

Reducing Industrial Energy Use and CO₂ Emissions: The Role of Materials Science

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Abstract

Nearly one-third of the world's energy consumption and 36% of its carbon dioxide (CO₂) emissions are attributable to manufacturing industries. However, the adoption of advanced technologies already in commercial use could provide technical energy savings in industry of 27–41 exajoules (EJ), along with a reduction in CO₂ emissions of 2.2–3.2 gigatonnes (Gt) per year, about 7–12% of today's global CO₂ emissions. Even more significant savings can be attained on the supply side if fuel switching and CO₂ capture and storage are considered. However, such changes must start in the coming decade to have a substantial impact by 2050.

Introduction

Rising population and increasing wealth are fueling growing global demand for products, services, buildings, and public infrastructure. The industrial sector, which manufactures these products and structures, has many opportunities to make them using less energy and emitting less carbon dioxide (CO₂). This article discusses these opportunities, highlighting those in the materials industries and those depending on advances in materials science, engineering, and management. Industry also has a role in developing, producing, using, and recycling improved materials (e.g., stronger, lighter weight, and better insulating) to manufacture products that consume less energy when used, but with some exceptions, these issues and the full lifecycle energy and emissions consequences thereof are beyond the scope of this article and are addressed elsewhere in this issue.

In 2004, the total global primary energy supply was 469 exajoules (EJ). Industry, when apportioned the energy losses from the electricity and heat it uses, accounted for more than 147 EJ, or nearly one-third of this supply. Total final energy use (excluding electricity and heat losses) by industry amounted to 113 EJ (**Table I**). These totals exclude energy used for the transportation of raw materials and finished industrial products, which is not negligible. The mentioned quantities include oil feedstocks for the production of synthetic organic products.

Most industrial energy consumption occurs in industries that produce raw materials: chemicals and petrochemicals, iron and steel, nonmetallic minerals, and nonferrous metals. Together, these four materials groups consumed 69.9 EJ of final energy in 2004 (62% of total final industrial energy use). The chemicals and petrochemical industry alone accounts for 30% of industrial energy use, followed by the iron and steel industry with 19%; the production of nonmetallic minerals is responsible for 10% and that of nonferrous metals for nearly another 4%. The food, tobacco, and machinery industries, along with a large category of unspecified industrial energy users, account for the remaining 37% of total final industrial energy use.

Direct industrial CO₂ emissions (excluding emissions from electricity generation and heat use) amounted to 5.8 gigatons

(Gt) of CO₂ in 2004. Three sectors were responsible for nearly 70% of the direct industrial emissions: iron and steel, nonmetallic minerals (notably cement), and chemicals and petrochemicals (**Figure 1**). These values include 1 Gt of CO₂ of process emissions (originating not from fuels but from feedstocks, e.g., limestone calcination in cement production), but exclude downstream emissions from the incineration of plastics and other synthetic organic products (0.1–0.2 Gt of CO₂). The total direct and upstream emissions (3.9 Gt of CO₂ from the production of electricity and heat used by industry) equal 36% of all energy and process CO₂ emissions worldwide. This does not include the emissions from the freight transportation involved in bringing raw materials to manufacturing facilities and delivering products made from them to consumers, which would add another 10–12 percentage points. Thus, between one-third and

Table I: Final Industrial Energy Use by Energy Carrier and CO₂ Emissions, 2004.

Industrial Sector	Energy Use (EJ/year)	CO ₂ Emissions (Gt of CO ₂ /year)
Coal and coal products	28.92	2.72
Natural gas	23.56	1.32
Oil and oil products	28.00	0.73
Combustible renewables and waste	7.03	no data
Electricity	21.50	3.59
Heat	4.21	0.29
Other	0.03	–
Process emissions	–	1.08
Total	113.25	9.73

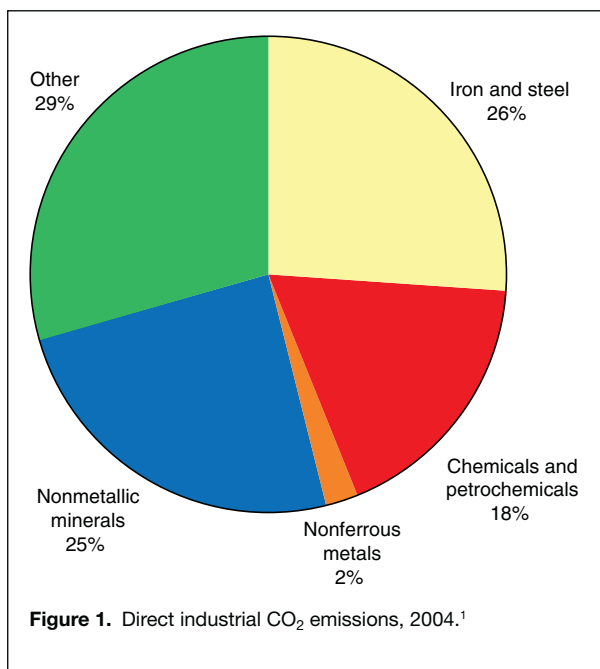


Figure 1. Direct industrial CO₂ emissions, 2004.¹

one-half of global CO₂ emissions are generated in activities related to materials and product supply.

