MEETING OUR MATERIAL SERVICES WITHIN PLANETARY BOUNDARIES

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Introduction

Materials form the fabric of our present society; materials are everywhere in our lives. Life as we know it would be impossible without them. Today's industrial society has become entirely dependent on materials, as it produces more of them, builds an increasingly complex society, and accumulates an incredible volume of materials in use. The production of materials is a large energy user and source of greenhouse gas emissions, producing about 25% of all anthropogenic CO_2 emissions. However, materials will also play a key role in the transition of our society towards future sustainability, as novel (energy) technologies need (new) materials. The challenge of sustainability for the material system is rooted in the way that we now process resources to make materials and products, and in the current industrialised route towards economic development. More efficient use of materials could play a key role in achieving multiple environmental and economic benefits.[1,2] Material efficiency entails the pursuit of technical strategies, business models, consumer preferences and policy instruments that would lead to a substantial reduction in the production of new materials required to deliver well-being. While many opportunities exist, material efficiency is not realised in practice to its full potential. In producing the materials, society produces large volumes of waste both in production and at end of life disposal. By-products such ashes and slags are currently used for various applications. These current uses however may not be optimal from a materials and climate perspective (*e.g.* air-cooled slags *vs.* granulated slags as additive in cement manufacturing). Moreover, the future dynamics of materials demand and production will demand an efficient and effective use of currently produced slags to ensure sufficient future availability. This paper evaluates the role of material efficiency improvement to limit the impacts of climate change and remain on a sustainable development path, including a preliminary evaluation of the future needs of slags in cement production in a climate constrained world.

Materials and the Environment

Industrial production is in many countries responsible for a large share of environmental impacts and pollution, especially as materials production grows rapidly (see Figure 1).

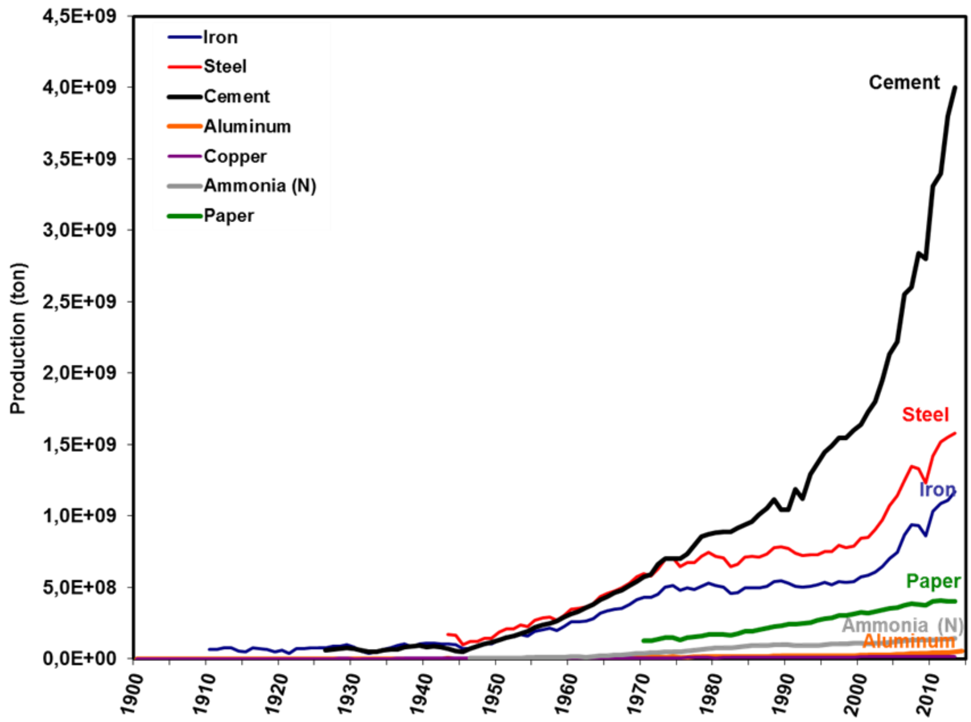

Figure 1: Global material production trends (1900-2014)

