

Industrial Energy Use, Status and Trends[☆]

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Glossary

Cross-cutting Energy technologies found throughout the industrial sectors and processes.

Energy efficiency improvement Decreasing the use of energy per unit activity or service without substantially affecting the level of this activity or service.

Energy intensity The amount of energy used per unit of activity or service.

Energy service The activity or service supplied by the use of energy (e.g., lighting a room).

Energy-intensive industries Industries for which energy costs represent a large part (e.g., more than 10%) of total production costs.

Specific energy consumption The amount of energy used per unit of activity, expressed in physical terms (e.g., energy use per ton of steel).

Introduction

Industrial production is the backbone of economic output in nearly all countries. Over the past decades, manufacturing industrial production has been growing in most economies. Industrial energy use can be broken down into that of the energy-intensive industries (e.g., primary metals, pulp and paper, primary chemicals, oil refining, building materials) and the non-energy-intensive industries (e.g., electronics, food). Energy use in the industrial sector is dominated by the production of a few major energy-intensive commodities such as steel, paper, cement, and chemicals. In any given country or region, production of these basic commodities follows the general development of the overall economy. Rapidly industrializing countries will have higher demands for infrastructure materials, and more mature markets will have declining or stable consumption levels. The regional differences in consumption patterns (expressed as consumption per capita) will fuel further growth of consumption in developing countries. In these 'heavy' industries, energy is a very important production cost factor in addition to labor costs and raw material costs, driving a change toward higher energy efficiency. Fig. 1 depicts the growth in the global production of the key energy-intensive materials, which combined are responsible for half of all industrial energy use.

Markets in the industrialized countries show a shift toward more service-oriented activities and, hence, non-energy-intensive industries. Still, energy-intensive industries will remain the largest energy consumers during the coming decades. Because of the great difference in energy intensity between energy-intensive industries and all others, changes in output shares of these industries can have a major impact on total industrial energy use. Many commodities (e.g., food, steel) are traded globally, and regional differences in supply and demand will influence total industrial energy use. Production trends also depend on regional availability of resources (e.g., mineral resources, scrap) and capital. Manufacturing energy use will also depend on the energy efficiency with which the economic activities are done.

This article discusses energy use patterns in industry and then assesses trends in industrial energy use and energy intensities. This is followed by a discussion of the potential for energy efficiency improvement and the future trends in industrial energy use.

Global Manufacturing Energy Use

In 2010, manufacturing industry consumed approximately 170 EJ (Exajoule, 10^{18} J), and accounted for approximately 38% of global energy-related GHG emissions. Between 1971 and 2010, industrial (primary) energy use grew from 91 EJ to nearly 170 EJ, equivalent to an average rate of 2.1% per year (see Table 1).

Energy use in industry is (globally, and in many countries) still dominated by the energy intensive industries, such as cement, steel, and chemicals. Since 1970, global annual production of cement has increased sixfold, by a factor 2.5 for steel; 4.6 for aluminium; 3.5 for ammonia (the key ingredient for fertilizer); and 3.2 for paper. Energy use in the industrial sector was until the turn of the century dominated by the industrialized countries, but since that time by developing countries, especially China. Much of the world's energy-intensive industry is now located in developing nations. In 2006, developing countries accounted for 74% of global cement manufacture, 63% of global nitrogen fertilizer production, about 50% of global primary aluminium production, and 48% of global steel production.

[☆]*Change History:* November 2013. E Worrell updated the statistical data throughout the chapter. New Figures 1 through 4 have been inserted. Table 1 has been updated to include recent years of energy statistics.

