A Global Assessment of Manufacturing: Economic Development, Energy Use, Carbon Emissions, and the Potential for Energy Efficiency and Materials Recycling

Timothy G. Gutowski,[1] Julian M. Allwood,[3]
Christoph Herrmann,[4] and Sahil Sahni[2]

[1]Department of Mechanical Engineering, [2]Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139; email: gutowski@mit.edu

[3]Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, United Kingdom

[4]Institute of Machine Tools and Production Technology, Technische Universität, Braunschweig D-38106, Germany

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Abstract

We present in two parts an assessment of global manufacturing. In the first part, we review economic development, pollution, and carbon emissions from a country perspective, tracking the rise of China and other developing countries. The results show not only a rise in the economic fortunes of the newly industrializing nations, but also a significant rise in global pollution, particularly air pollution and CO_2 emissions largely from coal use, which alter and even reverse previous global trends. In the second part, we change perspective and quantitatively evaluate two important technical strategies to reduce pollution and carbon emissions: energy efficiency and materials recycling. We subdivide the manufacturing sector on the basis of the five major subsectors that dominate energy use and carbon emissions: (*a*) iron and steel, (*b*) cement, (*c*) plastics, (*d*) paper, and (*e*) aluminum. The analysis identifies technical constraints on these strategies, but by combined and aggressive action, industry should be able to balance increases in demand with these technical improvements. The result would be high but relatively flat energy use and carbon emissions. The review closes by demonstrating the consequences of extrapolating trends in production and carbon emissions and suggesting two options for further environmental improvements, materials efficiency, and demand reduction.

Contents

1. THE REOCCURRING AND CHANGING PATTERNS OF MANUFACTURING

We start with a historical review of the changing geographical patterns of manufacturing over the past four decades, as well as the reoccurring pattern for newly industrialized countries experiencing economic growth and increased pollution.

1.1. Economic Growth and Pollution

The term manufacturing applies to a wide range of industrial activities generally focused on making products. This includes producing not only automobiles, airplanes, buildings, electronics, clothing, and other products but also the input materials, including steel, aluminum, concrete, timber, coal, oil, and silicon, and the energy resources needed to produce them. Manufacturing plays an important economic role by providing jobs and the means by which an economy can grow, but it is also disruptive and often harmful to both humans and the environment.

It is hard to overstate the historical importance of manufacturing as an economic force. It has been and remains the major mechanism by which large nations develop economically, resulting in higher per capita incomes, a better standard of living, and eventually better health and longer life expectancy. Amsden (1) describes the economic dynamic succinctly:

> Economic development is a process of moving from a set of assets based on primary products, exploited by unskilled labor, to a set of assets based on knowledge, exploited by skilled labor. The transformation involves attracting capital, human and physical, out of rent seeking, commerce, and "agriculture" (broadly defined), and into manufacturing, the heart of modern economic growth. (p. 2)

Many of the major economic leaders for the past century, such as the United Kingdom, Germany, the United States, and more recently Japan, have risen to their developed status due in large part to their mastery of manufacturing, and many emerging economies such as China, India, and Brazil are also relying on manufacturing to build infrastructure, create jobs, and sell exports to transition to new, higher living standards. Besides these two groups, other countries such as South Korea and Taiwan have greatly improved their economies, again by using manufacturing as a principal means of development.

This development, however, comes with a cost. For example, the transformation from agrarian society to manufacturing can be wrenching, uprooting people from their traditional rural setting, separating them from their family and friends, and subjecting them to new, much more regimented lifestyles, in unfamiliar and sometimes unsafe circumstances. These new circumstances can lead to the abuse of the workers, as well as of the environment.

Throughout history one can observe the reoccurring pattern of economic development and harm, both environmental and human, as manufacturing grows to become a significant economic activity. Accounts of the Industrial Revolution in England include not only significant increases in income, but also significant pollution and human tragedy. For example, as Manchester rose to an international center for steam-powered cotton production in the nineteenth century, it also significantly degraded its air quality by burning coal for heat and power. An 1840s government report referred to the Manchester air as "intolerable" and "visibly impure" (2, p. 81). The resulting living conditions for the residents significantly shortened their life expectancy. For example, the poor of Manchester lived for only 17 years on average, compared with 38 years for the rural poor of England, and the wealthy of Manchester lived for only 38 years, versus 52 years for their rural counterparts (2, 3). Such differences are due not only to increased coal burning for industry but also to increased coal burning in the home (4). Similar patterns of pollution and hardship have been recorded for all the major manufacturing countries as they transitioned from largely agricultural societies, lacking experience with or need for environmental and labor laws, to developed countries. In the process, the transitioning nations have addressed labor and environmental issues to varying degrees, and living standards have risen accordingly. Each of these countries has improved, and average life expectancies have increased, often dramatically. For example, according to the UN, life expectancies in the United Kingdom, Germany, the United States, and Japan—currently between 76 years (men in the United States) and 87 years (women in Japan)—are among the top 20% globally (5).

Today, we see similar patterns of development as the so-called developing and emerging economies work to build a manufacturing base for their economies. For example, in recent decades China has skyrocketed to a major economic and manufacturing power in the world, maintaining near double-digit economic growth, but simultaneously it has fouled its water and air and sickened its people (6, 7). According to the World Bank, China's cities are among the most polluted in the world, with fine particulate matter PM_{10} and $PM_{2.5}$ exceeding the EU's air quality standard of 40 $\mu g/m^3$ for 99% of the country's urban population. For example, measured $PM_{2.5}$ concentrations in Guangzhou in 2007–2008 averaged 70.1 $\mu g/m^3$, or approximately seven times the World Health Organization's (WHO's) annual average standard for $PM_{2.5}$ (8). Furthermore, some data show that NO_x and SO_2 pollutants in the air in China have been constantly rising (6, 9).[1] By WHO estimates, ~300,000 people died prematurely in 2001 as a result of China's unhealthy urban air, and more recent estimates place the toll much higher. For example, the Global Burden of Disease Study 2010 report places at 1.2 million the premature deaths in China due to air pollution (10). And although China appears to have put in place additional policies to address SO_2, PM, and NO_x emissions, local utilities are resistant to implementing these improvements without financial support (6, 11). As a consequence, the trend of constantly declining global SO_2 emissions (from combustion and processing) that began in 1975 has been reversed and has been rising again since about 2000. For example, in 2005 China and India contributed ~34% of global SO_2, whereas in 1970 they contributed less than 7% (9). However, China's National Bureau of Statistics reports improvements in its industrial wastewater discharge quality (6), and evidence of carbon monoxide emissions from 2005 to 2009 shows improvement due to energy efficiency and emissions-control regulations (12).

This pattern of growth and pollution followed by significant net benefits, including pollution reduction, has been observed by many and generalized in the so-called environmental Kuznets curve (EKC). The EKC hypothesizes that pollution rises as per capita income rises and, after some critical point, declines. The

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[1] In a historical comparison, Grübler (4) described how London's nineteenth-century coal burning resulted in high levels of smog and led to particulate and SO_2 concentrations of up to 4,000 $\mu g/m^3$.

Industrial Revolution in the United Kingdom and the emergence of China as a manufacturing power seem to suggest this same pattern. And many have reported similar patterns in studies of specific pollutants in certain countries and regions (13). However, recent reviews of EKC models show that they do not stand up to econometric scrutiny. That is, although there is clear evidence of improvements, particularly when looking at concentrations of specific pollutants in urban areas, the EKC hypothesis is much less secure when looking at total aggregated pollutants. Stern (14) provides a heuristic explanation for this observation by breaking down the phenomenon into scale effects (i.e., growth) and efficiency effects (i.e., improvements in pollution intensity or pollution/output). For wealthy countries, growth is slower, and efficiency effects can overcome scale effects; however, the reverse can be true in emerging countries. Furthermore, the efficiency effects in wealthy countries may be due in part to outsourcing. In addition, just as one pollutant comes under control, new toxins appear. For instance, if pollutants are aggregated to include CO_2 and waste, then they continue to rise monotonically (14), and still other potential new categories of pollutants, such as nanomaterials or genetically modified biological materials, which are not yet fully understood, might come into play. It often takes decades to identify the consequences of the new chemicals and materials we are constantly developing. Nevertheless, there are circumstances in which pollution from developing countries can be reduced because of both the availability of new technology and the adoption of stringent regulation standards as currently practiced in the developed world (13). Ultimately, we need a more detailed understanding of the actual changes in society as wealth increases before an EKC mathematical framework can be confidently proposed (15).

