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The Role of Material Efficiency in Environmental Stewardship

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Abstract

Materials production requires a large amount of energy use and is a significant source of greenhouse gas (GHG) emissions, producing approximately 25% of all anthropogenic CO₂ emissions. It produces large volumes of waste both in production and at end-of-life disposal. More efficient use of materials could play a key role in achieving multiple environmental and economic benefits. 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. Although many opportunities exist, material efficiency is not realized in practice to its full potential. We evaluate the potential for material efficiency improvement, highlight the drivers to realize material efficiency, and anticipate ways forward to realize the potential of dematerializing our lives and the economy to limit the impacts of climate change and remain on a sustainable development path.

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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. In fact, terms such as the Bronze Age and Iron Age demonstrate that materials have defined our society. 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. Materials will also play a key role in the transition of our society toward 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 industrialized route toward economic development. Our growing and increasingly affluent global population with high demands for materials and resources is driving an exponential growth in material production (see **Figures 1** and **2**), and it is increasingly clear that this "economic success story" is now running into physical limits.

Mankind now dominates the global flows of many elements of the periodic table (1). The Earth's resources are not infinite, but until recently, they have seemed to be. Increasingly, we realize that our society may be approaching certain limits. Our society has operated as an open system on a finite planet, transforming resources to products that are eventually discarded into the environment. This, coupled with the massive increase in the use of materials, has led to growing impacts on the environment, as large amounts of energy, greenhouse gas (GHG) emissions, water, solid wastes, and other emissions to air and water are directly tied to the production and use of materials, and also affecting land use change, and increasingly biodiversity. In 2013, industry emitted (directly and indirectly) approximately 37% of global CO₂ emissions; this is equivalent to 10.1 Gt CO₂ (2, 3), of which an estimated 67% tends to be from materials production (see also **Figure 3**). It is clear that this development path is environmentally not sustainable.

In this article, we review the role that more efficient use of materials could play in managing our climate, reducing key environmental impacts, and ensuring we stay on a development path fitting within planetary boundaries. Since the 1980s a wide body of literature (e.g., 4–7) has examined the reality and drivers of dematerialization. This article uses the relationship between materials and energy use as a proxy for environmental impacts, as (fossil) energy correlates well with many environmental impacts (8). The term material efficiency in the context of climate change was first used in the scientific literature in the 1990s. Studies in several countries explored the potential contribution of reduced materials use to climate change mitigation (9–11). Allwood et al. (12) more recently reintroduced material efficiency as a climate change mitigation strategy, which has

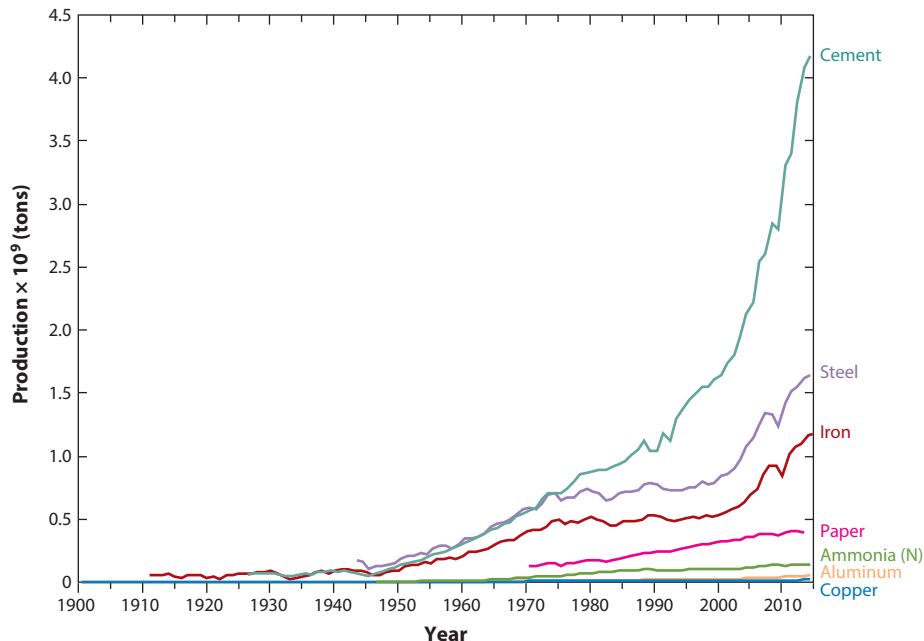


Figure 1

Global material production trends (1900–2014). Data derived from the US Geological Survey, UN FAO, and World Aluminum Association.

increasingly gained attention as an option to address industrial GHG emissions and environmental impact. Twenty-five percent of all energy and process related global CO₂ emissions are due to materials production (see **Figure 3**). This production is relatively energy efficient compared to other energy uses. However, still significant potential exists for energy efficiency improvement (13, 14), and it may be possible for some industries to shift to renewable energy (15). The delivery of energy and carbon intensity improvements in recent decades has been slow, however, due to many barriers. Other options such as carbon capture and storage (16) are difficult to implement due to high costs, high energy use, and the lack of a CO₂ infrastructure. Achieving the necessary deep reductions in industrial emissions will require all of the above options. Even if they are adopted universally, however, anticipated growth in demand for materials is likely to match or exceed the relative improvements of these measures.

Allwood et al. (12) therefore suggest that material efficiency is an essential option on the menu, as it highlights the need to address the growth in the sheer volume of materials used by society, and underlines the need to develop different (economic) paradigms and business models to meet the service needs of society. While some degree of dematerialization of the economy is taking place [i.e., material use per unit of gross domestic product (GDP)], material use per capita seems to stabilize (but not decline) in most industrialized countries. Material use grows rapidly in developing countries as infrastructure is developed and affluence increases. Pauliuk et al. (17) illustrate this for steel stocks and demand in many countries. These developments demonstrate the need to assess material efficiency in the broader context of our society. The contribution of material use to GHG emissions can be described by the temporal developments of various drivers that consist of general factors (i.e., income, demographics), the material intensity of supplying services to society, the energy intensity of material production, the carbon intensity of energy