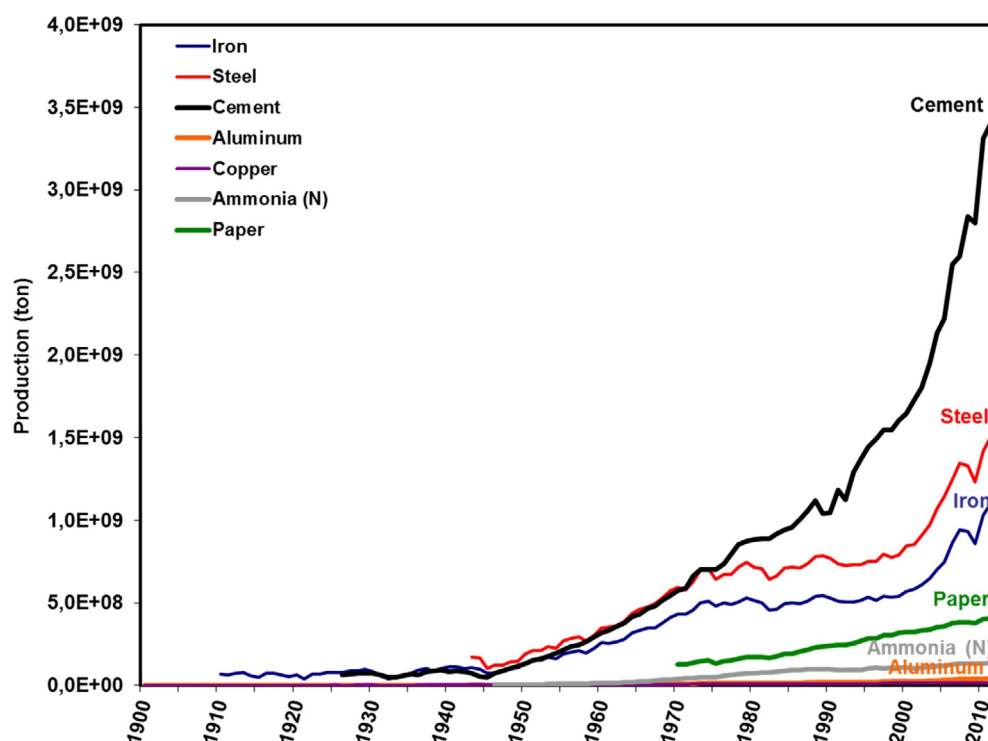


Fig. 1 Global production of key materials produced by energy-intensive industries.

Table 1 Estimated industrial energy use (1) in various world regions (in EJ, 10^{18} J/year), including non-energy use for feedstocks. Based on statistics of the International Energy Agency

| | Final Energy (EJ) (2) | | | | Primary Energy (EJ) (2) | | | |
|----------------------------|-----------------------|-------|--------|--------|-------------------------|--------|--------|--------|
| | 1971 | 1990 | 2004 | 2010 | 1971 | 1990 | 2004 | 2010 |
| Pacific OECD | 6.02 | 8.04 | 10.31 | 9.92 | 8.29 | 11.47 | 14.63 | 14.08 |
| North America | 20.21 | 19.15 | 22.66 | 20.02 | 25.88 | 26.04 | 28.87 | 24.13 |
| Western Europe | 14.78 | 14.88 | 16.60 | 15.19 | 19.57 | 20.06 | 21.52 | 18.00 |
| Economies in Transition | 4.89 | 23.11 | 12.68 | 13.47 | 21.13 | 31.67 | 17.78 | 16.60 |
| Asia (excl. OECD) | 7.34 | 19.88 | 34.51 | 53.19 | 9.38 | 26.61 | 54.22 | 75.01 |
| Latin America | 2.79 | 5.94 | 8.22 | 9.28 | 3.58 | 7.53 | 10.87 | 10.76 |
| Sub-Saharan Africa | 1.24 | 2.11 | 2.49 | 2.50 | 1.70 | 2.98 | 3.60 | 3.31 |
| Middle East & North Africa | 0.83 | 4.01 | 6.78 | 8.77 | 1.08 | 4.89 | 8.63 | 10.47 |
| World | 68.18 | 97.13 | 114.25 | 132.33 | 90.61 | 131.25 | 160.13 | 169.77 |

Notes: (1) Biomass energy included. (2) Industrial sector 'final energy' use excludes energy consumed in refineries and other energy conversion operations, power plants, coal transformation plants, etc. However, this energy is included in 'primary energy.' Upstream energy consumption was reallocated by weighting electricity, petroleum and coal products consumption with primary factors reflecting energy use and losses in energy industries. Final energy includes feedstock energy consumed, for example in the chemical industry. 'CO₂ emissions' in this table are higher than in IEA's Manufacturing Industries and Construction category because they include upstream CO₂ emissions allocated to the consumption of secondary energy products, such as electricity and petroleum fuels. To reallocate upstream CO₂ emissions to final energy consumption, we calculate CO₂ emission factors, which are multiplied by the sector's use of secondary energy.

Due to the economic crisis that started in 2008, industrial output and energy use in the OECD countries has declined. The share of industrial sector energy consumption within industrialized countries declined from 40% in 1971 to roughly 30%. The decline partly reflects the transition toward a less energy-intensive manufacturing base, a shift towards more a more service-oriented economy, as well as the continued growth in transportation demand, resulting in large part from the rising importance of personal mobility in passenger transport use. The industrial sector dominated in the economies in transition, accounting for more than 50% of total primary energy demand, the result of the emphasis on materials production, a long term policy promoted under years of central planning. Average annual growth in industrial energy use in this region was 2.0% between 1971 and 1990 (from 26 to 38 EJ). However, this emphasis and growth radically declined since the 1990's due to the economic restructuring.