Opportunities for Energy Efficiency and CO₂ Reduction in Industry

Globally, industry's energy consumption and direct CO₂ emissions have been growing, with increases of 61% and 34%, respectively, between 1971 and 2004, and show no signs of abating. For the most part, growth in energy demand has been high in developing countries and moderate or stagnant in Organisation for Economic Cooperation and Development (OECD) countries.

To some extent, growth in both energy demand and emissions has been mitigated by efficiency improvements in all sectors worldwide. However, these efficiency gains have not been geographically uniform. The rapid growth of production in less-efficient developing countries has contributed significantly to poverty alleviation, but it has also limited the average efficiency gains worldwide. Rapid growth in countries such as China and India has supported continuation of less-efficient "mom-and-pop"-type heavy industry in some sectors that does not exist in OECD countries. Small-scale manufacturing plants using outdated processes and low-quality fuels and feedstocks, as well as weaknesses in transportation infrastructure, contribute to industrial inefficiency in some emerging economies.

These overall energy and emissions trends can be mitigated through additional energy efficiency measures. Even though energy represents a manufacturing cost, to be managed and controlled like any other cost, industry is not always efficient in its energy use. A new study by the International Energy Agency (IEA) suggests a technical efficiency improvement potential of 18–26% for the manufacturing industry worldwide if the best available technology were applied.¹ These savings would equal 5–7% of total worldwide energy use and reduce CO₂ emissions by 7–12% worldwide (Table II), or one-half of the European Union's current energy consumption. These are conservative estimates based on proven technology. Most of the underlying energy-saving measures would be cost-effective in the long term, but their implementation is hindered by the long remaining lifespan of the standing capital stock and the priority given

Table II: Opportunities for Energy Efficiency and CO₂ Reduction in Industry.

	Energy Efficiency (EJ/year)	CO ₂ Emissions (Mt of CO ₂ /year)
Sector process improvements	12–17	1150–1550
Systems options	13–20	750–1650
Total	25–37	1900–3200
	(%)	(%)
Industrial improvement potential	18–26	19–32
World improvement potential	5–7	7–12

to avoiding production disruptions that can be caused by new equipment or new procedures. The IEA analysis excluded certain emerging technologies with unclear impacts such as nano-technology, fuel cells for stationary applications, increased use in industry of renewable energy sources other than biomass (e.g., solar and geothermal), logistical and infrastructural aspects such as co-siting (integration of energy and material flows on industrial sites), and heat integration, among others.

The adoption of advanced technologies already in commercial use could improve the performance of energy-intensive industries. The performance of the manufacturing industry as a whole can be made more efficient through systematic improvements to steam and motor systems, including combined heat and power systems, and through recycling of materials. The analysis suggests that more than half of the estimated energy and CO₂ savings potential is in systems approaches that often extend beyond the process level. Further significant savings can be attained on the supply side if industrial fuel switching and CO₂ capture and storage are considered.

The lifecycle flow of materials (e.g., end-use material efficiency improvement and cascading through reuse, recycling, and recovery) and their storage in the economy (stockpiling) are not well understood, and as a consequence, important options for efficiency improvements might be overlooked as attention is focused instead on energy efficiency in materials production.