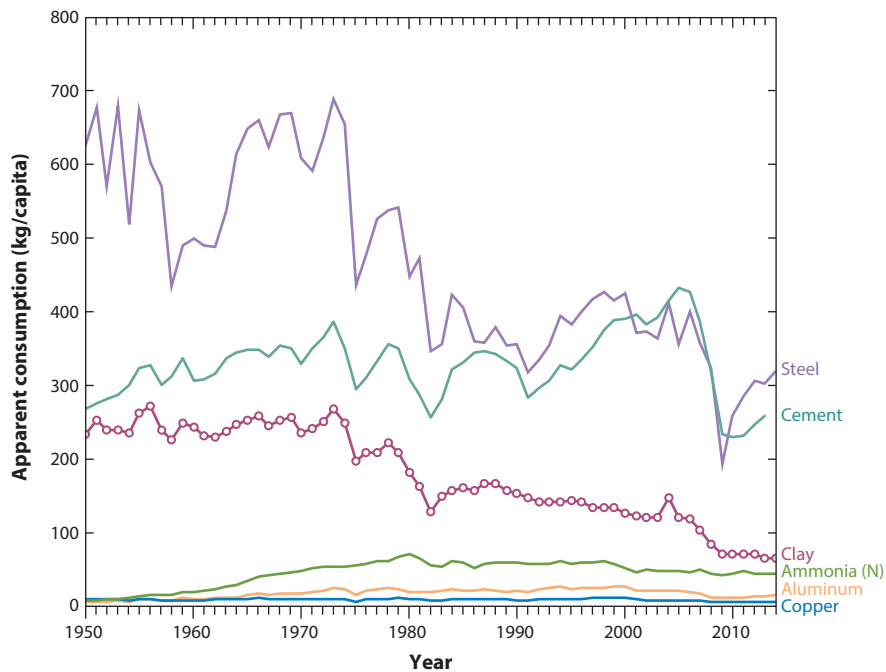


Figure 2

Apparent consumption of key materials in the United States for the period 1950–2014, expressed as kg/capita. Apparent consumption excludes the import and export of material containing products; hence, apparent consumption is not equal to actual (or final) consumption.

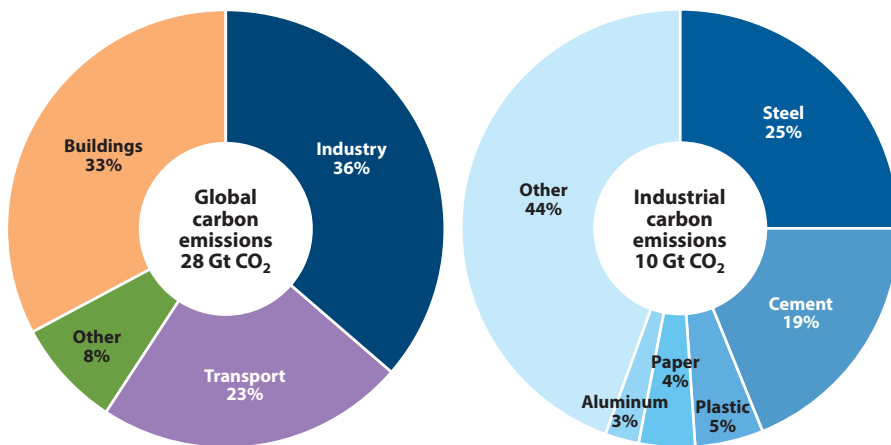


Figure 3

Distribution of global CO₂ emissions among sectors and materials production (2005).

supplies, and the associated process emissions. In this article, we focus on material efficiency to reduce the material intensity of a given service and touch on the factors that drive the demand for material services. Material efficiency means providing material services with less material production and processing (12). Our focus is on engineering materials—those used to create buildings, infrastructure, and goods—and excludes the use of hydrocarbons for energy.

We start with a review of the role of materials within the context of various environmental issues, to show how material efficiency could contribute to reducing impact. We follow with a discussion of the opportunities for material efficiency improvement in recent literature. In the next two sections, we put these developments in a wider context to assess how material efficiency can be realized, ending with conclusions and recommendations for future research to reduce the environmental impact of the materials system.

MATERIALS, ENERGY, AND ENVIRONMENT

Industrial production is in many countries responsible for a large portion of environmental impacts and pollution (18). Globally, industry today is responsible for approximately 20% of all water withdrawals, approximately 800×10^9 m³/year. Left unabated, this would almost double by 2030, while the world is already exceeding a sustainable withdrawal rate (19). Although environmental impacts and emissions of some pollutants may decrease over time due to increased efficiency in production and improved pollution controls, waste and GHG emissions typically go hand in hand with increasing materials production. Earlier work on environmental Kuznets curves assumed that the pollution intensity would decline as society develops, but this has more recently been discredited (20, 21); globalizing patterns of manufacturing have exported part of the emission reductions to other parts of the world (22, 23). Wiedmann et al. (24) 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 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 (i.e., floorspace and infrastructure per capita) currently found in industrialized countries, 35–60% of the carbon budget allowed until 2050 (while limiting temperature increase to 2°C) would be required for the necessary materials and construction alone (25).

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. This pattern is also called industrial metabolism (or urban metabolism for the more than 50% of the global population that lives in urban areas.) We are slowly beginning to understand the (social) factors shaping this metabolism (26–28). However, although we are learning more about the flows (29), little is known about the current stocks of materials in society (30). This is important, because at the end of life, these stocks become waste, could be recovered for recycling, or will be landfilled or incinerated. Liu & Müller (31) estimate that the current stocks of aluminum in society are equal to 10% of all aluminum in known bauxite reserves.

Waste management practices differ widely between countries, but in most countries recycling rates of solid waste are increasing (32, 33). Although in some countries recycling rates are high for selected materials (e.g., steel, paper), there is still considerable potential to recover and recycle material from various waste flows, especially municipal solid waste. Increased recycling leads to

reductions in waste volume and generally leads to reduced GHG emissions (34); additionally, on a regional scale reuse and waste prevention may result in economic benefits by retaining the value of products and materials and local job creation (35). Nevertheless, some materials (such as cement) have limited recycling potential, although they may still be used in downgraded end-of-life applications.

