of the saturation effect – for China as an emerging economy.

Another novel element of our analysis is that the build-up of stocks is a relevant feature of the use of materials over time. Stock accumulation saturates with a delay of at least 20 years compared to demand, depending on lifetimes of capital goods. Our analysis thus also underlines their relevance for decoupling processes, adding a future perspective as those stocks will also be a potential source of future supply through extended circular economy efforts.

We also conclude that the early findings of resource economics on the intensity-of-use made in the 1970s and 1980s can now be enriched through more sophisticated indicators from the MFA debate, and indeed more data available through input-output datasets. Our approach of looking at a time period that is longer than the available MFA data and applying our method to single commodities and a few core indicators should contribute to and enhance the decoupling debate with a global perspective.

Another implication derived from this material interaction is that the proposed indicators, which are material specific, should complement but certainly not replace other more aggregated indicators, such as DMC or MF. Future research on DMC/MF could therefore reveal a different dynamic in terms of economic and social material intensity for decoupling processes through disaggregation into functional groups (construction minerals, fossil fuels, biomass and metal ores) and into key materials. The latter is important for any alignment to changes in industrial sectors and for economic modelling purposes. It also has implications for the Paris Agreement on climate change, as it is related to energy-intensive processes in emerging economies, although more straightforward impact analyses go beyond the scope of our paper.

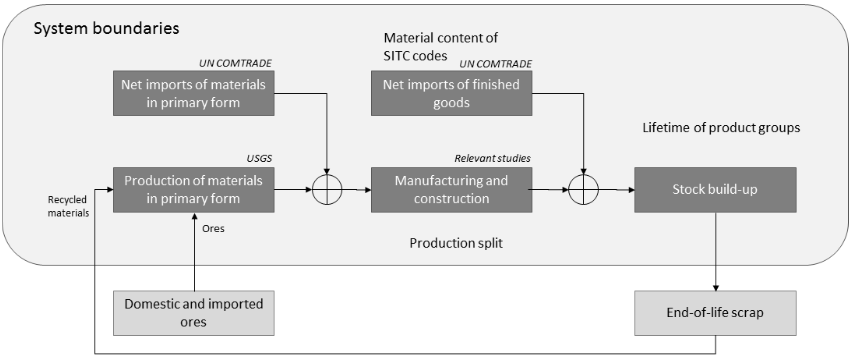
Looking ahead, our research suggests that any extrapolation of previous trends (for example, the last five to 10 years) for material consumption should *not* be regarded as a guiding rule for future market trends and investments. Emerging economies can rather be expected to decouple GDP from resource use through drivers of such a saturation effect, as well as through resource efficiency, circular economy and low-carbon economy efforts. In particular, for steel, copper and cement in China, we would suggest future scenarios with a demand that is much flatter than extrapolations from the past 10 years. Closing the efficiency gap that seems to exist between China and the industrialized countries will further contribute to such lower demand. Future research – such as that facilitated by UNEP's International Resource Panel, the Asian Infrastructure Investment Bank or the emerging G7 Alliance for International Resource Efficiency – should enlarge its database and develop criteria that translate such a saturation effect into foresight analysis, with clear relevance for the SDGs and their 2030 timeframe for delivery. In the same spirit, scenarios and economic modelling efforts should take the saturation effect into account. Our treatment of product groups and sectors fits well into modelling frameworks such as Input/Output Analysis and Computable General Equilbrium (CGE), but probably also for other tools.

We would like to conclude with a word of caution and a call for more comprehensive research on the issue. Innovation and technical change will continue to enable industry to apply materials to new product areas. A comprehensive perspective that captures substitution effects and systemic innovation will thus be needed. Altogether our findings should encourage more economic research on decoupling, MFA, and a saturation effect from an international perspective.

Annex: Material Flow Analysis

Our research follows the general principles of the material flow analysis (MFA) framework. The MFA considers a system in which all matter that goes into its boundaries either stays within the system or exits at the end of the considered period. Our text applies this method to four key material types (steel, cement, aluminium and copper) for five countries (the United States, the United Kingdom, Germany, Japan and China) using production and trade data covering the 1900–2013 period.

Our representation of the four considered system topologies (one for each key material) is simplified to a few nodes (see Figure A-1): production and trade of materials in primary form, manufacturing and construction, international trade of finished goods and stock build-up. These nodes are sufficient for determining the Apparent Domestic Consumption (ADC) of materials and consequently to compute stocks by factoring the lifetime of the different product groups. The inclusion of international trade enables a consumption-based view of the saturation hypothesis. This approach is more comprehensive than the earlier saturation literature focused on production, and our approach also addresses main parts of the hidden flows that are not included in the "Domestic Material Consumption" (DMC) indicator of MFA databases that is usually applied (for example, in EU documents or UNEP's International Resource Panel).