Globally, industry currently is responsible for about 20% of all water withdrawals, around 800·10^9 m^3/year. Left unabated, this would almost double by 2030, while the world is already exceeding a sustainable withdrawal rate.[3] While environmental impacts and emissions of some pollutants may decrease over time due to increased efficiency in production, improved pollution controls, waste and GHG emissions typically go hand in hand with increasing materials production. Earlier work on Environmental Kuznetz Curves (EKC) assumed that the pollution intensity would decline as society develops, but this has more recently been discredited [4,5]; globalising patterns of manufacturing have exported part of the emission reductions to other parts of the world [6,7]. Wiedman *et al.*[8] used the material footprint of nations to go further and show that there is almost no decoupling of material use with development. They show that as wealth grows, countries tend to reduce the fraction of their materials requirements extracted domestically through international trade, and accounting for this, their materials footprint increases by 6% for every 10% growth in Gross Domestic Product (GDP). If this development continues globally, material consumption would grow rapidly over the next century, resulting in dramatic increases in GHG emissions conflicting with climate goals as agreed in December 2015 in Paris. For example, if the average global building stock expanded to the levels of provision currently found in industrialised countries, 35-60% of the carbon budget allowed until 2050 (while limiting temperature increase to 2°C) would be required.[9] High demand for materials in the form of products and services require material flows, which vary over time as development and consumption patterns change, and which are accumulated in “stocks”, such as buildings, cars, and equipment. While we are learning more about the flows[10], little is known about the current stocks of materials in society.[11] This is important, as at the end of life, these stocks become waste, which could be recovered for recycling, or be landfilled or incinerated. Waste management practices differ widely between countries, but in most countries recycling rates of solid waste are increasing. While in some countries recycling rates are high for selected materials (*e.g.* steel, paper) there is still considerable potential to recover and recycle materials from various waste flows, especially municipal solid waste. Increased recycling leads to reductions in waste volume and generally leads to reduced GHG emissions. Nevertheless, some materials (such as cement) have limited recycling potential, while other materials are not utilised efficiently (*e.g.* slags). Note that still most materials are downgraded in recycling.

Industry is one of the largest energy using sectors, emitting about 37% of global GHG emissions associated with energy and processes. The production of bulk materials leads to around 25% of all these emissions. This makes materials a key sector for climate policy, yet to date they have received little attention beyond policy on emissions associated with energy. Overall, the global consumption of materials such as aluminium and steel is likely to double if current developments continue, while the recycling rates of these metals are already high.

In summary, if current trends in global demand for materials continue, the environmental impact (greenhouse gas emissions, water withdrawals, pollution) of materials production is likely to increase. These developments are clearly not sustainable, which suggests that alternative pathways are required in which global material production does not continue to grow at current rates.

Material Efficiency

To maintain our level of welfare, the resource efficiency of our society should be improved: services should be provided more efficiently using less (environmental) resources per unit of activity and emitting fewer harmful releases including GHGs. This requires that we move to an economy that uses and nurtures materials efficiently to reduce extraction rates by maintaining, improving, reusing and recycling products and materials. Material efficiency describes actions that lead to a reduction in the amount of primary material required to provide a specific material service.[12] Examples of material services are the containment of a litre of liquid, the provision of a square meter of load-bearing floor, or the delivery of a given amount of nitrogen to a plant.

The opportunities to reduce material use are often categorised like the hierarchy in waste management: reducing demand for the service, extending the life of a product, light weighting the product, reducing losses in the supply chain, product and/or component reuse, recycling, and down-cycling (see Figure 2). The net savings in energy (and emissions) achieved by material efficiency strategies typically depend on the importance of energy use in manufacturing versus that in the use phase. If most energy is required in the use phase, the emission reductions of material efficiency will generally be small, but may still be important.