Although the pattern of economic development through increased manufacturing may still change, currently it is typically accompanied by a significant amount of pollution side effects but, of course, with a promise of future benefits. What is clearly different today from the period of the Industrial Revolution, however, is both the scale of manufacturing and the location displacement of the pollution side effects. In terms of scale, global manufacturing's annual output (value added) grew by a factor of 200 between 1800 and 2010 and by a factor of 60 between 1900 and 2010, the latter approximating the same increase as in the world production of steel [25 million tonnes (Mt) to 1,500 Mt] in that same period. The growth from 1900 to 2008 translates into a compound annual growth rate of ∼3.7%. This is faster than the ∼3.1% increase in world GDP over the same period (4, 16–19). The result of this expansion is that manufacturing is now an enormous venture, 200 times larger than it was in 1800 on an absolute scale and approximately 30 times larger on a per capita scale. Such a pervasive and widespread activity results in enormous material flows and emits huge quantities of waste products. These flows now rival natural geologic flows and extend pollution well beyond the borders of the polluter, even to the extent of altering the ecology of the planet. For example, world industry now uses ∼190 exajoules of primary energy, approximately one-third of all energy used globally, and emits ∼14 billion tonnes (Gt) of CO_2 and 50 Mt of SO_2, or almost 40% of all global anthropogenic emissions from energy and industrial processes each year for each of these gases, respectively (9, 20, 21). Furthermore, global manufacturing is growing and increasing its energy use and carbon emissions.

In this review, we focus particularly on energy use and carbon emissions in manufacturing. This is because energy use in manufacturing is dominated by fossil fuels (more than 90%) (22), and these fuels, especially coal, are responsible for the majority of the CO_2 emitted by manufacturing and for many pollutants (e.g., SO_2, NO_x, PM_{10}, and $PM_{2.5}$). In general, CO_2 from manufacturing also includes process emissions, for example, for the calcination of limestone, and for the carbon reduction of various metal oxides, especially iron oxides. Because climate change responds to the absolute amount of CO_2 in the atmosphere, we primarily report total absolute quantities of CO_2 emitted by various countries or industrial sectors. Attempts to normalize these values to create so-called emission intensities or energy intensities are explained in the context of the problem being addressed.

1.2. The Changing Geography of Manufacturing

Manufacturing is a competitive sport, and as such it is constantly changing as the source of comparative advantage shifts. For example, several hundred years ago, China and India dominated world manufacturing; in 1750, they produced well over one-half of the world's manufactured goods. But then they lost out to Britain and the Industrial Revolution that spread quickly through Western Europe and the United States, reducing their share to well below 10% by 1900. In the twentieth century, the United Kingdom, Western Europe, and the United States completely dominated manufacturing with a combined world share well above 50% for the first three-quarters of the century and then declining slightly as Japan rose to prominence circa 1975 (3). More recently, the world has seen a historic shift, with a surge in manufacturing coming primarily from China, but with notable growth coming from several other Asian and Latin American countries, particularly India and Brazil who ranked among the top 10 manufacturers in the world in 2010. **Figure 1** illustrates this pattern of relative decline in the West and advancement in the East, with regions categorized as the West (United Kingdom, United States, Germany, Japan) and the East (China, India, Indonesia, Taiwan, South Korea, and Brazil). Although our descriptors are not quite geographically pure, they do capture the main players in this relative transition in manufacturing. The individual plots for China and the United States indicate a historic return of China as one of the largest manufacturers in the world, with approximately 20% of global manufacturing's GDP in 2010.

Although the percentage of world manufacturing output (current dollars, international exchange rates) is shown in **Figure 1** as decreasing for the West and the United States, their absolute outputs increased during this time. Hence, the percentage for the East increased even faster. In fact, the growth rates for these countries have been exceptional and prolonged, a combination that is absolutely required if they are to join in the lifestyles enjoyed by the developed nations. Allen (3) argues that, although

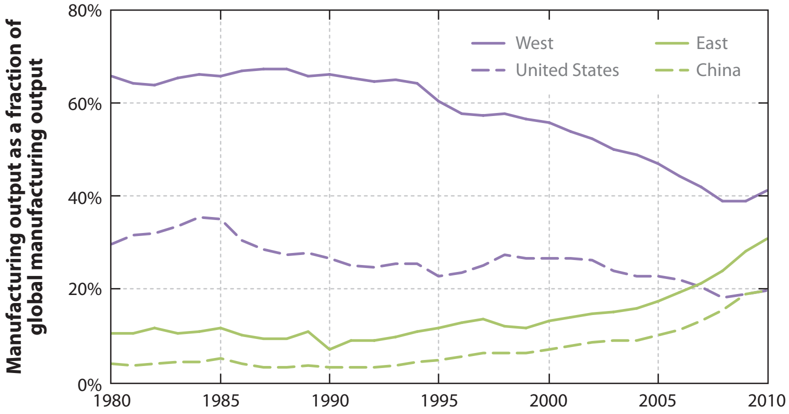

Figure 1

Manufacturing output (current dollars, international exchange rates) as a fraction of the total for the West (United Kingdom, United States, Germany, Japan) and the East (China, India, Indonesia, Taiwan, South Korea, Brazil), with China and the United States also shown separately (23, 24).

the developed nations can grow only at the pace of new technology development (∼1–2% per year in GDP per capita), to join the developed world in two generations (60 years) the emerging nations must grow at ∼6% or higher (GDP) depending on population growth. This assumes that the developing nation started out with a GDP per capita of one-fifth to one-quarter that of the developed world. If the ratio is smaller, then the growth rate must be higher.

The transition shown in **Figure 1** for manufacturing GDP is also found in the pattern for the use of resources and the emissions from these different regions, only with a twist: The emissions for the emerging nations of the East are generally considerably larger than those for the West. The result is that even when the East accounts for only a small fraction of manufacturing GDP, its emissions of CO_2, SO_2, PM, and NO_x account for much higher fractions of the world total. For example, consider an earlier period circa 1995 when the East contributed only a small fraction to world manufacturing output (∼10%; compared with 60% for the West). Even then, these fledgling manufacturing industries of the East were already significant contributors to world manufacturing CO_2 output (more than 30% and slightly larger than that of the West). This result is due in large part to the nature of their manufacturing, building heavy industries, and a heavy dependence on coal, as is true for China and India. As the East grew, and particularly as it expanded heavy industry (i.e., iron and steel, cement, and chemicals in particular), their manufacturing CO_2 emissions grew significantly. This is shown in **Figure 2**.

Currently, the East contributes ∼50% of the total global manufacturing CO_2. This is almost a complete role reversal with the West, which dominated in the early 1970s with its CO_2 fraction in the vicinity of 38–44%. **Table 1** gives the rank order of the top 10 countries in terms of manufacturing output and CO_2 and in the production of steel and cement for 2010.

Table 1 indicates that many of the developing countries rank much higher in terms of CO_2 emissions than in terms of manufacturing output. The exception to this pattern is Brazil, with a relatively low carbon electric grid due to a significant contribution by hydroelectricity. (See Reference 27 for a discussion of greenhouse gases from hydropower.) Furthermore, four of the top ten manufacturing carbon

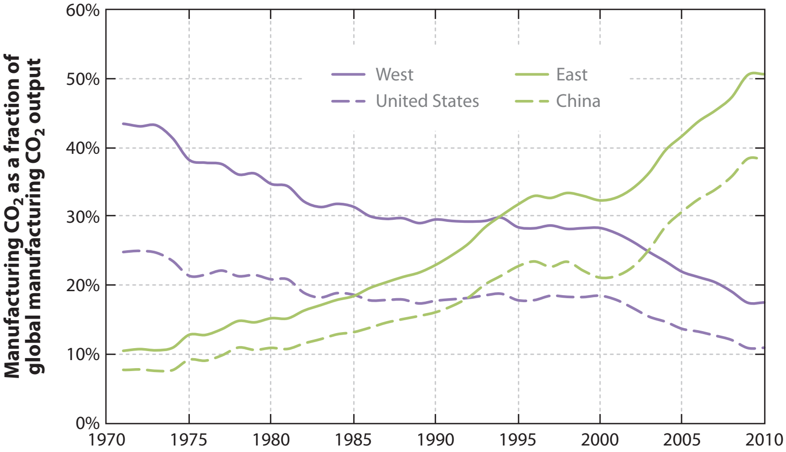

Figure 2

Manufacturing CO_2 emissions (including direct, allocations for heat, electricity, and construction) as a fraction of the global manufacturing total for the West (United Kingdom, United States, Germany, Japan) and the East (China, India, Indonesia, Taiwan, South Korea, Brazil), with China and the United States also shown separately (25).