Source: *own compilation.*

Figure A-1: System overview of the simplified MFA design

As detailed in the material flow accounting section below, other activities such as recycling and mining of new ores fall outside the aim of this study. Although these activities are important for the wider impacts of raw material extraction, the choice of primary (ores) or secondary (scrap) sources at the production stage is not thought to influence ADC significantly.[13]

MFA studies may consider intra-period accumulation of inventories. Given the long time horizon of the analysis, it was considered that any primary material stock that was accumulated over one given year was possibly employed at some later point. Thus, inventories do not appear as a separate account.

Data treatment

Production information for materials in their primary form was obtained through the US Geological Survey (USGS) *Minerals Yearbooks* with reported data starting in 1928. Production figures prior to 1928 were estimated assuming a linear increase in production, which was considered to have started at an industrial scale from 1850 for steel and cement and from 1900 for aluminium and copper.

As non-US copper refining was absent from the USGS Yearbooks prior to 1976, refined copper production was estimated by using smelting data as a proxy – a country-specific smelting-to-refining conversion ratio was employed for this purpose. The ratio was calculated using a multi-annual average.

The international trade component of ADC was introduced through the Physical Trade Balance of each country derived from UN Comtrade data. For steel, copper and aluminium, the relevant Standard International Trade Classification (SITC) trade codes were selected and a material intensity of goods traded was determined either from existing literature or estimated by the authors. For cement, only the international trade of its primary form (Portland cement) was considered. Quantities of cement contained in transformed goods were assessed to be negligible

[13] One may hint at an indirect effect as secondary material re-enters economies and demand for extracted materials thus declines; see also Table 1.

relative to both apparent demand and Portland cement-traded quantities; they were also relatively difficult to identify in any international trade codification.[14]

Table A-1– Data sources for material intensity of internationally traded goods

Material	Data source
Steel	Pauliuk, Wang, and Müller, 2013
Cement	*Not applicable*
Copper	Copper Alliance
Aluminium	Authors' estimates

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 the production $P_{pf,m}$ and physical trade balance $PTBP_{pf,m}$ of materials in primary form (1). These quantities were then distributed as inputs $D_{tr,m}$ to the manufacturing of main product groups tr (2) using production split shares derived from other studies (Table A-2). Irremediable material losses in the transformative industries tr were considered to be negligible – most new scrap[15] would be recycled and returned as a secondary material to the production of primary forms, thus remaining within the system boundaries.[16] Hence, the material input quantities $D_{tr,m}$ equal the materials embedded in the output of the transformative sectors.

The economy-wide apparent domestic demand was calculated by adding materials from net-traded finished goods $PTB_{fg,m}$ and the output of the transformative industries (4). Materials embedded in internationally traded goods were determined by applying material intensities $\theta_{fg,m}$ (3) specific to each SITC trade code fg.

[14] We estimate that this approach comes close to the incorporation of embedded materials in the material footprints approach (Raw Material Consumption - RMC).

[15] "New" scrap represents the excess material resulting from production processes as opposed to "old" scrap, which is embedded in products at the end of their lifetime.

[16] This is a simplified assumption for the purpose of this paper.

Finally, stocks were calculated using different product group lifetime assumptions (Demand for materials in primary form (1) Table A-2).[17]

Demand for materials in primary form

$$D_{pf,m}^{t} = P_{pf,m}^{t} + PTB_{pf,m}^{t} \quad (1)$$

Distribution of materials to transformative sectors

$$D_{tr,m}^{t} = \delta_{tr,m}^{t} * D_{pf,m}^{t} \quad (2)$$

Net imports from finished goods

$$F_{tr,m}^{t} = \sum_{fg,tr} \theta_{fg,m}^{t} * PTB_{fg,m}^{t} \quad (3)$$

Apparent domestic consumption

$$ADC_{m}^{t} = \sum_{tr}\left(D_{tr,m}^{t} + F_{tr,m}^{t}\right) \quad (4)$$

Table A-2 – Product groups associated with steel, cement, aluminium and copper

Material	Product groups (lifetime)	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)	Aluminium Association –

[17] It seems we slightly deviate here from MFA accounts by including product groups and materials used in transportation in our "stocks". We justify it, however, through a lifetime > 10 years for this product group and the relevance this has in the overall in-use material stocks.

	Machinery (30 years) Construction (50 years) Small consumer products (15 years) Packaging (1 year)	Global Aluminium Model
Copper	Transport (13 years) Non-electrical machinery (30 years) Electrical equipment (15 years) Construction (50 years) Small consumer products (15 years)	USGS Copper End-Use Statistics

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