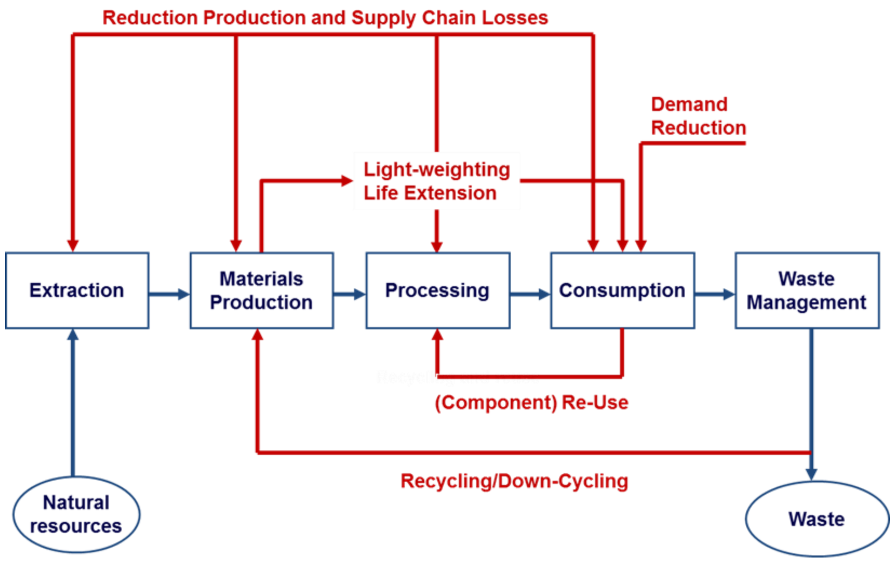

Figure 2: Depiction of material efficiency opportunities in the life-cycle of materials and products. Material flows are depicted in blue. Intervention options are depicted in red

Demand reduction is the primary opportunity to reduce material production by critically evaluating the need for the service, or looking for alternative means to deliver it. Technological change may make some services obsolete, if they can be provided by less material intense means. For example, electronic communication has significantly reduced the demand for physical media (*e.g.* newspapers, books, CDs), although the actual reduction in energy use may depend on the use phase.

Life Extension is a key option for services that are material-intensive, such as buildings and heavy equipment. Even for domestic equipment, life extension may be an effective way to deliver material efficiency, depending on the rate of energy efficiency improvement. Today, typical buildings have a much shorter time-span than in previous periods in history, which is often the result of changing needs. Unless new buildings have a much better energy performance, life extension would be a valuable strategy.

Light-weighting reduces the amount of material required per unit of service by re-designing the product or through material substitution. It is often applied in transportation equipment, as well as in packaging. Light-weighting in transport is primarily driven by the need to improve fuel efficiency of cars and planes. However, although this motivation is essential to the operators of aeroplanes, cars are also indicators of social status, so despite great industry attention on lightweighting individual components, cars have generally increased in weight in the past 30 years, as they have become larger. It is also possible that light-weighting may not be an effective climate strategy if the new material is more energy or CO_2-intensive in production, or cannot be recycled (*e.g.* composites). As production emissions may be offset in the use phase, the net climate impacts of substitution must be evaluated on a case-by-case basis.

Reducing material losses in the supply chains has been studied by Milford *et al.*[13] who found that a high fraction of material is scrapped in typical metal supply chains. While, this material is often recovered for recycling, this still requires energy inputs and leads to material losses. The typical losses for components made from sheet metal are around 50% and even higher for machined aircraft parts (up to 90%). Similar losses were found for boxes for luxury products. Yet, losses due to unused products can also be large. It is estimated that up to a quarter of newspapers are never read, while food waste in the food supply chain is estimated at 25-33% of the produced food.[14,15]

Product and component reuse aims to extend the life-time of equipment by re-using, repairing or refurbishing it, or through re-using parts for new equipment. This strategy has been used for a long time for many applications, both formally organised and informally, and is still found in many areas, ranging from car and equipment parts, re-treading of tires, rewinding of motors, to refilling of printer cartridges. A number of companies have made re-manufacturing part of their business models (*e.g.* Caterpillar, Xerox, Renault) with large economic gains.