Table 1 World manufacturing rankings: output, CO_2, and steel and cement production in 2010[a]

Manufacturing output rank	Country	Manufacturing output[b]	CO_2 production rank	Country	CO_2 production[c]	Production quantity rank	
						Steel	Cement
1	USA	1.77	1	China	5,097	1	1
2	China	1.76	2	USA	1,457	3	3
3	Japan	1.06	3	India	858	4	2
4	Germany	0.61	4	Russian Fed.	765	5	7
5	Italy	0.31	5	Japan	452	2	6
6	Brazil	0.30	6	South Korea	280	6	12
7	South Korea	0.28	7	Germany	278	7	18
8	France	0.25	8	Canada	209	16	31
9	UK	0.23	9	Indonesia	196	37	19
10	India	0.23	10	Saudi Arabia	192	27	12
Source:	World Bank		IEA			WSA	USGS

[a] Data compiled from References 19, 23, 25, and 26. Abbreviations: WSA, World Steel Association; IEA, International Energy Association; USGS, US Geological Survey.

[b] In trillions of US dollars.

[c] CO_2 production is given in million tonnes. CO_2 emissions with electricity and heat are allocated for the sum of manufacturing industries, construction and other energy industry uses.

emitters are not in the top ten manufacturers based on monetary output. And six of the top ten carbon emitters are not in the high-income group.

Putting these trends together produces a world manufacturing CO_2 plot as shown in **Figure 3**. The pattern shows a period of gradually increasing CO_2 emissions from 1970 to 2002, followed by a relatively sharp rise after 2002. During the earlier period, the developed world reduced its CO_2 emissions largely by slowing or even reducing its outputs in the heavy industries, with the developing and emerging nations picking up that slack with their increased production, so that total global emissions continued an upward slope (**Figure 3**). The sharp rise starting in 2002 corresponds to a significant expansion in China, which joined the World Trade Organization in 2001 and directed much of its expansion into exports.

This combination of rising carbon emissions and increasing exports for the manufacturing nations means that a significant amount of carbon is being traded as embodied emissions in products. Recent studies suggest that approximately one-quarter of all CO_2 emissions are embodied in international trade. For example, Peters & Hertwich (28) estimate the figure to be 22% (5.3 Gt CO_2) in 2001, while Davis and colleagues (29, 30) estimate it at 23% (6.2 Gt CO_2) in 2004.

Regional studies show that, on balance, the developed world is a significant importer of carbon emissions, whereas the developing world is primarily an exporter. That is, when accounting for the carbon emissions from the manufacturing of products that are traded, the major direction of carbon flow is from the developing to the developed world. For example, Weber & Matthews (31) estimate carbon emissions embodied in trade for consumption in the United States at between 9% and 14% in 1997 and between 13% and 30% in 2004. Similar results were found for carbon imports to Switzerland, Sweden, Austria, the United Kingdom, and France, where Davis & Caldeira (29) estimate CO_2 embodied in imports to

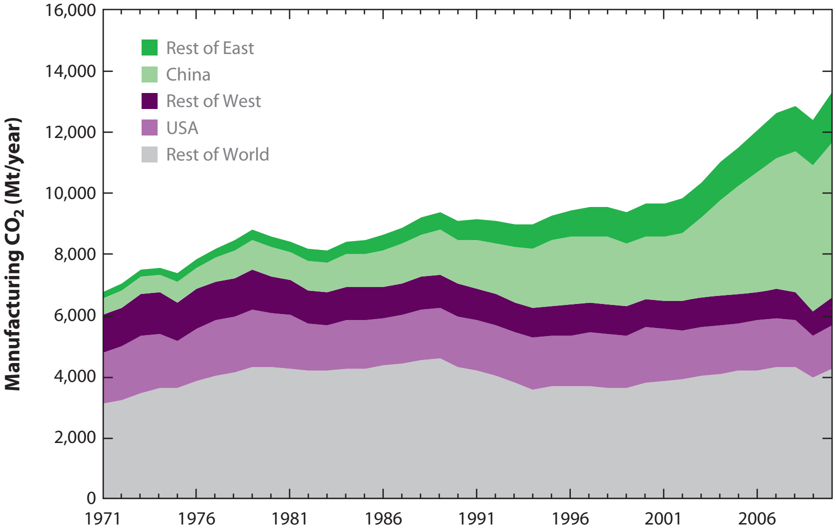

Figure 3

CO_2 emissions from the manufacturing sector, including direct allocations for heat, electricity, and construction, for various regions of the world (25).

constitute more than 30% (of consumption), or more than 4 tons per capita for these countries in 2004. The leading exporters of emissions in 2004 were China (1.4 Gt CO_2), the United States (0.5 Gt CO_2), and Russia (0.4 Gt CO_2); the leading importers were the United States (1.25 Gt CO_2), Germany and Japan (0.4 Gt CO_2 each), and China (0.3 Gt CO_2) (29–31).

Whether the responsibility for carbon emissions should be assigned to exporters or importers is a debate with many opinions. Both sides presumably gain by the trade but would suffer different consequences should a carbon tax be imposed. For example, in one study the consequences of a US\$50/t CO_2 tax levied on producers was found to result in an effective average tariff on Chinese exports of 9.7%, whereas for the United States it would be 2.9% and for the EU 1.4% (32, 33). Of course, if the taxes were levied on the consumer, the high carbon intensity products would again be exposed, but the mechanisms and locations for the financial transactions would differ. A problem arises, however, if not all countries participate in the carbon tax policy. Then, there is the possibility of production moving to nonparticipating countries resulting in so-called carbon leakage if the emissions are assigned to producers. In this case, there is a clear advantage to using consumption-based inventories. Such a scheme could then include nonparticipating polluters and work against the so-called race to the bottom, when production moves to nonregulated countries. At the same time, from a practical point of view, it is much more difficult to estimate consumption-based carbon. These estimates are calculated using multiregional input-output models. There are significant challenges in collecting the data and converting the country data to a consistent set of global data. Generally, there has been a five-year lag between data collection and model availability. In addition, because the consumption-based calculations are much more complex than production-based calculations, they are also somewhat less accurate. Nevertheless, the advantage of discouraging the so-called production pollution havens favors consumption-based accounting (28). At the same time, the implementation of consumption-based accounting and regulations could be interpreted as establishing trade barriers and will require further refinements in international trade agreements.

Because of the significant magnitude of China's carbon exports, much attention has been paid to them. A recent paper in *Energy Policy* (34) examined China's annual CO_2 emissions from exports from 2002 to 2008 using a structural decomposition analysis. The paper gives reasonably good agreement with other studies during this period and shows a trend of increasing trade emissions as a fraction of total domestic CO_2 emissions for China, rising from approximately 15–20% in 1997 to an estimated 48% in 2008. The decomposition analysis revealed the main driver for this increase: a change in export composition, primarily due to an increase in the fraction of metal products, and to a lesser extent electronics, in China's exports. Other smaller factors included an increase in exports, a small change in economic structure, and a significant reduction in emissions intensity. However, the emissions intensity is measured in terms of CO_2 per monetary value of exports, and because Chinese exports are becoming more valuable as they transition from low-end products such as textiles to higher-end products such as machinery and electronics, this could have the effect of making emissions intensity improve. Overall, however, the study suggests that CO_2 emissions attributable to exports increased rather dramatically as a fraction of total domestic emissions to approximately 50% in 2008 (34).

1.3. The Reoccurring and Changing Patterns of Manufacturing: Summary

In summary, then, global manufacturing appears to be in the middle of a historic transition, with emerging economies, led by China, challenging the industrialized nations' dominant position. **Figure 2** shows this trend. Such a transition is necessary if the developing nations are to raise themselves to a higher standard of living through industrialization. Whether this pattern continues, however, is not assured. Surges of this type have faltered before, most notably with Japan in the 1990s. What is important from an environmental point of view is that the growth of the developing nations will require heavy industry, and this will most likely be fueled by coal. This would be particularly true for China, India, and Indonesia, all large coal producers. The question is whether this industrial development will take place in an environmentally benign way. Although there is no absolute answer to this question, it is the central dilemma that faces global manufacturing. Below, we summarize six important parts of this problem, and in the next section we review two general strategies that could help reduce the environmental load associated with manufacturing.