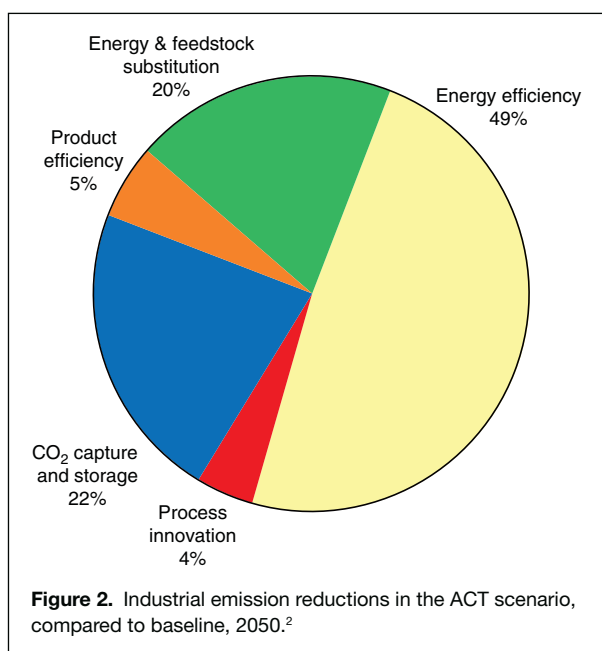
The realization of part of this potential for technical improvements would entail immediate significant costs because it would imply replacement of the existing capital stock before the end of its technical life. Over the longer term, however, these gains seem affordable. A key factor is the age of the capital stock. New plants tend to be more efficient than old ones, as more efficient technologies are developed and adopted. As a consequence, the most efficient industries can sometimes be found in emerging economies where production is expanding. For example, the most efficient aluminum smelters are in Africa, and Brazil has some of the most efficient cement production facilities. Aging capital stock also explains why the least efficient cement kilns are in the United States and why Canada has a low-efficiency pulp and paper sector. The general notion of efficient manufacturing in industrialized countries and inefficient production in developing countries with the main obstacle being technology transfer is a myth; reality is far more complex. Although rapidly expanding economies allow speedy introduction of the latest energy-efficient technology, capital scarcity might favor smaller plants with lower efficiency. Also, low-cost and subsidized energy processes often pose a disincentive for energy efficiency. In addition, resource quality constraints play a role. For example, the low coal quality in



India explains the emergence of relatively inefficient direct reduction plants for iron making, as coking coal is an expensive imported resource.

The discussion so far has focused only on technical potential, based on existing technology and current production volumes. Part of this potential will be realized by the market without new policy efforts. New CO₂ policies might result in a greater uptake of these efficiency options, as well as in the use of further CO₂ mitigation options that entail additional costs. These possibilities were analyzed using the IEA Energy Technology Perspectives model, a bottom-up least-cost optimization program. This model was developed to study the global potential for energy efficiency and CO₂ emission reduction in the period to 2050, particularly in the industrial sector.² In a baseline scenario (that considers only energy and CO₂ policies put in place to date), industrial CO₂ emissions (including the emissions in power generation from electricity used in industry) would rise by 82% between 2003 and 2050. In the Accelerated Technology (ACT) scenario, a global CO₂ incentive of \$25/t of CO₂ was assumed, in combination with more energy research, development, and demonstration (RD&D) and more stringent efficiency standards and measures. The incentive reflects a policy effort that can be based on a range of policy instruments such as taxes, subsidies, emissions trading schemes, sectoral agreements, or others. In this scenario, where total global CO₂ emissions in 2050 are 6% above 2003 levels, the industrial emissions would decrease by 21% during the same period—compared to a 36% decline in the power generation sector, a 9% increase in the buildings sector, and a 66% increase in the transportation sector. A mix of CO₂ emissions reduction incentives, efficiency regulations, and support measures would be needed. A range of new technologies plays a role in this scenario (Figure 2). Further emissions reductions are possible, but the costs will increase substantially.

The following discussion focuses on three key materials industries—namely, iron and steel, cement, and chemicals and petrochemicals—providing some examples of the materials science, engineering, and management challenges of improving their energy efficiency and emissions performances. The purpose is to explain key aspects and R&D needs of the accelerated



technology scenario (i.e., the CO₂ incentive in combination with RD&D) for these three sectors.

Iron and Steel

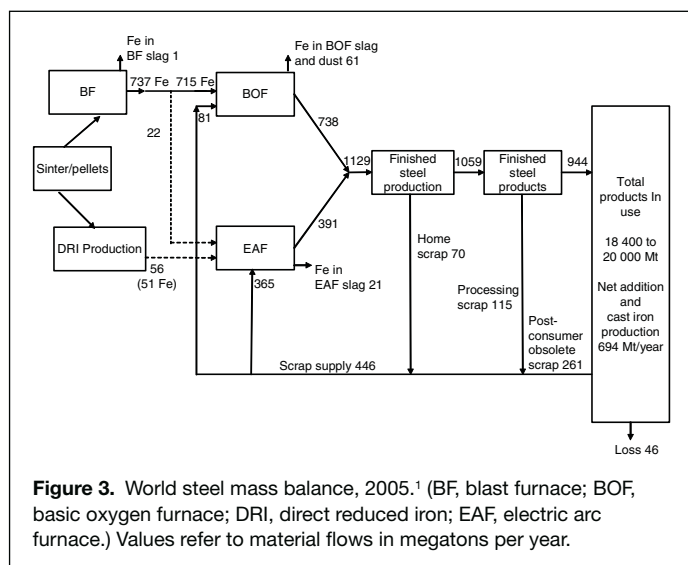
In 2005, 1129 million tons (Mt) of steel was produced, making it by far the most important structural metal (Figure 3, all values in Mt). Steel is used in a number of markets such as transportation equipment, infrastructure, machinery, buildings, and packaging. From 1971 to 2004, annual steel production grew 93%, while its energy use rose by 30% to 21.4 EJ/year and its CO₂ emissions increased by 17% to 1.7 Gt/year.