Throughout their life cycle, as materials are produced, converted to products, consumed, and discarded, the transformations use energy at every step. Industry is one of the largest energy using sectors, emitting approximately 37% of global GHG emissions associated with energy and processes. The production of bulk materials leads to approximately 25% of all GHG emissions. This makes materials a key sector for climate, environmental, and economic policy; however, to date they have received little attention beyond policy on emissions associated with energy (36). Although there is still considerable potential for reductions in the energy and GHG intensity of material production (13, 14), ultimately there are limits (37). Materials also play a key role in the planned transformation to a low-GHG-energy system. Sustainable energy technologies need novel materials as well as traditional materials such as steel and copper (38, 39). Hence, the transformation of the energy system is likely to lead to a changed and increased appetite for specific materials as new energy infrastructure is built. Overall, the global consumption of materials such as aluminum and steel is likely to double if current developments continue, while the recycling rates of these metals are already high (40). Simultaneously, in some products there is a trend toward substitution with more energy-intensive materials (e.g., replacing steel with aluminum, polymers, or carbon fibers), which may lead to increased use of energy in production, although it could reduce energy use during the operation of the product.

In recent years, access to critical materials has received much attention in response to (potential) supply disruptions of rare earth metals. Many studies for various countries have looked at this and, depending on their economic priorities, have created a variety of lists of critical materials (41, 42). Scarcity has been less studied from a sustainability perspective. Henckens et al. (43) studied scarcity from an intergenerational perspective (44) and found that a few elements could be depleted within a few human generations.

In summary, if current trends in global demand for materials continue, the environmental impact (GHG emissions, water withdrawals, pollution) of materials production is likely to increase. For the bulk materials, future relative improvements in the intensity of production are constrained given the processes are already relatively energy efficient and are likely to be eclipsed by absolute growth in demand. For the critical materials, demand may rise ahead of current trends driven by the development of new energy supply technologies, and this may increase the probability of supply risks in today's economy and scarcity for future generations. 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 from a linear and expanding economy, which extracts resources from the environment and discharges the wastes to the environment, to one that uses and nurtures materials efficiently to reduce extraction rates by maintaining, improving, reusing, and recycling products and materials. In pursuit of this goal, the phrase “material efficiency” is used to describe actions that lead to a reduction in the amount of primary material required to provide a specific material service (10). Examples of material services

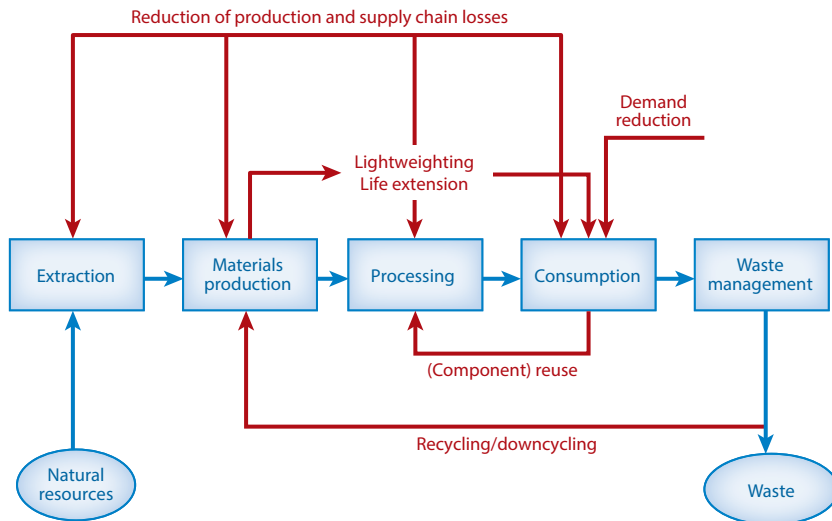


Figure 4

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.

are the containment of a liter 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 categorized like the hierarchy in waste management (based on 10, 45): reducing demand for the service, extending the life of a product, lightweighting the product, reducing losses in the supply chain, product and/or component reuse, recycling, and downcycling (see **Figure 4**). **Table 1** provides an overview of case studies based on a review of the (recent) literature.

There are few estimates of the overall potential for material efficiency. At a macroscale using a frontier production function of national economies and energy to express the (solar) energy equivalent of resources, Hoang (46) estimated the potential at 31–38% with current technology. Earlier analyses with an energy optimization model showed that including material efficiency could significantly reduce the costs of climate change mitigation (47). Estimates of the potential for specific services also showed considerable potential to reduce associated GHG emissions, ranging from 41% for nitrogenous fertilizer use in agriculture (9) to 51% for packaging (48). However, unlike supply-side options, the ultimate technical potential of material efficiency depends on consumer acceptance. A broad strategy of “half as much for twice as long,” as outlined by Allwood & Cullen (49), would reduce material demand by 75%, and there is evidence to suggest that this is technically not difficult. For example, Moynihan & Allwood (50), based on detailed analysis of 23 recently constructed multi-story buildings in the United Kingdom, demonstrate that the Eurocode safety standards for the buildings could have been met with approximately half the steel actually used in practice, whereas Cooper & Allwood (51) demonstrate that 40% of global steel demand is for replacement goods, out of which only infrastructure and packaging are discarded because the goods have reached the end of their useful life. Most goods are replaced either because users’ needs have changed, or because new and more attractive goods have been introduced to the market, resulting in disposal before the end of their technical life.

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 (52). If most

Table 1 Material efficiency opportunities based on case studies and analyses, as found in the scientific literature

Opportunity	Definition	Case studies	References
Demand reduction	Reducing the need for the service or for materials to provide the service	Plastic shopping bags Packaging Office paper	10, 117
Life extension (and refurbishment)	Extending the life of a product through design or repair	Washing machines Refrigerators Car, machinery, rolling mill, office block	53, 56, 118
Lightweighting	Reducing the amount of material needed for a given service	Packaging Universal beams, food cans, car bodies, reinforcing bars, deep-sea line pipe Commercial steel-framed buildings	50, 57, 58
Reducing production and supply chain losses	Reducing the material lost in and between steps in the supply chain	Car and aircraft body parts Aluminum cans Boxes	60, 119
Product and component reuse	Reusing products in their current forms or components thereof for remanufacturing/refurbishing (assuming 1:1 replacement)	Car parts Washing machines Drinking cups Packaging Office machines Office paper Steel- and aluminum-intensive goods Composite construction Office furniture Clothing Some computer components	48, 51, 52, 56, 120–123
Recycling	Recycling the material contained in a product, replacing primary (virgin) material (assuming 1:1 replacement)	Steel Aluminum Metals	33, 40, 124
Downcycling	Recycling of the material, partially replacing the use of the primary material	Aluminum	33, 124

energy is required in the use phase, the emission reductions of material efficiency will generally be small but may still be important. If the energy efficiency of appliances in the use phase improves rapidly due to technological change (53), material efficiency alone may not be the best way to reduce life-cycle emissions, and may even result in increased energy use in the use phase of the appliance (52). Skelton & Allwood (54) explore the benefit of increasing the intensity of use of products that are currently replaced too early such that product failure is “brought forward” through increased use, to the point that it would be replaced for other reasons. The above discussion demonstrates that for services that require significant energy in the use phase, material efficiency opportunities should be evaluated carefully.