1. Product mix: Significant carbon emissions from manufacturing become noticeable when emerging countries develop heavy industries. This is part of the so-called "big push industrialization," as has been practiced by many former emerging countries such as Japan, Taiwan, and South Korea and is currently being practiced by China (3). Developing nations have many physical needs for infrastructure, housing, and transportation, and providing for them locally creates opportunities for jobs and nurtures local industry as it grows and develops. While other forms of development are possible such as agriculture, trading, mining, and services, they have not been as successful as manufacturing for large developing countries. **Figure 4*a*** shows how industrial CO_2 is dominated by just five of the basic materials from the so-called heavy industries: iron and steel, cement, plastics, paper, and aluminum. In a subsequent discussion, we refer to these as the big five. Notice in **Table 1** how the top seven CO_2-producing manufacturing nations are also the top seven steel producers, and, with the exception of Japan, they are in the same order.
2. Scale and future demand: The number of people in the world with basic needs still unmet is enormous. Of the current seven billion people on the planet, only approximately one billion are in the

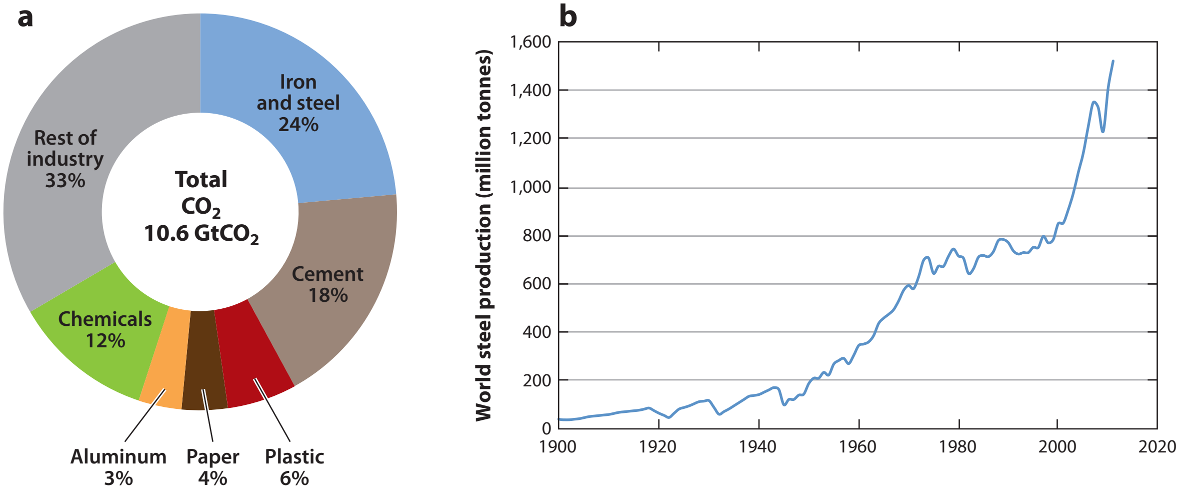

Figure 4

(*a*) Total industry CO_2 (from fuels and process emissions) broken down by major subsectors (39). (*b*) Growth of steel production from 1900 to 2011 (18, 19).

high-income category (i.e., gross national income per capita greater than approximately \$12,000), and approximately three billion people are below \$3,000 (35). Despite indications of materials saturation (in iron, steel, and concrete) in a few developed countries (36–38), there are still many materials to be produced, especially if poor countries aspire to the rich countries' levels of consumption. Most of the growth shown for steel in **Figure 4*b*** after circa 2001 is due to China's production growth.

3. Efficiency: The large investments required for primary materials production facilities can take decades to recover, and thus once built, these facilities are closed down only reluctantly; as such, some number of inefficient facilities continue to operate. But here the emerging countries can have the advantage. New facilities can employ the most energy-efficient technologies. According to the International Aluminium Institute, Africa and China are the most efficient aluminum smelting regions in the world (39–41). However, as an industrial subsector, materials are only moderately traded compared with other products, meaning most demand is local. This can act to shelter regional industry and potentially allow for low-efficiency operation. Furthermore, not all automation is cost-effective in low–labor rate countries, and future energy-efficiency improvements for the traditional heavy industries are limited (3, 42, 43). Section 2 addresses this issue in more detail.
4. Fuels: By definition, manufacturers competing in commodity materials must be very cost conscious, and energy is a significant component of cost. It is still the case that coal is the cheapest fuel, and in some locations often the only one available in large quantities. As a result, coal has powered most of the emerging countries' manufacturing. For example, of the ten largest manufacturing CO_2 producers in **Table 1**, six are among the ten largest coal producers, and the top three rank in exactly the same order as coal production (44). In addition, coal-exporting countries such as Russia and Australia increasingly supply the East with coal. This high use of coal by the emerging manufacturing countries results in high production not only of CO_2 but also of other air

pollutants. Future development of natural gas, though uncertain at this time, could very well modify this pattern.

5. Pollution control: Although we have not emphasized pollution control in this review, there are clear differences in the level of implementation in the developing versus the developed world. For example, an analysis of the SO_2 emissions from the global manufacturing sector indicates a 10% decline between the years 1990 and 2000, with the US manufacturing sector declining by 25% even while output rose by 24% over roughly the same period (1987–2001). A decomposition analysis reveals that most of this improvement came from technology (pollution controls) and not offshoring (45). In fact, total global SO_2 emissions had been on the decline since the mid-1970s. However, with the rise of the East, led by China, and significant increases in coal burning without adequate pollution controls, global SO_2 emissions again began to rise starting in 2000 (9, 46). National aggregate sulfur coal emission factors (tS/kt coal) indicate a steady decline for North America, Europe, South Korea, and Japan from 1970 to 2005, whereas China, Australia, New Zealand, and the former Soviet Union have remained essentially flat during this period, with at most modest improvements (9).
6. Trade: The purpose of trade is to improve the economic well-being of the partners, but the ultimate effect on environmental impacts is less clear (47, 48). The answer one gets to this question depends in part on how long one is willing to wait. From the historical record, early heavy industrial development based on coal always leads to increased pollution. With time, and increased affluence, however, clean water and urban sanitation usually improve and SO_2 emissions decrease, whereas such outputs as CO_2 and solid waste generally do not follow this pattern (14, 47). The issue of industrial migration to poorly regulated countries is an ongoing area of research, often called the pollution haven hypothesis. Most studies in this area have been inconclusive, pointing out that corporate location decisions involve many factors including distance to market, skilled labor availability, taxes, and many other issues (47, 49). However, some more recent studies find more mixed results, with some suggesting that the pollution haven hypothesis is real and possibly large (48).

2. EFFICIENCY IMPROVEMENTS AND MATERIALS RECYCLING

In this section, we turn our attention to two strategies to improve the environmental performance of manufacturing: energy efficiency and materials recycling. Taken together, these strategies can reduce not only energy use (which is predominantly from fossil fuels), but also carbon emissions as well as other pollutants. For example, the current increases in global manufacturing CO_2 as shown in **Figure 3** are in large part due to coal use in China, and without proper controls, coal is a major source of several important air pollutants (i.e., PM, SO_2, and NO_x) (50). Any strategy that reduces coal use will also work to reduce these pollutants.

To examine these strategies, we shift our focus from exploring the historical shift in the national character of manufacturing, as in Section 1, to look at the industrial subsectors that dominate energy use and carbon emissions. As mentioned earlier, we focus on the big five materials: (*a*) iron and steel, (*b*) cement, (*c*) plastic, (*d*) paper, and (*e*) aluminum. This approach allows us to assess the technical improvement potential for manufacturing, and hence to speculate about possible future scenarios. We do this without regard to cost and proceed as if the financial incentives exist to promote these activities. We start by looking first at the energy-efficiency potential and then at the materials recycling potential. Finally, we bring this together to estimate manufacturing's self-improvement potential, and in particular how it will fare compared with projected increases in demand.

2.1. The Energy Required to Produce Materials

The energy required to produce materials has received considerable attention in the literature, and we now have in hand several estimates for potential efficiency improvements through the adoption of best available technology (BAT). For example, **Table 2** gives global average values for the direct energy required to produce the big five materials for primary and secondary production, and reports ranges for potential efficiency improvements to primary production (the third column). The last column is simply the theoretical benefit of replacing all primary production by secondary production.[2] The energy values (columns 2 and 4) include the fuels and other direct energy inputs (e.g., electricity) required to extract and produce these materials per kilogram of material output (38, 42). These numbers are approximations based on a review and reconciliation of various references, and are probably no better than ±10% (38, 42, 51). The direct energy values include neither the electricity generation losses of the utilities nor the fuel value of the material.