Materials recycling reduces the energy needs and direct CO₂ emissions substantially, by a factor of 2 to 4. Total scrap recovery in steel production increased from about 325 Mt to 450 Mt from 1970 to 2003. This increase is the net result of a decreasing amount of home scrap (an indication of fabrication yield improvements) and an increasing amount of so-called obsolete scrap (i.e., post-consumer waste, in contrast to processing waste or preconsumer waste). Even though the recycling rate is high, an expanding economy has meant that the total crude steel production is roughly twice the amount of scrap collected and used. Net additions to the stock of materials in the economy constitute a major materials sink. Materials losses from the lifecycle of steel are small, so increased recycling is an improvement option of secondary importance.

The CO₂ breakthrough program of the International Iron and Steel Institute aims for the development of CO₂-free steel production processes. The European activities under this heading are named ULCOS (Ultra-Low CO₂ Steel). In the second stage of this project, industry has selected three process routes for further development:³ (1) blast furnaces in combination with CO₂ capture and storage; (2) natural-gas-based reduction processes (with CO₂ capture and storage); and (3) electrolysis production processes, similar to aluminum smelting.

Another interesting development is the Finex process that has been in testing by Posco since 2007 at the demonstration-plant scale (1.5 Mt/year). This process avoids coke production and iron agglomeration by applying fluidized-bed technology and has the potential to become more energy-efficient and less CO₂-intensive than the conventional blast furnace process.

Between one-tenth and one-quarter of the energy use and CO₂ emissions in steel production is related to the processing of crude steel into finished steel products (depending on the





product type). Near-net-shape casting is a process for casting metal in a form close to that required for the finished product and with minimum reheating, thus reducing both energy use and CO₂ emissions. This technique is highly cost-effective, but it is limited in its ability to generate steel of the right quality. Better understanding of steel transformations and process control could allow wider use of near-net-shape casting.

Materials properties enhancements are an important element of the steel industry's effects on sustainability. Steel strength, quality, and other properties have a significant influence on how products made from steel use energy. For example, stronger steels allow for the use of thinner-gauge, and thus lighter-weight, product components. Reducing the weight of automobiles has received much attention and could yield 10–15% fuel efficiency gains, provided that it is not offset by trends toward larger and higher performance vehicles (see article on transportation by Carpenter et al. in this issue). Improved collection and separation practices and processing technologies for scrap metal will allow further growth in the use of recycled steel in areas that have been the domain of virgin steel. However, scrap availability is the main limiting factor here, not scrap quality. In the case of coal-fired power plants, steel quality determines maximum operating efficiencies by limiting the temperatures and pressures in steam sections. However, the development of new steel types that can resist higher steam temperatures and yield higher power plant efficiencies has stalled. Instead, new strategies have been developed that focus on the use of alloys or other materials in key parts of the plant. This development should enable up to 50–55% efficiency in coal-fired ultrasupercritical steam cycles (which are characterized by conditions of >250 bar and 600°C for the main steam and >600°C for the reheat steam) in the coming decades, compared to 45–46% for the most efficient recent plants and a world average of 35%.

Current steel alloys have reached their limits at a maximum steam cycle temperature of about 600°C. Research in the 1990s that focused on ferritic (up to 650°C) and austenitic (up to 700°C, so-called P91 and P92 alloys) steels for higher temperatures has not yielded satisfactory results. In recent years, research has focused on nickel alloys. These alloys have the necessary properties to withstand temperatures of 700–750°C.⁴

The problem with these nickel alloys is their price, which is 10 times that of ferritic and austenitic steels and 100 times that of carbon–manganese (C–Mn) steels. Moreover, the use of significant tonnages of nickel could increase its price. This has hindered the widespread use of these alloys so far. New power plant designs are being proposed in which nickel alloys are used only for critical parts of the power plant. Novel plant designs such as two-pass, inverse twin tower, and horizontal boiler concepts can reduce investment costs and have been developed in the framework of the European 700°C power plant project. Their introduction would limit the use of nickel alloys and enable the construction of power plants with a maximum steam temperature of 700°C.⁴

Not only steel quality but also coke quality is an issue that deserves attention. The impact of coke quality on coal and coke consumption in blast furnaces is still not well understood. Blast furnace operation is still largely based on engineering experience, and the impact of coal quality and ore quality on process operation cannot easily be transferred from one blast furnace to another. This limits the potential to translate the operating experiences of the best blast furnaces into a global improvement. The experimental blast furnace test facility of the Swedish company LKAB (Luossavaara-Kiirunavaara AB) is of key importance to making progress in this area.⁵ The steel industry has already shown great interest in LKAB because many of the

risks involved in full-scale trials in a production blast furnace can be avoided.