Recycling aims at recovery of the materials in products, and generally captures less value than product re-use. In theory, recycling means that the material should be re-used at a similar level of quality as the recovered material. This is especially important for metals, as it allows re-use of alloying elements in an efficient manner resulting in considerable environmental gains. Achieving this form of high-grade recycling would require more product-centric approaches to collecting, sorting and separating materials.[16] However in practice, most recovered material is down-cycled (see below), and some addition of primary material is needed to retain quality (*e.g.* new fibres in papermaking), or recycled material is added to primary material in a certain degree (*e.g.* in steel production, and increasingly in aluminium production). Recycling generally reduces the energy needed for the material production compared to the primary route. The larger the difference between the energy needs for primary production and recovery/recycling, the larger the environmental benefits. Recycling is common for most materials these days, and is found in virtually every country and economy, and is also part of the climate strategies of many countries and cities. Yet, recycling rates vary, and still a lot of material ends up in landfills or in incineration plants. There is a wide body of literature on recycling and environmental gains, while a number of studies evaluated the climate impacts of recycling. Current trends in product design are leading to more chemically and physically complex products using many more materials. This trend makes the materials separation tasks much more difficult, requiring more complex separation schemes and often necessitates the addition of primary material to reduce the residual alloying ingredients to below critical levels. This last step results in the ultimate loss of these residual alloying ingredients and reduces the expected CO_2 emissions benefit.[17]

Down-cycling is the reality of many current recycling schemes, as material gets polluted (or the composition of alloyed metals becomes less controlled) and is hence downgraded so can no longer be used for its original application. Materials can still find good use through well managed cascading of material properties, to ensure a good match of needs for a specific application. In practice, this is often not the case, as it is difficult to distinguish and separate material based on properties (*e.g.* aluminium alloys), or because there are mismatches between (the economics of) different markets for the secondary material (*e.g.* recycled PET used for fibres).[18] Hence, open loop recycling often results in sub-optimal use of material, increasing the need to add primary materials to increase material quality, while "losing" additives and alloying metals.

The discussion of the opportunities to improve material efficiency is primarily aimed at managing the flows of materials. However, over time, the stocks will play a key role. Yet, we know still little about the current stocks of materials in society. This is important, as at the end of life, these stocks become waste, could be recovered for recycling, or will be landfilled or incinerated. Liu and Müller[19] estimate that the current stocks of aluminium in society are equal to 10% of all aluminium in known bauxite reserves. Similarly, a large part of future steel demand can be met by recovering current stocks.[11] Understanding these dynamics is important, as it may affect strategies towards more sustainable production and meeting the Paris goals on climate change mitigation.

Slags and Material Efficiency

The latter is also important for the role of slags. Below we focus on blast furnace slags, as they lay a key role in the decarbonisation strategy of the cement industry by producing increasingly blended cement, replacing the carbon intensive clinker. In 2014 global cement production reached 4,200 Mtonnes.[20] The global average clinker to cement ratio for the same year was 74.5%.[21] This equals the consumption of more than 850 Mtonnes of clinker substituting materials (excluding gypsum). The materials mostly used to replace clinker in cement were limestone, blast furnace slag (BFS), fly ash and pozzolanes.[21] Supplementary cementitious materials (SCMs) are globally available, but their availability can vary among region and places limiting their utilisation. The availability of two main SCMs, fly ash and BFS, depends on the activity of coal-fired power plants and blast furnaces used in primary steel making.

In 2050, it is forecasted that cement production will increase to about 4,600 Mtonnes and by 2100 to about 4,800 Mtonnes increasing the demand for SCMs (see Figure 3). In the same period, although global steel production increases, steel production with the primary steel making route decreases. This is due to the increased volumes of steel scrap becoming available and which take over the role of pig iron as the main iron source in steel production.