As seen in the table, the potential reductions in energy intensity through the implementation of BAT vary considerably; for example, according to Saygin et al. (52), the potential to reduce energy used in steelmaking varies from 9% in the industrialized world to ~30% in the developing world. When aggregated over the materials production sector, estimated reductions generally range from 20% to 30% (38, 39, 42, 52). For example, Saygin et al. (52) suggest an overall efficiency improvement potential of 27 ± 8%. Although these gains are significant and constitute a necessary part of a future reduced energy scenario for the industrial sector, they are small compared with past gains in these industries and with the needed improvements if we are to meet carbon reduction targets to limit global warming. For example, the Intergovernmental Panel on Climate Change recommends a minimum reduction in carbon emissions by half by the year 2050 (22). If we make the reasonable assumption that the materials sector will see a doubling in demand by that time, then the carbon intensity of the materials sector must be reduced by 75%. Clearly, this magnitude of improvement cannot be met through efficiency improvements alone.

The irony here is that the reason this sector's future improvements are limited is that it has been paying close attention to efficiency, which it has already improved significantly. In fact, the basic processes to make these materials have been in place for a long time [~80 years for some plastics (the newest materials on the list) and more than 200 years for iron and steel]. This is important because during this time the primary processes have been improving, and the very best are now approaching their thermodynamic limits. For example, the best available smelting processes for iron and aluminum are now in the vicinity of 55–65% efficient. Although not all of the material production efficiencies are this high, they are high, and future improvements will be limited as indicated in **Table 2**. In fact, the energy efficiency of industry in the industrialized world is well above the other major energy-using sectors, including residential and commercial buildings and transportation. For example, in a recent paper Ayres et al. (53) calculated the second law exergy efficiency for US industry and for the US economy as a whole, with the result that industry is almost four times more efficient (30% versus 7.7%) (49). More details on potential energy-efficiency improvements for the materials sector can be found in Reference 52, which differentiates between the improvement potentials in the developing countries versus the industrialized countries.

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[2] The meaning of the numbers in the last column is quite different from the meaning of the values in the third column. Although BAT values are generally practical and achievable, the recycling values are only theoretical and there are many barriers to obtaining these high values, as is discussed in the next section.

Table 2 The estimated global average direct energy intensity of materials production [in megajoules/kilogram (MJ/kg)] and the estimated reductions from best available technology (BAT) as percent of primary

Material	Primary[a] (MJ/kg)	BAT reduction[b]	Secondary[a] (MJ/kg)	Max recycling reduction
Steel	25	9–30%	9	64%
Aluminum	93	12–23%	6	94%
Cement	4	20–25%	—	0%
Paper	23	18–28%	12	48%
Plastics	32	9–27%	15	25%

[a] See References 38 and 42.

[b] See References 38, 39, 42, 43, and 52.

Their work includes the surprise that although it is generally true that there is more improvement potential in the developing countries compared with the industrialized countries, the situation is reversed for aluminum smelting and pulp and paper production (52).

The last two columns in **Table 2** do suggest, however, that potentially larger efficiency gains can be had by increasing recycling. The gains look very significant for steel, aluminum, and paper. The low value for plastics is a result of our not including the fuel value of the material, which is substantial. For example, if the fuel value for the plastics is estimated as 40 MJ/kg and this is charged to primary production, then the maximum potential reduction from recapturing this material could be portrayed as 80%. Because of these potentially large gains, and because of several recent publications that allow global estimates for recycled materials, we turn our attention to recycling and the general notion of closed-loop manufacturing in the next section. Note that no secondary energy value is given in **Table 2** for cement because cement is not recycled (54).

2.2. Materials Recycling and Closed-Loop Manufacturing

The idea that material recycling is good for the environment is well known. For decades, it has been discussed in the literature, analyzed, debated, and promoted (55–61). The principal benefits come from the assumption that the recycled material can substitute for the primary material and therefore displaces various activities that use energy, emit pollution, and alter the landscape. That is, recycling should result in less mining and extraction, less smelting, less material refining, and less end-of-life (EOL) treatments such as incineration and landfill. In fact, recycling is often considered a cornerstone of a broader vision for the sustainability of a closed-loop society or of closed-loop manufacturing. Although all of this is well known, what is new are significant advances in our understanding of global material flows and recycling that allow for first estimates of global recycling rates. Some of this work has been going on for some time and is now bearing fruit. In particular, this includes the work of Graedel and coworkers (62–65), Allwood and coworkers (43, 66), and Ashby (51).

To frame this discussion, we provide a simplified materials flow diagram to emphasize two return routes for secondary supply, one from industry as prompt scrap (PS) and the other from EOL products as old scrap (OS).

The parameters c and f represent the fractions of the source streams that are returned to recycling: $f = Q_{\mathrm{os}}/Q_{\mathrm{EOL}}$ and $c = Q_{\mathrm{PS}}/Q_{\mathrm{p}}$. In practice, you want c to be small (because $1-c$ is the yield) and f to be large. The recycling rate as a fraction of total materials production output is r; i.e., $r = Q_{\mathrm{sec}}/Q_{\mathrm{p}}$. Because of growth and time delays in the use phase due to the long lifetimes of some products such as buildings, roads, and infrastructure generally referred to as stocks, EOL materials are less than demand: $Q_{\mathrm{EOL}} \leq Q_{\mathrm{D}}$. Manipulation shows that

$$r = c + f \cdot \frac{Q_{\mathrm{EOL}}}{Q_{\mathrm{p}}}. \qquad 1.$$

This reveals that making the early production processes more efficient (making c small) will actually reduce the recycling rate r. We return to this topic in the next section.

2.2.1. Recycling rates. Environmental gains from recycling cannot be realized unless the dispersed products are first collected and separated. These practical requirements greatly favor used materials that can be found in large quantities with known properties. Unfailingly, this occurs close to home while the materials are still in some stage of manufacture. In fact, this so-called internal recycling (of PS) currently constitutes approximately one-half of the secondary supply for steel and aluminum. Calling this material recycled, however, hides the fact that internal recycling actually is a form of inefficiency. That is, significant energy has been invested and carbon emitted to produce new material only to return a part of it to be reprocessed again before it can be turned into a useful product. Efforts to reduce the energy use and carbon emissions of materials production would rightly make every effort to reduce this fraction. For example, data from German steel production show this fraction decreasing from ∼46% of production in 1960 to ∼12.5% in 2005 (with corresponding yields improving from 54% to 87.5%) (40), and still other improvements can reduce it further (66, 67).

Because of this complication, studies of recycling often focus on what is collected and processed after the EOL of the product. Recent literature reports this rate as the EOL recycling rate, or EOL-RR (64). This rate is similar to f in **Figure 5** but accounts for losses in the secondary process; hence EOL-RR = fraction of Q_{sec} from Q_{os} minus secondary losses divided by Q_{p}. This means EOL-RR $\leq f$. A review of this literature indicates that recycling rates vary enormously across materials and that in general material recycling rates could be improved significantly. Two exceptions with already high values of EOL recycling are some metals and paper. For example, EOL-RR for metals used in the highest volumes (e.g., iron and steel, aluminum, copper, and lead) can be well above 50% (64), and we estimate that paper and cardboard are in the range of 40–50%. One of the highest metals recycling rates is for lead (Pb), a success story based on significant (but not yet totally inclusive) worldwide efforts to avoid the toxic effects of lead. The result is that the EOL-RR for lead is estimated to be more than 90%. In terms of climate change, however, the most important metal is iron (Fe), because steel is the single largest energy user and carbon emitter in the world materials sector. According to the United Nations report, the EOL-RR for steel is impressive, ranging from 70% to 90% (64).