Cement

Worldwide cement production amounted to 2284 Mt in 2005, with the vast majority of the production occurring in developing countries. In 2005, China accounted for 47% of global cement production, whereas India, Thailand, Brazil, Turkey, Indonesia, Iran, Egypt, Vietnam, and Saudi Arabia together accounted for 17%. From 1971 to 2004, annual cement production nearly quadrupled (285% growth), and in the non-metallic minerals sector, energy use rose by 136% to 10.6 EJ/year and CO₂ emissions increased 147% to 1.7 Gt/year. Cement is a special case among major materials industries because more than half of its direct greenhouse gas emissions emanate from process sources (the calcination of limestone during clinker production) rather than energy use, and these emissions cannot be reduced through changes in the process conditions. Clinker is the material produced by heating limestone, clay, bauxite, iron ore, and quartz to 1450°C in a rotating kiln.

China merits special attention because of its high share of world production and its production technology. Thus far, inefficient vertical shaft kilns dominate in China, but the country's capacity base is changing quickly. Since 2001, China has been building 100 rotary kilns for cement production per year, and today, these more energy-efficient kilns account for nearly one-half of Chinese cement production. In fact, China is now exporting these kilns and has 30% of the world market. Rotary kilns are an order of magnitude larger than shaft kilns, which makes a much higher level of heat integration economical, resulting in much better energy efficiency.

Four approaches can be applied to increase the energy efficiency and reduce CO₂ emissions in the cement industry: (1) increase the process energy efficiency, (2) use coal fuel substitutes, (3) capture and store CO₂ (an option for CO₂ reduction only; not yet commercialized), and (4) develop new cement types that reduce the use of cement clinker.

The fourth approach involves materials substitution. The world average clinker/cement ratio is about 0.81, with the balance comprising gypsum and additives such as blast furnace slag, fly ash, and natural pozzolana. As clinker production is the most energy-intensive and CO₂-emitting step of the cement-making process, reductions in the clinker/cement ratio (through use of clinker substitutes) reduce energy use and process CO₂ emissions. Blast furnace slag is already a widely used clinker substitute; other examples are fly ash, pyrite ash, and phosphogypsum (from flue gas desulfurization and phosphoric acid production). A key parameter determining the suitability of a material as a clinker substitute is the compressive strength, in addition to tensile strength and water absorption. Increased use of steel slag and fly ash from coal-based power plants could generate an additional 350 Mt of cement clinker substitute, which would reduce world CO₂ emissions by about 250 Mt.

High-basidity (high-pH) steel slag (whose main components are SiO₂, Al₂O₃, CaO, MgO, and FeO) that has been cooled properly can exhibit cementing properties. Ground steel slag has been used in several different cementing systems, and it provides some advantages over conventional cements. In many countries, most steel slag is currently being used as unbound aggregate for asphalt concrete pavement. However, the use of steel slag as a cementing component should be given a priority for technical, economic, and environmental reasons.⁶ About 200 kg of steel slag is generated per ton of steel. Given an annual steel production of 1129 Mt, about 220 Mt of clinker substitute could be generated.



Fly ash can also serve as a clinker substitute. Fly ash is the finely divided mineral residue that primarily originates from the combustion of coal in power plants (collected with electrostatic precipitators). However, most fly ash requires upgrading, through froth flotation, triboelectrostatic separation, or carbon burn-out in a fluidized bed. These processes reduce the carbon content (and loss on ignition) to less than 5%, but are just emerging and are not yet widely applied. Especially in China and India, a significant potential exists to increase the use of fly ash. Total world fly ash production is about 300 Mt/year; only one-half this amount is used today, and the remainder is landfilled.

In addition, special grinding (the so-called energetically modified cement, or EMC, process) is being studied as a way to possibly increase the fly ash content of cement to 70% (compared to a maximum of 30% today).⁷ The grinding process markedly reduces the size of both cement grains and fly ash and creates flaky agglomerates with a high specific surface area. This change in properties is reflected in improved strength because the pozzolanic reaction rate is increased for the fly ash.

As with steel, materials properties enhancements are an important element of the cement industry's effects on sustainability. A growing demand exists for high-strength concrete and effective structures utilizing such concrete. Super-high-strength concrete with a compressive strength of 250 MPa, high flexural strength, and remarkable ductility is under development. Better cement grinding technology yielding greater surface areas and a more uniform particle size distribution merits special attention in this respect.