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 (see, e.g., 55, for a discussion on alternative music delivery). Earlier experiments

showed that customers would reduce the use of plastic shopping bags by 25% when given a choice (10), and currently many cities and (developing and industrialized) countries have abolished free plastic shopping bags to reduce litter. In Ireland, a reduction of bag use by 90% is claimed following the introduction of a bag levy, equaling approximately 0.28€ per bag (see <http://www.environ.ie/environment/waste/plastic-bags/plastic-bag-levy>).

Life extension (through service, repair, and maintenance) 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 for, e.g., refrigerators (53) and washing machines (56). Today, typical buildings have a much shorter life 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 more valuable strategy.

Lightweighting reduces the amount of material required per unit of service by redesigning the product or through material substitution. It is often applied in transportation equipment, as well as in packaging. Lightweighting 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 airplanes, 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 lightweighting may not be an effective climate strategy if the new material is more energy 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. Van Sluisveld & Worrell (57) showed that lightweighting is the preferred approach to reduce packaging weight, although this generally results in minor gains,

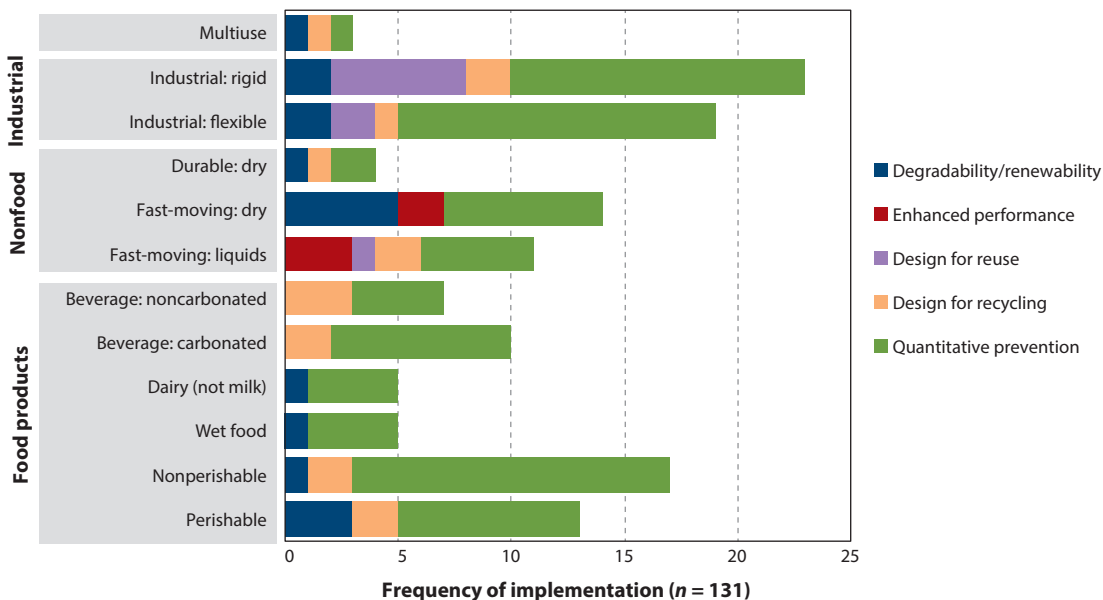


Figure 5

Material efficiency options identified in a study of packaging in The Netherlands. Note that the packages with material efficiency improvements represent a small minority of the total number of new packages introduced, suggesting that material efficiency is not yet a widespread strategy. Figure reprinted from Reference 57.

compared to other options (see **Figure 5**). Carruth et al. (58) used several case studies to show that on average, goods could be made one-third lighter than they are today if structural optimization were prioritized over the economies of scale. For commercial multi-story construction, Moynihan & Allwood (50) show that half of the current use of structural steel is not required to meet the safety standards of the Eurocodes. However, in the developed economies, labor costs generally exceed material costs, so the lowest cost route to production will often use excess material to substitute for labor. This may be an area where new, more flexible production technologies, such as variable section I-beam rolling (59), could change the balance of labor and material costs.

Milford et al. (60) study reducing material losses in the supply chains and find that a high fraction of material is scrapped in typical metal supply chains. Although 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 approximately 50% and even higher for machined aircraft parts (up to 90%). Similar losses were found for boxes for luxury products. Losses due to unused products, however, can also be large. It is estimated that up to one-quarter of newspapers are never read; food waste in the food supply chain is estimated at 25–33% of the produced food (see e.g., 61, 62), and estimates of up to 50% have also been identified (63).

Product and component reuse aims to extend the lifetime of equipment by reusing, repairing, or refurbishing it, or through reusing parts for new equipment. This strategy has been used for a long time for many applications, both formally organized and informally, and is still found in many areas, ranging from car and equipment parts, retreading of tires, rewinding of motors, to refilling of printer cartridges. Numerous companies have made remanufacturing part of their business models with large economic gains. In some cases, the remanufactured product may function less well (52), but we lack data on the conditions of this loss in performance and the impacts. At the same time, two important nuances for product reuse should be mentioned. The first is the importance of the use phase for the reused product versus the potential new replacement. The second is that the assumed 1:1 substitution for a new product is not completely correct. In general, reused products displace some primary production but they tend to expand the lower end of the market, thereby providing more product services, but also limiting the expected reduction in demand for new material production (64).