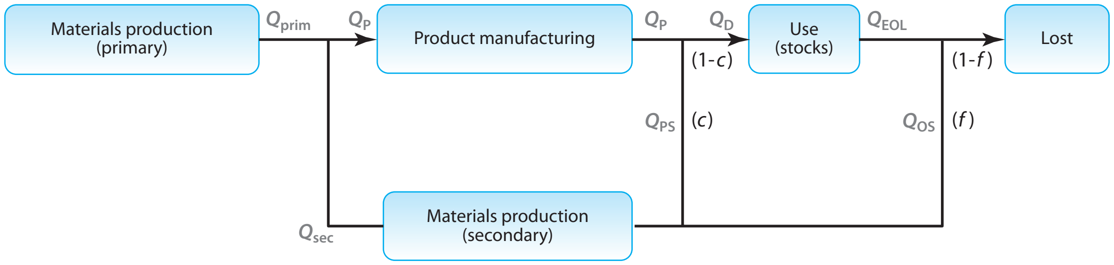

Figure 5

Simplified materials flow diagram for primary and secondary materials production, product manufacturing, and use phases. (To simplify the discussion, we do not show losses at the materials and manufacturing boxes. These are discussed in References 64–66.)

A counter example and indicator of the significant work that needs to be done at the other end of the scale comes from other metals, often valuable, but used in small quantities in various applications. These include alloying ingredients (vanadium, tellurium) or materials used in magnets (neodymium, samarium), batteries (lithium), lighting applications (europium, ytterbium), and thin-film photovoltaics (PVs) (tellurium, indium) that are essentially not recycled (EOL-RR reported as <1%) (64).

However, overall, and especially compared with the recycling of most other materials, metals recycling is a relative success story. That is, if one looks at an aggregate measure of metals recycling based on total mass, the EOL-RR for metals is high; we calculate it to be in the range of 51–87% using the UN Environment Programme (UNEP) estimates for EOL-RR and US Geological Survey (USGS) data for world production quantities for 37 of the most highly used metals. This is because the mass of steel and iron is so large (at least an order of magnitude larger than the next largest metal—aluminum—which also has a relatively high EOL-RR) that any aggregate statistic would be dominated by steel and iron. We get this result even though there are many examples of metals used in smaller quantities that are not recycled at all.[3]

However, the flipside is that other materials—nonmetals, with the exception of paper and cardboard previously mentioned—generally have rather low recycling rates compared with metals. For example, overall, plastics have low materials recycling rates even though bottles made from polyethylene terephthalate are often collected for curbside recycling in some communities. Plastics are victims of their own success: That they can be altered by a wide array of fillers and additives means that there is a great deal of uncertainty concerning their physical properties when they are collected. A second point is that plastics, although used in large volumes, usually are not incorporated as large masses in any given product. This presents a challenge to their collection and recycling. We estimate the EOL-RR for plastics to be ~2–7%. And, for cement, which plays a major role in energy use and carbon emissions, second only to steel in the materials sector, the situation is worse. Cement is not recycled. Concrete, however, can be reused in some instances (for example, as roadside barriers and cement blocks), can be downcycled (used, for example, as riprap for a seaside barrier), and can thereby be thought of as displacing some need for primary cement and concrete. However, this is not closed-loop recycling.

Overall, if one makes an estimate of the aggregate EOL recycling rates for mass aggregated metals, cement, paper, and plastics, the result would be in the range of 20–44%. These results are shown in **Table 3**. Again this result is dominated by two materials: steel, which is recycled at high rates, and cement, which is not recycled.

This result is important because future potential improvements would need to exceed the range given in **Table 3**. For example, in a world where half the total mass of these materials is unrecyclable cement and the other half is completely recycled, then the maximum mass average recycling rate EOL-RR would be 50%. A comparison of this value with the last row in **Table 3** (20–44%) gives an indication of the maximum potential improvement. This exercise underscores the importance of future research to further refine our knowledge of recycling rates.

2.2.2. Scrap availability. To successfully reduce the environmental impacts associated with materials production, it is important not merely that we collect EOL materials and have a high value of EOL-RR but also that these recycled materials actually displace a significant fraction of primary production. For a steady-state (no-growth) economy, this is not difficult, but when

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[3] For example, the number average recycling rate for the 37 metals mentioned above is only 19–31% (versus 51–87% for the mass average) indicating that many metals are recycled at low rates or not at all, whereas the majority of the mass is recycled.

Table 3 Estimated current global EOL material recycling rates[a,b]

Material	EOL-RR	Calculation details and references
Steel	70–90%	UNEP (64)
Metals (mass average including the 37 most highly used metals)	51–87%	Calculated using UNEP (64) and USGS data
Cement	0%	54
Plastics	2–7%	51, 66
Paper	40–50%	51, 66
Overall (mass average for metals, cement, plastics, and paper)	20–44%	Calculated using data from References 42, 51, 54, 64, and 66 and from USGS data

[a] Plastics and paper could be recycled by collecting and burning them for their fuel value. This would not be material recycling per se and is not considered here.

[b] Abbreviations: EOL-RR, end-of-life recycling rate; UNEP, UN Environment Programme; USGS, US Geological Survey.

there is growth, and particularly when the products have long lifetimes, the EOL recycled material may make up only a very small portion of materials demand. A simple compound annual growth rate model can be used to illustrate this point. Consider that a product with a lifetime of n years is produced in year o in the amount of Q_o. If production grows at an annual rate of i, then when this product is retired and available for recycling in year n, production will be Q_n, or

$$Q_n = Q_o(1+i)^n. \qquad 2.$$

If we assume some fraction of Q_o is captured and instantly recycled without losses (f = EOL-RR), then the maximum fraction of EOL material that could displace production would be

$$\frac{Q_{\text{EOL max}}}{Q_n} = \frac{f}{(1+i)^n}. \qquad 3.$$

A few examples can illustrate the effect of growth rate. If $n = 1$, i is small (a few percent), and f is high, then the EOL material can cover a very large fraction of production. However, consider the extreme example of recycling PV systems. Over the past several decades, these systems have been growing at an annual rate of ~35% per year. If we assume a PV lifetime of 25 years, continued growth at 35% per year, and $f = 1.0$, Equation 3 would give us a ratio of 0.00055. That is, even with an EOL-RR of 100%, these recycled EOL materials will represent less than 1% of demand. Of course, this is an extreme example. Most products do not grow at 35% per year, nor do they have lifetimes as long as 25 years. But even for more modest situations, the growth effect can be quite noticeable and could prevent us from obtaining the closed-loop system performance one might expect. Another example for steel recycling illustrates this point. Although world steel recycling rates (as a fraction of supply) were quite high in 1980 (~60%) after a period of production stagnation, they began to decline as production grew, and then declined precipitously between 2000 and 2006 to ~34% while steel grew during this period at a rate in excess of 8% per year (see **Figure 5*b***) (18, 19, 39). Hence, although recycling will continue to hold significant potential to reduce our demand for primary materials and, in doing so, reduce our energy use and carbon and toxic emissions, in the face of significant growth there is no such thing as closed-loop manufacturing. Growth must be much slower for this idea to work well.

Although there are many additional issues concerning recycling that could be discussed, for the sake of brevity we list only some here with references that provide an in-depth discussion of these issues. These issues include the difficulties of materials separation [including thermodynamic limits (65, 68–70) and the resulting loss of materials often after only one or two recycling cycles (71–73)] and the increased complexity of new products [including

Table 4 Current and estimated future recycling rates, *r* (References 38, 42, 43)

Material	Current, *r*%	2050, *r*%
Steel	37	69
Aluminum	30	65
Cement	0	0
Paper	45	70
Plastics	4	28

more complex material combinations and the addition of power and controllers to products (74–77)], both of which continue to challenge our ability to turn scrap materials into acceptable inputs for new products.

Considering these effects, recent publications have made estimates of current and future potential recycling rates *r*. The values given in **Table 4** are from References 38, 42, 43. The current rates listed in the table are perhaps more modest than some people would think. The low rates for steel and aluminum are strongly influenced by improvements in yield and recent rapid growth in these materials, and they have in earlier times been higher. However, the low rate for plastics is primarily due to technical problems. The estimates for 2050 include the assumption that primary production improves substantially, thereby significantly reducing the fraction of PS, *c*. They also include significant advances in our ability to capture materials, thereby increasing the fraction of EOL material *f*. However, in two cases—steel and aluminum—the maximum values are limited by estimates of future growth. Although this growth is relatively modest—approximately 1.5% per year—the estimated long life spans for the major products made from steel and aluminum result in the limiting values of 69% and 65%, respectively.[4] The estimate for paper is set at 70%. Because primary paper uses biomass for energy, and secondary paper often uses fossil fuels, setting the recycling rate too high can actually increase CO_2 emissions (see Reference 78), and the estimate for plastic is only at 28% because of the technical problems we have already mentioned.