Another development is the use of chemical admixtures (e.g., lignosulfonates, vinyl polymers, and melamine formaldehyde condensates), which have become an essential part of modern concrete technology. Added to a concrete mixture in relatively small amounts, the chemical admixtures significantly change the required parameters and behavior of fresh or hardened concrete. Developed from industrial waste and used in special formulations engineered for optimal interaction with concrete, modern admixtures can remedy almost any problematic property of concrete.

Admixtures help create "high-performance cements" based on mechanochemical activation of certain ratios of clinker, gypsum, admixture, and optionally, a mineral additive of industrial or natural origin that imparts a high strength and extreme durability to the concrete or mortar made from it. A wide range of natural pozzolanic materials, sand, limestone, granulated blast furnace slag, fly ash, and broken glass can be used as mineral additives in these cements.⁸ This approach alleviates the problems of clinker substitute availability, and it could pave the way to a 50% reduction in energy use and CO₂ emissions. A major problem is that extensive testing is needed and cement and concrete standards must be revised, a slow process that limits the potential in the short and medium term.

Chemicals and Petrochemicals

From 1971 to 2004, energy use in chemicals and petrochemicals production rose by 206% to 33.6 EJ/year and CO₂ emissions increased by 160% to 1.0 Gt/year.

Certain inorganic chemicals such as fertilizers, chlorine, and soda have some energy relevance, but petrochemicals (accounting for approximately 10% of the total final consumption of petroleum products) represent the bulk of the energy and feedstock use in this sector.¹ In mass terms, the predominant share of the final output of the petrochemical industry is polymers (approximately 85%). **Figure 4** shows the global mass balance of the petrochemical portion of the sector. In 2004, 345 Mt of hydrocarbons (about 16 EJ of feedstock, half of all fossil

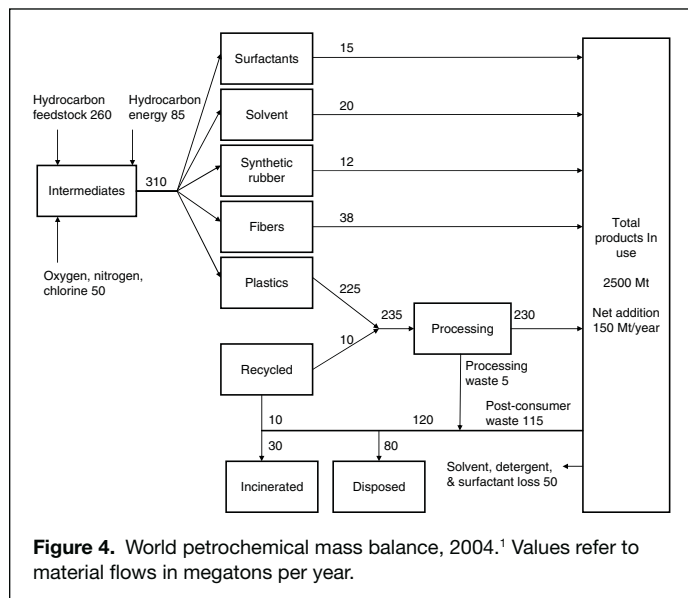
fuel use in this sector) was converted into 310 Mt of petrochemical products. Plastics represented 73% of the total petrochemical product mix, followed by synthetic fibers, solvents, detergents, and synthetic rubber. About 120 Mt was stored in increasing product stock, with the remainder released as gaseous, solid, and liquid waste. Across the globe, the majority of this waste was discarded in landfills.

Materials substitution of biomass feedstocks for petroleum feedstocks holds great potential for reducing energy use in the petrochemicals industry. Interest in realizing this potential has risen, in tandem with the increased attention paid to the development of liquid biofuels stemming from surging oil prices, supply security considerations, environmental policies, and technological progress. Apart from these factors, the success of bio-based chemicals will depend on biomass prices and the availability of land, for which there is increasing demand for food and nonfood purposes. At the same time, there are largely untapped sources of raw materials in some parts of the world, for example, in some parts of Africa and Eastern Europe.

The four principal ways of producing polymers and other organic chemicals from biomass are as follows.

Several naturally occurring polymers can be used directly, usually with some thermal treatment, chemical derivatization, or blending. Examples include thermoplastic starch polymers, cellulose, and chitin/chitosane. These materials are derived from plants (e.g., cereals) and animal material (e.g., crab shells). Cellulose for textile fiber production is currently the largest bio-based polymer by far, with a total worldwide production of nearly 3 Mt. In comparison, the quantities of all other bio-based chemicals are as yet negligible (including those listed in the next section).