Recycling aims at recovery of the materials in products and generally captures less value than product reuse. In theory, recycling means that the material should be reused at a similar level of quality as the recovered material (33). This is especially important for metals, as it allows reuse of alloying elements in an efficient manner, resulting in considerable environmental gains (65, 66). Achieving this form of high-grade recycling would require more product-centric approaches to collecting, sorting, and separating materials (33). However, in practice, most recovered material is downcycled (see below), and some addition of primary material is needed to retain quality (e.g., new fibers in papermaking), or recycled material is added to primary material in some degree (e.g., in steel production, and increasingly in aluminum production). Recycling generally reduces the energy needed for the material production compared to the primary route. The larger the difference between the energy needs of 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 (33). Recycling rates vary (32), however, 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, and numerous studies evaluate the climate impacts of recycling. Corsten et al. (34) showed that increased recycling of plastics, in particular in The Netherlands, would lead to strong net environmental benefits.

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 necessitating the addition of primary material to reduce the residual alloying ingredients to below critical levels. This final step results in the ultimate loss of these residual alloying ingredients and reduces the expected CO₂ emissions benefit (67, 68).

Downcycling 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 such that it can no longer be used for its original application (68). Materials can still find good use through well-managed cascading of material properties (69), to ensure a good match of needs for a specific application and material properties. In practice, this is often not the case, as it is difficult to distinguish and separate material based on properties (e.g., aluminum alloys) and because there are mismatches between (the economics of) different markets for the secondary material [e.g., recycled polyethylene terephthalate (PET) used for fibers] (70). Hence, open-loop recycling often results in suboptimal use of material, increasing the need to add primary materials to increase material quality, while dissipating additives and alloying metals.

MATERIAL EFFICIENCY FROM A SYSTEMS PERSPECTIVE

Material efficiency was normal practice prior to the Industrial Revolution, and still is in many developing nations, as the relatively high value of materials compared to labor ensured that products were maintained, repaired, and upgraded. In today's developed economies, however, materials contribute only a small fraction of the total cost of products, which decreases the motivation to nurture the value of the material. In parallel, the characteristics of mass production and marketing techniques tend to drive a rapid increase in (primary) material consumption.

Many opportunities exist to improve material efficiency in our society, and considerable potentials remain. Material demand is the result of a complex interaction between different stakeholders in society, as simplistically depicted in **Figure 6**.

Materials choice and use are the result of the interaction between the needs and wants of different stakeholders in society, resulting in impacts on the commons (e.g., environment, public health) due to choices in this system. The interactions lead to changes over time in the materials system. The demand for material efficiency is driven by the need to reduce the impacts of the materials system, while supplying the material services demanded by society. In **Figure 6** we

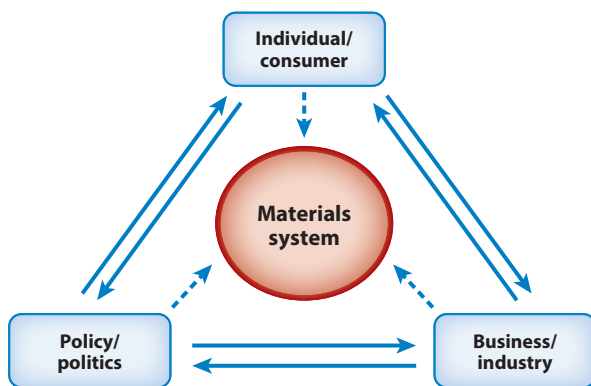


Figure 6

A systems perspective on material use and efficiency.

distinguish producers (i.e., business/industry), the individual (consumers), and policymaking. As shown, all stakeholders affect the pattern of service demand and material use through myriad decisions (71), which are also the result of many interactions over time, although the stakeholders do not always have the same power to affect change.

Material efficiency aims to reduce the amount of material produced per unit of service delivered, and in this way it reduces the climate impact of the services provided. It contributes to a decoupling of material use and service demand, and to a reduction of total material use, assuming service demand does not change. However, if the economy grows the service demand grows, and as shown by recent papers the net decoupling between GDP [as a (flawed) expression of service demand] and material use is currently minor. Hence, options to intervene in materials use, choice, and efficiency do not currently receive sufficient attention. For example, R&D related to construction materials hardly addresses environmental impacts (72). These environmental externalities, however, are sufficient grounds to introduce policies aimed at improving material efficiency (71).

In a traditional view, the producers produce the goods needed by the market (consumers) while regulated by policymakers to manage the commons and/or externalities of the system. In reality, demand is the product of many interactions, including marketing by businesses producing new wants (and not necessarily needs) (73). The fashionization of durables is another result of these practices, as is planned obsolescence (74), and the nudging of consumers to increased consumption. However, regulation may also lead to new products or changed product designs and may affect material efficiency. Recognizing that the transition is a complex system of interactions, we discuss the key factors for each of the stakeholders.

Individual/Consumer Perspective

The word consumption is often used to describe final demand for goods and services and usually refers to households—individuals buying for themselves. Typically, as income grows, materials use increases (75, 76). As economies develop, several theories such as Maslow's hierarchy of needs can help to illuminate individual motivations and hence purchasing behavior. Today, however, we have surpassed our needs, as defined by Keynes (77), for most people in industrialized countries, and demand in industrialized countries is driven more and more by wants (78). Wants (especially given the relative low costs of materials and products) not only may be driven by convenience or security, but are also influenced by trends and marketing (73), and as such can lead to resource inequality (76).

Sustainable consumption patterns can also reduce the material intensity of lifestyles, as people react to environmental and economic crises (e.g., the Tiny House movement in California, no-impact lifestyles) to exchange ownership for a higher quality of life (73, 78), or develop different ways to express themselves (e.g., emerging lower rates of car ownership among younger generations). Sustainable consumption patterns support sustainable development but may not be supported by current economic paradigms (79). Emerging social practice theory places the resource-consuming habits of consumers in the context of economic, cultural, as well as governance drivers (80). This suggests that change in consumption includes changing the whole practice, and not just the provision of alternative goods (see below, as well). This demands different governance approaches and structures.

Some of the most material-intensive purchases cannot be affected by consumers themselves but are the consequence of business decisions (e.g., buildings, infrastructure, cars, machinery). In other cases, consumers have limited opportunities to affect material intensity (e.g., houses,

packaging). Hence, business decision making and sustainable production practices are equally essential to improve material efficiency.