2.3. Estimated Improvement Potential

The two previous sections provide the background information necessary to understand the future self-improvement potential for the materials production sector of manufacturing. In fact, several different publications have addressed this problem for the global manufacturing sector focusing on energy use reduction (38–40, 42, 79) and carbon reductions (22, 40, 43), and although some of the details of the scenarios examined differ, the overall conclusions are quite similar. By combining cutting-edge and other efficiency improvements, yield improvements, and aggressive scrap collection in the recycling processes, manufacturing may be able to just offset modest growth (~1.5% per year) and maintain relatively level energy usage and carbon emissions. Put another way, manufacturing should be able to halve its energy and carbon intensity in the face of a doubling in demand by 2050, resulting in high but essentially flat energy use and carbon emissions. For example, one study estimated that by combined and very aggressive actions the energy needed to make the big five materials per unit of aggregated mass could be reduced by 50–56%, but the total mass was expected to roughly double by 2050, offsetting these improvements (42). More specifically, a high-demand scenario would result in a slight overall increase in energy used by this group of materials (+6%), and a low-demand scenario would result in a slight overall reduction (−20%) by 2050 (38, 42).

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[4] Of course, these could be estimated to be larger by including larger contributions from PS, but this would actually increase the energy intensity of primary production by reducing its yield. The overall effect would be to increase energy use, not to reduce it.

Although this appears to be an improvement compared with current trends (see **Figure 3**), this would not be sufficient to meet current international targets to limit climate change, as mentioned above. In other words, manufacturing needs yet another 50% reduction to meet the minimum target. We conclude this article with a few suggestions as to how these additional reductions might be obtained, but before doing this, we briefly review the larger nature of the manufacturing enterprise, which is important to keep in mind.

3. THE MANUFACTURING GAME

In Section 1, we touched on the very positive role manufacturing can play in helping developing nations raise their standard of living by both creating jobs and providing for their own material needs, but it is also important that we reckon with the market nature of manufacturing. In a free-market society, manufacturing is an activity for profit, with ambitions that go well beyond providing for people's basic needs. Manufacturing is actually a collusion of sorts, between manufacturers and consumers to create yet new needs. The results of these new needs are more production and more consumption [and affluence (80, 81)]. This growth can work to lessen and sometimes defeat the efforts focused on efficiency improvements. The trend is very clear in the historical record for the production of goods, and for power requirements and combustion emissions of CO_2. For example, **Figure 6** shows global patterns of growth for 13 indicators, expressed as per capita trends, averaged over the world population.

The figure gives a clear message about growth in manufacturing: Every graph rises, mainly linearly, so in addition to forecast population growth, the per capita impacts of production, if they continue along this path, will increase steadily in the near future. More specifically, the graphs show that the past 50 years have led to a more-than-average doubling of economic prosperity, with an increase in life expectancy from 55 to 70 years, whereas per capita power requirements and consequent emissions, having been steady for 40 years, have begun to rise in the past 10. This increase in prosperity has led to increased mobility, with per capita flights quadrupling and per capita transport emissions rising by a quarter. Personal consumption of steel, cement, and paper—three of the key materials that drive most industrial emissions—has risen absolutely steadily for paper and with a recent surge for steel and cement, largely driven by a rapid expansion of construction in China. In turn, this growth in material consumption has led to increased material service provision, with one car operating for every eight people on the planet, and an astounding increase of built space leading to provision of ~30 m^2 per person.

The growth in per capita demand for energy, materials, products, and services illustrated in **Figure 6** is averaged over the global population and as such disguises a key question: Does this growth reflect improving prospects for the poor or an increasing gap between rich and poor? The answer to this question is that both are happening, and it is those who are actively engaged in manufacturing, as indicated in **Figure 1**, who have the best chance to catch up. Furthermore, if this trend continues, the world will experience yet another remarkable transition, a crossover in consumption from the rich world to the poor. That is, just as **Figure 2** shows a crossover around 1994 between the East and the West in CO_2 emissions from manufacturing, and **Figure 1** suggests a crossover in manufacturing output possibly occurring in the next decade, there is a chance that a similar crossover for consumption is not too far off. For example, a recent McKinsey report (95) estimates that by 2025 developing economies could account for nearly 70% of global demand for manufacturing products. At the same time, some observers are not this optimistic (96), but it will be a historic event should it occur.

Table 5 summarizes the current levels of global per capita consumption from the data shown in **Figure 6** and reports the current annual growth rate in per capita consumption, based on a linear regression fit to the data from

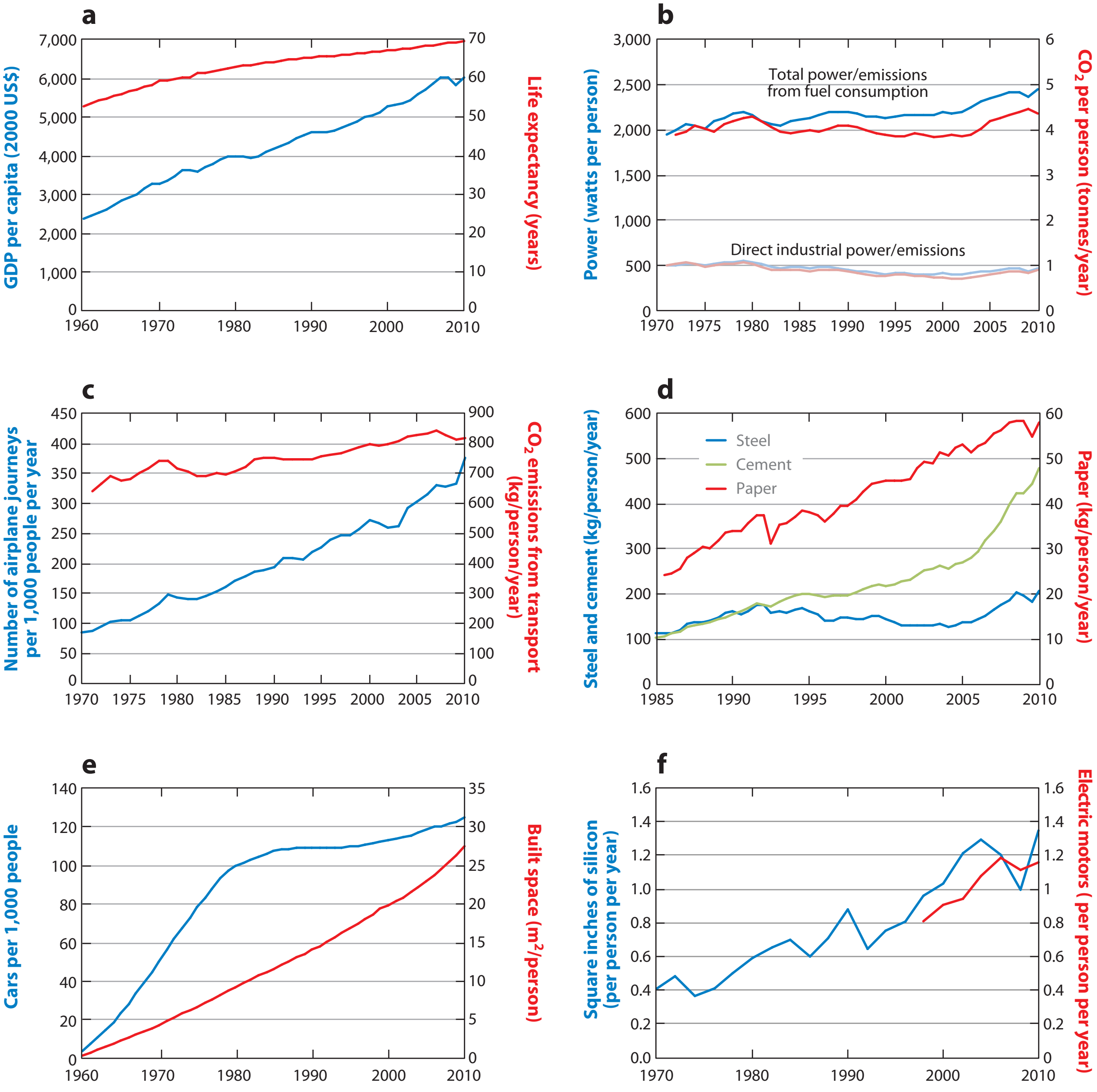

Figure 6

Trends of manufacturing growth. The graphs have been normalized by population data from Reference 82, which correlates closely with Reference 83: (*a*) Global GDP in constant 2000 US$ (24) and life expectancy (5); (*b*) emissions figures taken from Reference 25 refer to direct fuel combustion only, and so ignore process emissions, and the industry figures show no reallocation of emissions from electricity generation relating to electricity use in industry; energy figures from Reference 84, converted to power by dividing annual consumption by 31,536,000 seconds; (*c*) airplane passengers carried and transport CO_2 emissions from References 85 and 86; (*d*) steel data from Reference 87, cement data from Reference 26, and paper data from Reference 88; (*e*) global car production data from Reference 89, table 1–23, converted to in-use stocks, assuming a 20-year car life with zero stock in 1960; built space calculated from cement production (26), assuming all cement used as concrete to create building floors lasting for 40 years. Cement usage estimated at 300 kg/m^2 based on bottom-up estimates for a 200-mm floor slab (in References 90 and 91), and a top-down estimates of Chinese construction (in Reference 92); (*f*) silicon wafer production data from Reference 93, and electric motor data from Reference 94.