Polymers can also be produced through the thermochemical conversion of biomass (e.g., pyrolysis or gasification), followed by synthesis and further processing. Examples include the conversion of biomass to bio-based naphtha (conventional naphtha is a light product of crude oil refining) through the Fischer-Tropsch process and its subsequent conversion to olefins and aromatics in the so-called steam-cracking process. (In a steam cracker, saturated hydrocarbons are broken down at 850°C in the presence of steam into smaller, often unsaturated, hydrocarbons.) As an alternative, olefins can be produced by methanol synthesis and subsequent application of the methanol-to-olefins





process, which is performed in a fluidized- or fixed-bed reactor in the presence of a catalyst.

A few polymers can be produced by so-called “green biotechnology,” which produces biopolymers (or their precursors) in genetically modified field crops such as potatoes or miscanthus. A prominent example is polyhydroxyalkanoates (PHAs), a family of bio-based polyester that also occurs naturally.

So-called “white biotechnology” (also referred to as industrial biotechnology) makes use of fermentation processes (for most bulk products) or enzymatic conversions (mainly for specialty and fine chemicals). The most accessible raw materials for these processes are C₆₆ sugars (commonly produced from starch crops and sugar crops such as sugar beet and sugar cane); major efforts are currently being made to produce fermentable sugar (a mixture of C₅₅ and C₆₆ sugars) from cheaper woody biomass such as wheat straw, maize straw (maize stover), or wood (also referred to as lignocellulosic feedstocks).

Detailed analyses show that bio-based chemicals offer substantial potential savings of nonrenewable energy and greenhouse gas (GHG) emissions. For example, to produce 1 t of cellulose fibers (e.g., viscose), approximately 40 gigajoules (GJ) of nonrenewable energy is required,⁹ as compared to 100–110 GJ/t for synthetic fibers made from polyethylene terephthalate (PET). The resulting savings potential of 60% (for both nonrenewable energy use and fossil CO₂ emissions) might not be representative of all current worldwide production capacity, because the savings differ by fiber type and process type, and also because further steps in the lifecycle should be taken into account (textile production and use). Nevertheless, this example shows that large-scale bio-based processes for material production hold great potential for energy and emissions savings.

This conclusion is also valid for bio-based chemicals produced by white biotechnology. The bio-based chemical with the largest potential market is likely ethylene made from bioethanol. Bio-based ethylene can be used to produce bio-based polyethylene and all other bio-based ethylene derivatives such as ethylene oxide, ethylene glycol, or acetaldehyde; these, in turn, can be used for a wide range of chemicals such as polymers, solvents, antifreeze agents, and lubricants. It has been estimated that nonrenewable energy use and lifecycle GHG emissions can be reduced by more than one-third compared to petrochemical-based approaches if ethylene is produced from bioethanol made from maize in a moderate climate and using the current level of technology. Using the same feedstock and more advanced fermentation and separation technology, the savings can be increased to 50%. If fermentable sugar from sugar cane is used instead of maize, ethylene production is a net producer of energy instead of a consumer (even using current technology). This is a consequence of the high yields of tropical sugar cane cultivation and the large amounts of waste biomass, so-called bagasse, produced; this bagasse is used to generate power and hence replaces fossil-fuel-based electricity.

According to recent company announcements, two large-scale bioethylene plants with a total capacity of 500,000 t/year will be brought into operation around 2010. Depending on the boundary conditions, the production of bioethylene could grow to more than 50 Mt by the year 2050 in Europe alone (based on the status of the European Union before 2007, EU-25).¹⁰ Other polymers that have the potential of replacing bulk petrochemicals are polyhydroxyalkanoates (PHAs) and polylactic acid (PLA).¹⁰

Technically speaking, the overwhelming share of the total demand for organic chemicals and polymers could be covered from bio-based feedstocks. The ultimate diffusion will primarily depend on the relative price levels of bio-based and petrochemical feedstocks, technological progress, government

support, and synergies with biofuel production. The largest benefits in terms of energy savings and GHG abatement could be achieved by uniting bio-based chemicals with a combined strategy of reuse, recycling, and energy recovery.

As with steel and cement, the ways in which materials or products are used constitute an important element of the chemical industry's effects on sustainability. Nitrogen fertilizer is a case in point. About 6 EJ or 20% of all energy use in the chemical and petrochemical industry is for the production of ammonia, which is largely used for the production of nitrogen fertilizer. This synthetic fertilizer has been a key driver for increased agricultural yields, but also a source of environmental problems. Production of nitrogen fertilizer causes about 0.2 Gt of direct CO₂ emissions, and its use causes about 0.8 Gt of emissions of nitrous oxide (N₂O), another potent greenhouse gas. Both of these emissions streams could be reduced through more thorough use of natural nitrogen fixation processes. The biological reduction of atmospheric N₂ to ammonium (nitrogen fixation) provides about 65% of the biosphere's available nitrogen. Most of this ammonium is contributed by legume–rhizobia symbioses, which are initiated by the infection of legume hosts by bacteria (rhizobia), resulting in the formation of root nodules. Establishing a fully functional symbiosis requires a successful completion of numerous steps that lead from recognition signals exchanged between the plant and bacteria to the differentiation and operation of root nodules, the plant organ in which nitrogen fixation takes place. To increase knowledge of this system of particular importance in sustainable agriculture, major emphasis should be placed on basic research. More work is needed on the relevant genes in rhizobia and legumes, the structural and chemical bases of rhizobia–legume communication, and the signal transduction pathways responsible for the induction of the symbiosis-specific genes involved in nodule development and nitrogen fixation.¹¹