In the coming decades, pig iron production is forecasted to experience only a slight annual increase to reach a peak at about 1,200 Mtonnes in 2065 and then start a slow but gradual decreasing trend. BFS production will follow a similar development, reaching a peak at about 340 Mtonnes in 2065; for every tonne of pig iron produced 0.25-0.30 tonnes of BFS are generated.[22] Under a stringent emission controls scenario, fly ash availability will be drastically cut down due to the closure of coal-fired power plants (about 70% decrease in coal consumption for power generation by 2040).

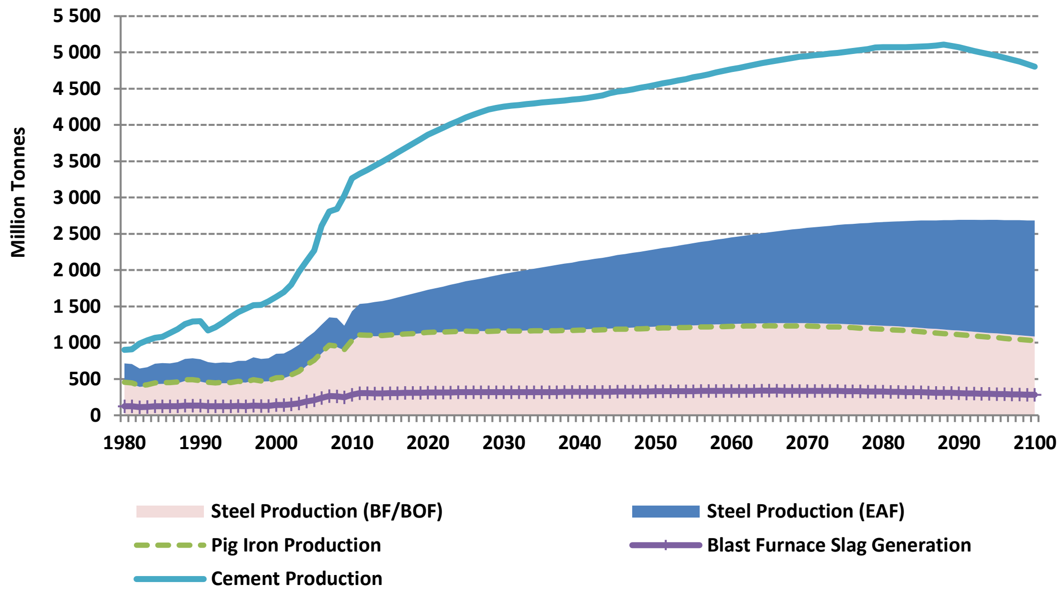

Figure 3: Projections of global cement demand, steel production, pig iron production and blast furnace slag generation (author own calculations)[23,24]

The future limited availability in BFS and fly ash is insufficient to meet the future increased demand in SCMs. It is therefore crucial to ensure that the specific industrial by-products deriving from the steel industry and the energy sector have the product characteristics required for the substitution of construction materials. Not all BFS can be used for cement making. When finely ground, granulated blast furnace slag (GBFS) develops strong hydraulic cementitious properties and it is therefore suitable as clinker replacement in blended cements. On the other hand, air-cooled blast furnace slag (ACBFS) is not suitable and is mainly used as an aggregate in construction activities. Pelletised slag is usually used as lightweight aggregate but when finely ground can have similar cementitious properties to GGBFS. The share of GBFS in total BFS production (granulation rate) increased from 67% in 1999-2000 [25, 26] to about 75% in recent years.[27] If 100% of BFS was granulated 33% extra GBFS would become annually available for clinker replacement.

In 2014, 325 Mtonnes of BFS were generated, but with only 244 Mt being granulated (75% granulation rate). This shows that there was an additional clinker replacing potential of 82 Mtonnes that was not exploited. Granulating and using the extra 82 Mtonnes of BFS would decrease the clinker to cement ratio in 2014 from 74.5% to

72.6%, if all GBFS would be used by the cement industry. For that year, the potential additional CO_2 emission reduction from increased utilisation of GBFS is estimated at 69 Mtonnes (3% additional reduction potential). If the goal of the cement industry is to reduce its GHG emissions to zero by 2050, it is critical that all well-known GHG mitigation measures are adopted. In 2050, it is estimated that 330 Mtonnes of BFS will be generated. Granulating and using 100% of BFS can reduce CO_2 emissions from cement making by about 280 Mtonnes; if only 75% of BFS is however granulated and used as clinker replacement, the reduction potential is limited to 208 Mtonnes.