Business/Industry Perspective

Industry is in the business of economically producing and providing the goods and services to meet the needs from the market. However, it also influences the markets. Industry is primarily economically driven, with competitiveness a key driver of strategy. The fundamental goal of business, increasing shareholder value (to meet the criteria of investors such as banks and pension funds), obliges managers to attempt to increase sales or reduce costs, or both. In theory, material purchasing is a cost, so reducing demand for materials while increasing revenue through other mechanisms appears to be a natural process. However, material inputs are just one of many inputs in the production process, and compared to the price of the final product, they often account for only a small fraction of the cost. Moreover, the cost of the bulk materials are typically very low compared to the cost of labor, and as a result shareholder value is often increased if managers choose to use more material to save on labor. As a result, 50% of all sheet metal made in the world is scrapped during manufacturing (60, 81) and never enters a product, and steel-framed commercial buildings in the United Kingdom are built with double the mass of steel required to meet safety codes (50). Reductions of 26–40% in metal production for sheets would be possible if material losses during production were reduced using available technology (60). Material efficiency improvement, as with energy efficiency improvement, is further impeded by a multitude of barriers. A wide body of literature on energy management in industry has shown that many economically attractive options remain unrealized due to various (organizational) barriers (82). Although several authors have studied them, we still lack sufficient insights into these barriers to realizing material efficiency in products. Extended producer responsibility is often seen as a way to extend producers' decision making to waste prevention across the whole supply chain, making material efficiency a strategic issue (83). However, the results of this approach in practice vary and do not necessarily lead to strategic changes or reductions in material use (84).

Competitiveness reduces the costs of many products and services, thus expanding the size of the market. However, reduced costs may also lead to new uses or to increased use beyond those needs the product was designed to address. This is often referred to as the rebound effect (85). The rebound effect claims that *ceteris paribus* if the costs/prices decline, consumption will increase (resulting in increased service) and in the end may offset any efficiency gains. Although in the literature on energy efficiency there is evidence of a limited direct rebound effect (i.e., increased use as the efficiency of the equipment increases), there is larger debate around the indirect rebound effect (i.e., additional activities due to “freed-up” money). For electronics, there is evidence that price reductions have increased demand, and hence material efficiency may also result in a rebound effect. However, as material costs are relatively small (for cars and housing, see 86), material efficiency alone is unlikely to result in a strong rebound effect. Moreover, as the purchasing power of consumers changes continuously, other factors may affect demand more, and it is hard to quantify the rebound effect.

The economies of scale favor mass production of standard components over tailored production of efficient designs. This leads to sheet metal made in long constant width strips, out of which products are cut, with significant yield losses. Structural designs use constant depth I-beams, where variable depth beams would be more efficient. Buildings are designed with the least variety in I-beam selection, to allow mass production of joints, even though total material use could be halved if each beam was tailored. However, research is underway to introduce material efficiency into modular design (87), but this will need more attention.

As markets for traditional products saturate, business tries to identify (and may even induce) new wants or to change the types and levels of services offered by adding (new) features. However, new business models may affect the material intensity of services through new concepts or new technology (e.g., music streaming instead of CD ownership, better utilization of spare capacity through car or tool sharing). These disruptive innovations and business models are normally not emerging within incumbent businesses, although there are a few exceptions. For example, in South Korea, appliance manufacturers compete in customer service to retain brand loyalty, by delivering excellent in situ repair services. This not only increases customer loyalty, but also improves material efficiency. Other new business models include leasing (e.g., copiers, carpet tiles, machinery, aluminum building cladding) and “off-site” (modular) construction, which may result in material efficiency in commercial buildings. The retained ownership also enables product or component reuse at the end of life of the product. Even if an innovation leads to reduced output of a sector as a whole, the first mover may gain economic advantage: The first steel company to deliver kits of long-lasting perfectly efficient building parts could see business growth, despite the fact that if the innovation spread, overall steel demand would reduce. However, innovation in this area is slow.

The Policy Perspective

Government is the broker of the interests of stakeholders in society, so it should be in a position to give weight to the interests of future generations, e.g., managing the commons in a sustainable way. However, to date bulk materials have received little policy attention and do not necessarily “belong” to a specific government department (88). Materials are, in most countries, currently the realm of waste management policy, whereas the environmental impacts of production may be managed separately. Strategic policy around bulk materials is thus weak, and there are few actors within governments who see it as a priority. Whereas recently resource scarcity/criticality has generated interest within government (41, 42), material efficiency gets limited attention. The response to interest in critical materials has typically focused on selected high-value low-volume metals while ignoring the bulk materials (which have the highest environmental impact). Only a few countries have developed agencies or R&D to address material use and efficiency from a strategic perspective (e.g., Finland, Germany) and have implemented policies to address material efficiency in industry (see, e.g., 89). Hence, current policy initiatives to address material use are scattered and focus on a few selected areas, whereas waste management and recycling of discarded materials are established areas.

Policy typically pays less attention to more fundamental transitions to sustainable consumption patterns, yet is an important force in these transitions (80). Today, in most countries, material efficiency is translated into recycling and is in the realm of waste management policy. Traditionally, waste management policy has aimed to achieve the sanitary disposal of waste at the lowest direct costs. This has resulted over recent decades in a shift from landfills to sanitary landfills and waste incineration. However, in preindustrial societies, when materials were relatively expensive, waste management strategies developed formal and informal routes for long-term use, reuse, and recycling for most of the materials. The increased environmental impacts associated with materials production and waste disposal, and rising energy costs, have shifted the focus to an increased role for recycling. Interest in resource productivity and the circular economy has recently generated interest in a broader and more strategic view of materials in the economy. A circular economy is often defined as an economy where the value of products, materials, and resources is maintained in the economy for as long as possible and the generation of waste is minimized. However, it may not necessarily lead to improved material efficiency or an overall reduction of material use in society,

if it maintains inefficient design of supplying material services and leads to increased consumption (45). The increased interest in resources has also highlighted the impact of the organization of our economic system and its incentives. For example, labor costs are high relative to material costs in all developed economies and also provide most tax revenue, thus increasing labor costs further. This strongly disincentivizes reductions in material use. Experiments with “green taxes” are taking place in some countries (90, 91) but are generally limited to specific materials/resources or uses. Many countries have introduced energy or carbon taxes for particular activities, typically excluding industry. A few countries have introduced taxes on specific materials (e.g., sand and gravel in The Netherlands) to manage the environmental impacts of resource extraction, and for a few years The Netherlands also had a levy on packaging. Typically, these experiments were limited in effort and time, did not really affect the tax base and distribution, nor led to reduced labor taxes. Given this very high weighting of current taxation toward labor, Skelton & Allwood (92) demonstrate that even if high carbon taxes were introduced, the incentives along the supply chain of production would still be toward minimizing labor rather than material use. This demonstrates that more fundamental changes in the fiscal systems may be needed to reorient the current production system to reduce its environmental impact.