Discussion: The Urgency of Materials Sciences Contributions

Increasing the efficiency of industrial processes and the flows of materials through the economy is a slow transformation process that will take decades. In the short and medium term, it is important that new plants be built with the best available technology. Materials sciences will play a key role in the further development of emerging solutions for increased energy efficiency and reduced CO₂ emissions. A range of disciplines is involved such as chemistry, mechanical engineering, and bioengineering, depending on the material and product categories. Progress from the laboratory to full market deployment is very slow because of barriers such as standards and regulations and the lifespan of the existing capital equipment stock. Therefore, options need to be demonstrated in the next 10–15 years to have a substantial impact from 2030 to 2050.

Whether a new technology is taken up by the market depends to a large extent on the economics. Cost-effective technologies are essential to achieving substantial emission reductions. However, development of these technologies depends on credible long-term signals that energy efficiency improvements and CO₂ emissions reductions will receive sufficient incentives in the long term, a situation that does not exist at present. A globally uniform CO₂ pricing and abatement regime, for example, is not yet in sight.

Apart from commodities, high-performance materials will help to improve materials efficiency, and materials with very specific properties (e.g., self-healing materials, self-cleaning materials) will reduce the energy and CO₂ footprints throughout the product lifecycle. At the same time, new materials will create new demands that might offset some of the efficiency gains.



A better understanding is needed about the use of materials in the economy. The issue of increasing stocks and losses from the materials chain needs to be improved. Toward this end, materials flow analyses, dynamic systems models, and other simulation tools need to be combined with actual measurements.

Efficient product system design can help to reduce materials consumption and reduce costs. However, the opportunities in this area are still not well understood, and product design remains a heuristic process. (The topic of lifecycle optimization is discussed in greater detail in the article by Lave in this issue.)

Although it is difficult to change existing consumption patterns, efforts to change emerging consumption patterns deserve special attention. An example is the rapid population growth and urbanization in developing countries. The ways in which these new cities are planned and developed will have a significant impact on the resulting materials consumption and transportation energy.

Developing countries are where most of the growth in industrial production in the coming decades will occur. Therefore, it will be important to develop sustainable consumption patterns in these countries in addition to fostering a renewable energy supply. Governments can play a role in advancing such a development, applying lessons learned from the experiences of industrialized countries. The development of fundamentally different production technologies seems unlikely, as industries operate globally and a few equipment suppliers deliver to all major companies. Technology transfer is not a major issue, but capital availability, equipment import barriers, a country's desire to develop its own equipment supply industries, and open or hidden energy subsidies often hamper the use of the best available technology. However, policies for ameliorating these problems can be applied through domestic measures, international financial institutions, development assistance programs, and international CO₂ incentives.

For maximum effect, new investments in the manufacturing industry in all countries need to be based on the best available technologies, and existing plants need to be retrofitted with energy recovery equipment. Energy efficiency is only part of the solution to achieving meaningful emissions cuts and minimizing the release of greenhouse gas emissions. It is a good starting point, especially for developing countries, as it can also reduce energy costs and thus manufacturing costs as well. Companies that address the CO₂ challenge robustly at an early stage will reap the benefits in the coming decades.

Conclusions

Efforts to achieve deep GHG emission reductions will have significant consequences for materials use. About 36% of all CO₂ emissions can be attributed to industry, mainly to materials production processes. Materials sciences can help to increase the efficiency of materials use and to develop new materials that allow for higher energy efficiency during product use. This includes chemical and mechanical processing technologies and biotechnologies. In addition, certain process improvements are dependent on a better understanding of materials transformation processes. About 18–26% improvement can be achieved based on existing technologies, but this is not sufficient to compensate for the projected growth in demand. Further improvements can be achieved only through better materials and new emerging production processes. Efforts to develop better cement materials, biomass feedstocks instead of coal and other fossil feedstocks, and substitutes for synthetic nitrogen fertilizer merit special attention. However, the development and widespread use of new materials and processes is a slow effort that is limited by capital stock turnover, norms and standards for new materials, and acceptance by the market. Therefore, such changes must start in the coming decade in order to have a substantial impact by 2050.

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