This means that to meet the Paris goals and beyond, part of the current decarbonisation strategy of the cement industry cannot guarantee results, as both fly ash and slags will not be available in sufficient quantity. While there are some alternatives (*e.g.* natural pozzolanes), these are not evenly distributed, and cannot replace clinker to the same extent as slags. Alternatives for cement (*e.g.* geopolymers) are still expensive and limited to specialty applications. This also means that production of slags needs to take into account future availability, and that the production of air-cooled slags should be strongly reduced to favour production of granulated slags. Stockpiling of granulated slags may be another strategy to overcome future supply problems.

A future Strategy for Managing our Materials

Material efficiency is defined as reducing the volume of new material production needed to deliver a specified material service. Despite growing attention to material efficiency in recent years, there is little traction in evaluating and realising its potential as part of a climate strategy. Material efficiency opportunities are not included in most of the tools used to evaluate policy strategies. Hence, material efficiency is still mostly driven by waste management concerns. Plenty of opportunities can be found in the life-cycle of products to reduce material use without reducing demand for the service, *i.e.* extending the life of a product, light-weighting the product, reducing losses in the supply chain, product and/or component reuse, recycling, and down-cycling. There is ample proof in the literature that material efficiency improvement may lead to multiple environmental and economic benefits. Studies have demonstrated the existence of high technical potentials to improve material efficiency. Reductions of up to 50% of the current material use for the material services provided in services such *e.g.* buildings and packaging. Still, in practice we see that only a limited part of the potential is realised in practice, while the overall consumption of material services increases. This is leading to increased global production of materials. Developing nations will increase material consumption to meet basic human needs. However, in industrialised countries there is limited, if any, evidence of even a relative dematerialisation of our economy, let alone the absolute dematerialisation. Dematerialisation will be needed to maintain a sustainable development pathway for our energy and materials system.

This paper has shown that material efficiency strategies should also apply to by-products such as slags, in order to meet future sustainable development goals. Current developments and policies are insufficient to realise the full potential of material efficiency improvement to contribute to reduced material use, energy use, and climate change mitigation. Well-known initiatives like cradle-to-cradle and the circular economy insufficiently address the multiple challenges facing system earth, and hence may not achieve an absolute reduction in materials use.

To meet the challenges, we need a better understanding of the role of materials and consumption as a key driver for material use. Material use, energy use, and climate change need to be addressed within the framework of more fundamental change of our economic system. This needs a broad interdisciplinary approach in policymaking, (corporate) decision making, and science, to develop an understanding of the drivers of change that can contribute to the pursuit of our wellbeing within planetary boundaries. Important contributions have been made in this discussion, but are still far from main stream of economics (despite increasing evidence that the current economic system is unable to address the key challenges of global sustainable development).

Change is generally slow, but history has shown that we and society can change quickly in response to sudden shocks. To insure ourselves against the negative impacts of forced sudden changes, we need to develop a ready portfolio of opportunities. For this, we need to invest in combined research on the (material) technologies, human behaviour (*e.g.* habits versus perceived rational decision making), and societal (innovation) processes, within the broader context of the required fundamental changes. Within this portfolio, material efficiency improvement is a key tool to ensure that the essential needs of people and society are met with the lowest environmental impact. As society is complex, and hard to change, we need to identify those areas where interventions can be effective, efficient, and contribute to improved wellbeing. Improving the efficiency with which we supply essential material services is an important area to start. It needs to be actively integrated with the current toolbox of climate policy, and in the evaluation of strategies to reduce the concentration of GHG gases in the atmosphere coherent with an acceptably constrained increase of global average temperatures.

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