The increasing interest in resource productivity has triggered the need for a better understanding of current material use and efficiency. Current metrics and data are insufficient to understand the efficiency with which materials are used. Wiedman et al. (24) question the use of current resource productivity indicators in policymaking and suggest the need for an additional focus on consumption-based accounting for natural resource use, and this is supported by Steinberger et al. (26). The pursuit of material efficiency may hence result in a need for different indicators. Moreover, different materials are like apples and oranges, and aggregation of different materials in weight (the most commonly used metric) may not always be suitable. As the world is currently not depleting the major commodities, it is energy use and GHG emissions that pose a limitation to our enthusiasm to extract and transform them, and these may form a basis for developing metrics. Material efficiency can be measured in different ways, i.e., by weight, by the energy (exergy) needed to produce the materials, by the GHG emissions associated with producing the materials, or by the land used (93, 94). Huijbregts et al. (8) proposed cumulative energy use as an indicator for environmental performance, whereas others use cumulative GHG emissions as an indicator (assuming that climate change is the most imminent environmental driver).

MANAGING OUR MATERIAL CONSUMPTION

When might using less material be seen as going forward rather than backward? In this section, we address the question of what might trigger a transition from today’s high demand for new material production to a different system. The section aims to learn from drivers in other contexts that might inform the search for drivers of change in the material system. This provides an opportunity to generate new research questions that need to be addressed to ensure that our energy and material systems remain environmentally sustainable, and to set a tentative agenda for a broad and highly interdisciplinary engagement about transitions to future material efficiency.

This article began by demonstrating the importance of materials production as a driver of environmental harm, and following a review of the technical options for using materials differently, the previous section has attempted to show how those options sit within consumer, business, and policy systems. Except for large groups of the population in developing countries that have not yet met their basic needs, it is relatively easy to demonstrate that we could live well with less new material production in today’s world. However, we have learned from human history that often today’s luxuries become tomorrow’s necessities and spawn new obligations (95). Hence, today we

are consuming more material than ever before. Absolute and even relative decoupling of resource intensity in most industrialized countries have recently been questioned, suggesting that the end of growth is not in sight, if left unabated. It also demonstrates that a large part of the potential of material efficiency improvement is not realized or is offset by a growing number of new material services. As described above, in the current economic system and with current business models, business and consumers may not be able to realize the full potential of reduced material use. However, the externalities associated with material use may well be sufficient reason for government to develop policies (71) to reduce the negative impacts of material use. As discussed above, resources are hardly taxed, whereas labor is often heavily taxed, resulting in reduced attention to material efficiency. Taxing resources to reflect the full cost of their negative externalities has been proposed to overcome this and shift the basis for taxation. This will “green” the tax base by taxing the activities that result in negative impacts on public welfare (i.e., resource extraction, pollution), and not the activities favored by society (e.g., labor) (90, 96). Research has shown that such tax changes would make reuse and refurbishing more attractive (35, 56). In a few countries, some “green” taxes have been introduced (sometimes for limited periods of time) for specific applications, with no or hardly any impact on labor taxes. However, large tax overhauls have not received a lot of traction, despite organizations pushing this change in some countries (e.g., ExTax in The Netherlands). Concerns over the (long-term) predictability of tax income and the transaction costs of implementing alternative tax systems seem to make tax regime shifts difficult.

Other (local) policies are also able to develop initiatives focused on improving material efficiency. Initiatives such as repair cafés or second-hand stores are supported by local governments to increase social inclusion and reduce waste. Various policy instruments have been introduced to manage the negative impacts of the extraction of specific resources or the waste due to specific material services (e.g., packaging). Government procurement has been shown to be a powerful tool to increase the markets for energy-efficient equipment in the United States (97) and could also be instrumental in increasing the development of markets for material-efficient services. This could be especially important in markets for building and construction materials, as governments represent a large market power. However, only very little prominence has been given to material efficiency in current green or sustainable procurement programs, and it is often limited to metrics of the use of recycled content (98). Labeling and standards are common instruments used to improve energy efficiency for buildings and energy-consuming products (ranging from appliances to cars and industrial motors) and have proven to be successful in achieving cost-effective energy savings (see, e.g., 99–101). Standards have been introduced to increase the share of recycled content in newsprint and waste bags in California (102), and following a recent initiative in The Netherlands, a 25% recycled content will be required for PET bottles. Recycled content requirements can also be included in procurement standards, as for the London Olympics (103). The eco-efficiency standards in the European Union can provide the opportunity to introduce material (efficiency) requirements for products covered by the directive, but have not been introduced. Labeling is frequently used in energy efficiency policy, but in materials policy has been limited to examples such as the voluntary environmental labeling program *Blaue Engel* (“Blue Angel”) in Germany, which requires recycled content for a few products. Application of labeling to material efficiency has been very limited.

Local communities (including local government) are in many places taking a stronger lead than national governments, resulting in a wide variety of initiatives marrying reduced materials inputs to social needs and goals. For example, today more than 900 repair cafés in 20 countries offer regularly repairs of equipment for free by volunteers, resulting in waste reduction, personal fulfillment, and social cohesion in the local community. In traditional terms, this is considered the informal economy, although this can also take the form of a commercial activity such as repair shops

for mobile phones and service concepts for customer loyalty. Local thrift stores, and platforms such as eBay, have contributed to a large market in used goods. Although it seems that the interest in used goods depends on the socioeconomic development of a community, there is little research on the impact of this market on the overall demand for materials and goods. For example, it is estimated that in The Netherlands three out of every four infant car seats are purchased on the used goods market. The sharing or collaborative economy (104, 105), supported by information technology, is another example of a development that may affect material consumption on a local scale, although not all types of sharing contribute to sustainable development and reduced resource consumption.