Table 5 Global per capita consumption of energy, materials, products, and services in 2010, and average annual growth rates for these goods deduced from the gradient of a straight line regression to the 2001–2010 data shown in Figure 6, divided by 2010 levels

Global per capita economic, environmental, and global consumption indicators	2010 global average per capita	Annual rate of increase
GDP (2000 US$/person/year)	6,009	1.4%
Total primary power (watts/person)	2,449	1.2%
Direct manufacturing and construction power (watts/person)	467	1.6%
CO_2 from fuel combustion (t/person/year)	4.35	1.7%
CO_2 from industry (t/person/year)	0.90	2.5%
Number of airplane journeys per 1,000 people/year	376	3.1%
CO_2 emissions from transport (kilogram/person/year)	820	0.4%
Steel (kilogram/person/year)	206	3.6%
Cement (kilogram/person/year)	480	4.6%
Paper (kilogram/person/year)	58	1.1%
Electric motors produced/person/year	1.16	5.3%
Square inches of silicon wafer produced/person/year	1.35	5.0%
Stock of cars (number of cars in use per 1,000 people)	125	0.9%
Stock of built space (m^2/person)	27.4	2.9%

2001 to 2010. The table shows positive growth in every variable, with GDP, energy, and emissions totals growing at ~1.5% per year, but with all industrial measures ahead of this: Direct emissions attributed to manufacturing are growing at 2.5% per year; materials requirements, particularly for construction, are growing at ~4% per year; and motors and silicon wafers, which were used as indicators of product complexity, are growing at 5% per year.

Figure 7 shows forecasts of future emissions from industry, with a range of three population forecasts, assuming either that the linear increase in industrial emissions per person continues or that industrial emissions per person stay at today's levels. This last scenario is similar to the result in Section 2.3. Global warming arises not from annual emissions but from their accumulation, and Allen et al. (97) show forecasts of the peak warming that will arise from different levels of accumulated emissions up to 2050. They highlight that an accumulation of one trillion tonnes (Tt) of carbon (3.67 Tt of CO_2), approximately half of which has already been emitted, equates to a peak warming of 2°C, which has been the target for most international negotiations on warming to date and forecast peak warming for higher accumulations. Fuel combustion contributes approximately two-thirds of all anthropogenic emissions (25), and approximately one-quarter of direct fuel combustion is attributable to industry, as shown in the emissions figures of **Figure 6** and **Table 5**. Therefore, **Figure 7** shows levels of CO_2 accumulation corresponding to the midrange forecasts by Allen et al. (97) for peak warming of 2, 3, and 4°C, assuming that the industrial share of anthropogenic emissions remains one-sixth.

Figure 7*b* makes for bleak reading: Under all six scenarios, the allowable accumulated emissions resulting in peak warming of 2°C will have been surpassed by the industrial sector by 2050, with annual emissions continuing to rise for all but the lowest population scenarios beyond that date. This is in agreement with our earlier assessment in Section 2.3 of the big five's limited ability to reduce their energy

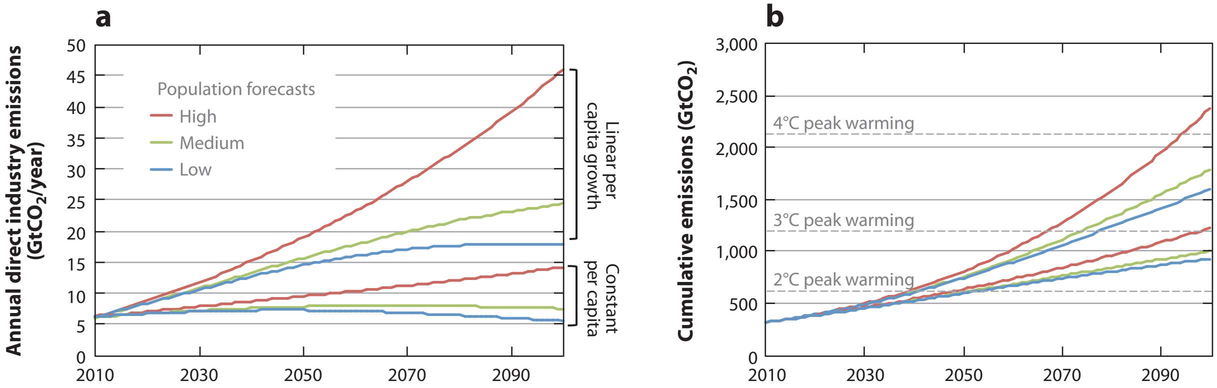

Figure 7

Scenarios of CO_2 emissions from direct fuel combustion in industry (*a*) per annum and (*b*) accumulated from current levels estimated in Reference 97. High and low population forecasts are from Reference 83. Medium population forecasts are from Reference 98. Industry emissions per person are assumed either to rise with the same linear trend as shown in **Figure 6** or to remain constant at today's levels.

consumption and CO_2 emissions. Again, very significant gains are possible and need to be pursued, but there appears to be a significant disconnect between what can be reasonably expected from energy efficiency and recycling if the targets for limiting climate change are pursued. There are, however, two other mitigation options that could have an equal or greater effect in reducing the environmental impacts of industry but that so far have received very little attention:

1. Material efficiency: A range of strategies aiming to deliver material services with less material production is referred to as material efficiency. As we have discussed, most energy is used in industry to make a few key materials, for which energy is a significant driver of cost. Although future opportunities for energy efficiency in producing these materials are limited (40, 42), there are still many opportunities to deliver material services using less material. This might come about through reusing old material without secondary processing or through material efficiency in product design (for example through designing lighter-weight, longer-lasting products). A white paper on this topic (99) has led to a book on material efficiency for steel and aluminum (66) and a focused Royal Society meeting and special issue on the topic (100), spanning all aspects from economics, sociology, and policy to technology; however, as yet, the strategy has received little attention either in policy or in commercial practice.
2. Demand reduction: Although apparently counter to all assumptions of most economic policies, demand reduction could transform manufacturing impacts, if strategies could be found to pull down the per capita consumption of richer consumers. Demand reduction has received attention in the literature of sustainable consumption (e.g., 101) and in more recent academic writing on well-being and happiness (e.g., 102–104). The thrust of this writing is that a substantial body of evidence shows that, beyond some threshold of wealth, individuals become no happier with increasing wealth/consumption; therefore, an economic policy aimed at ceaseless growth may not correspond with one aimed at increased well-being. In fact, according to Dasgupta (105), gross measures of aggregate consumption and investment are measures neither of current well-being nor of future well-being. To date, the sustainable consumption work has

> largely aimed to gather evidence and has led to few practical measures for implementation but along with material efficiency could be the most powerful key to reducing industrial impacts.

Current efforts to clarify the development of manufacturing, as discussed in this review, point to a looming conundrum: This development, which could be viewed as a moral imperative for the low-income countries (81), could also bring significant global environmental harm. Because manufacturing's carbon emissions are dominated by a few basic, high-volume materials that are very important for development, are already quite efficient, and are without obvious substitutes, additional measures beyond those reviewed here will be necessary. In closing, we have identified two possible options above, both emphasizing behavioral change more than technical prowess. Without these actions, ultimately, the manufacturing sector may not be able to meet even modest climate change goals. Manufacturing could be saved, however, by aggressive action in other sectors: a low-carbon grid, carbon capture and storage, and deeper cuts in transportation and buildings. We do not consider these here, but there are reasonable doubts about the first two arriving in time to have an impact before 2050 (43). Future work needs to consider the interactions between all sectors (manufacturing, transportation, buildings, and energy supply) and how they can work together to meet environmental goals and allow development for the poor.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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