The discussion above demonstrates that within the existing economic and policy environment, governments are slow in developing and adopting policies aimed at managing material consumption and production, let alone addressing the fundamental drivers for material use. However, this should be part of the fundamental transition to a low-carbon economy. The experience with other transitions in recent history (e.g., asbestos, DDT, ozone-depleting substances, cigarette smoking, and obesity) has a mixed track record. The lead time from knowledge to policy has always been long, often decades or sometimes even longer (106) after the science on the negative impacts has well been proven. Still, our society is different from other previous societies (107), as we have the knowledge and the foresight to evaluate the risks and design appropriate response strategies. Despite our current knowledge, society is slow to change. This may be partly due to the interests of powerful incumbents in the current status quo (108, 109), the lack of impact of knowledge about personal behavior (e.g., with respect to public health), the increased focus of policymakers and investors on short-term returns, as well as inertness in the political and economic system.

The discussion above shows that voluntary actions by individuals were never sufficient to achieve the required reductions. Government policy and regulation will be required to obtain and consolidate the required results. Researchers are studying the transition and innovation processes, and we may be able to learn from this how to reduce the use of materials and energy. Currently, few studies have looked at fundamental changes in the energy and materials systems. As energy and materials are so woven into the fabric of our current economically driven definition of welfare, a more fundamental discussion of the current economic system is necessary to address materials use within the context of environmental sustainability. In most countries today, policy aims at stimulating economic growth (expressed as GDP). Substituting materials and energy for human labor is considered the formula for improved productivity and economic growth in today's economic thinking. However, economic growth defined as GDP is just a derived index that even excludes most issues that affect the well-being of people. This suggests that current metrics are part of the problem. Although alternative metrics have been developed [e.g., the Human Development Index, Bhutan's Gross Happiness Product, the Inclusive Wealth Index (44)], these have not been widely accepted in (economic) policy. While it is recognized as inadequate by a wide body of literature (73, 78), GDP growth remains the mantra for virtually every government. As income grows, material and energy consumption grows, yet it does not make people's lives more fulfilling (110); individuals do not relate to GDP as a metric of their own well-being. Indeed, as Harari (95) puts it, the ownership of the material goods "spawns new obligations," and that is also reflected in an increasing imbalance between leisure and work life. Working hours in developed economies seem to keep rising, especially in the United States and Asia, partially in response to consumerism, and partially due to other causes, e.g., rising inequality that forces people to work multiple low-income jobs (111), globalization, and cultural differences. However, even in the United States, the wisdom behind long working hours is debated, as it does not necessarily add to productivity, and social movements are growing that focus on an improved life balance (e.g., simplicity, tiny homes). These movements question wants as defined by Keynes, and by voluntarily limiting

these, try to achieve a better quality of life. Hence, we need to learn from social sciences (e.g., anthropology, development studies), from these movements, and from societies that have reached high welfare levels with low levels of consumption, as well as from individual behavior affecting the relationship to material goods (112). In this context, the Pope, the organization Islamic Relief Worldwide, and the Orthodox Church have all issued recent statements linking environmental harm to overconsumption and the lack of (spiritual) fulfillment, suggesting a further area of research on the relationship between personal welfare, social status, and material consumption, and how this behavior may be changed for the pursuit of reducing material consumption.

Adopting a different economic paradigm, such as steady-state economics, degrowth, and a-growth (see, e.g., 78, 113–115), is discussed as a way to ensure that sustainability is fully integrated in economics. More importantly, discussions on a new economic paradigm need to address the fundamental drivers of life fulfillment of people and their relationship with materials, and the role of manufacturing as the only pathway to economic development in poor countries. A new metric for well-being is the first step and can build on the ways that people measure their personal well-being. As a second step, finding alternative development pathways (based on the research outlined above) can help plot a transition that would lead to well-being with lower material use.

CONCLUSIONS

Improving material efficiency is defined as reducing the volume of new material production needed to deliver a specific material service. Despite growing attention to material efficiency in recent years, there is little traction in evaluating and realizing its potential as part of a sustainability strategy. As evidenced by the recent IPCC AR5 report (116), 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, lightweighting the product, reducing losses in the supply chain, product and/or component reuse, recycling, and downcycling. There is ample proof in the literature that material efficiency improvement may lead to multiple environmental and economic benefits. Studies have shown the existence of large technical potentials for material efficiency improvement, up to reductions of 50% of the material use of such material services as diverse as buildings and packaging. Realizing these opportunities would result in environmental benefits, while enabling economic gains. Policymakers should include material-efficient service design and supply in policy design, and develop monitoring systems of material use. Experience, albeit limited, shows that opportunities can be successfully realized through a variety of instruments to, e.g., support enterprises in reducing waste in manufacturing and product design, in developing new business models, and in procurement. Companies are starting to recognize the importance of understanding and managing the whole supply chain, and new tools are introduced by some companies to not only demonstrate these benefits to customers, but also introduce manufacturing concepts to improve material efficiency. Still, today only a limited part of the potential is realized in practice, while the overall consumption of material services increases. This is leading to increased global production of materials. Whereas developing nations need to increase their material consumption to meet basic human needs, in industrialized countries there is limited, if any, evidence of even relative dematerialization, let alone the absolute dematerialization that is needed to maintain a sustainable development path for our energy and materials system. Current developments and policies are insufficient to realize the full potential of material efficiency improvement to contribute to reduced material use, energy use, and environmental impact. This review emphasizes the role of consumption patterns, which are embedded in our current economic and social systems.

This highlights the need for a better understanding of consumption as a key driver for material use. People have surrounded themselves with an increasing volume of material, but this has come at the cost of reduced leisure time, and even quality of life. Economy-wide, this is symbolized by the central policy drive to grow GDP, even though it is not necessarily improving the welfare of all of its citizens. Therefore, 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 well-being within planetary boundaries. Important contributions have been made in this discussion but are still far from mainstream 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 individuals and society can change quickly in response to sudden shocks. To ensure 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 behavior (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 well-being. Improving the efficiency with which we supply essential material services (“needs” as defined by Keynes) is an important area from which to start. It needs to be actively integrated with the current toolbox of climate, environmental, and economic policy, and in the evaluation of strategies to ensure that mankind does not exceed planetary boundaries.

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