In Asia (excluding OECD Asia), between 1971 and 1995 industrial energy use grew rapidly between 1971 and 1995, with an annual average growth rate of 5.9%, and even faster since. Today, Asia dominates global industrial energy demand, consuming approximately 75 EJ (or 44% of global industrial energy use). The fastest growth in this sector was seen in China and in other rapidly-developing Asian countries. Growth in other developing countries was slightly lower. The nature and evolution of the industrial sector varies considerably among developing countries. Some economies are experiencing continued expansion in energy-intensive industry, such as China and India. China now produces more than half of all the cement in the world and approximately 45% of all steel. In other countries, such as Thailand and Mexico, the share and/or growth of the transportation sector dominate. Many smaller countries have remained primarily agrarian societies with modest manufacturing infrastructure.

Future trends in industrial energy use will be affected by many different challenges. Globalizing trade patterns will affect industrial competition as well as technology transfer. Global environmental and economic challenges such as climate change will lead to an increased focus on energy efficiency and changing energy consumption patterns and fuel choice. Regional and local environmental problems will also drive changes in industrial energy use, both in industrialized and developing countries. In 2010 developing countries accounted for over half (57%) of primary energy use by industry, industrialized countries, 33%, and economies in transition, 10%. Since many facilities in developing nations are new, they sometimes incorporate the latest technology and are relatively energy efficient. However, many older, inefficient facilities remain in both industrialised and developing countries, and some are even exported as second-hand plants to developing countries.

Energy Services and Energy Efficiency

Energy is used to provide a service (e.g., producing a ton of steel, lighting a specified area). These services are called energy services. Energy consumers (including industry) are not interested in using energy; rather, they are interested in supplying the energy service in the most economic way. Energy efficiency improvement entails the provision of these services using less energy and without substantially affecting the quality of the service provided.

Approximately half of all industrial energy use is for specific processes in the energy-intensive industries. On the other hand, various general energy conversion technologies and end uses can also be distinguished (e.g., steam production, motive power, lighting). Hence, energy use in manufacturing industry can be broken down into various uses to provide a variety of services. A common breakdown distinguishes energy use for processes (called process specific) and energy use for buildings, utilities, and boilers (called cross-cutting). Note that boilers provide steam and hot water for processes as well as for cross-cutting energy services, as do motors.

Fig. 2 depicts the approximate distribution of energy use by industrial sector. Because of the wide variety in industrial processes, the discussion in the next section is limited to four energy-intensive sectors that are responsible for a large share of industrial energy use: iron and steel, pulp and paper, cement, and chemicals. This is followed in the subsequent section by a discussion of cross-cutting energy uses (i.e., boilers and motors).

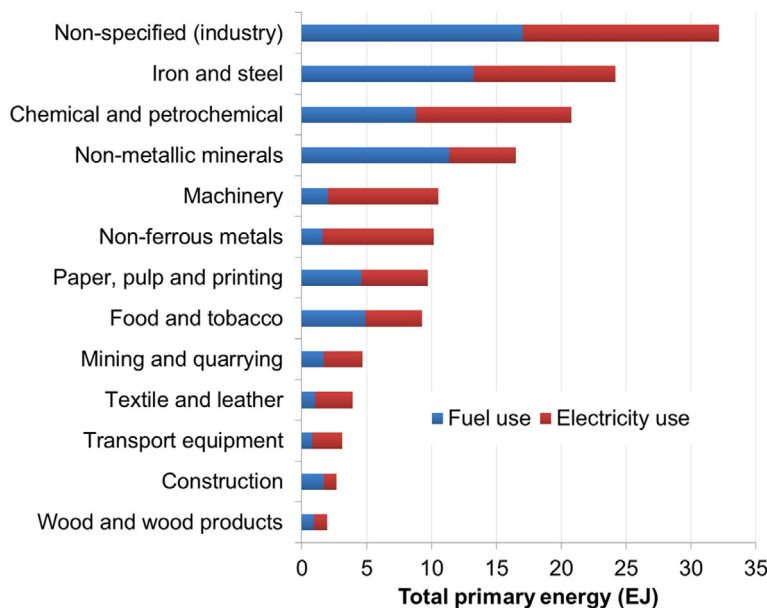


Fig. 2 Distribution of 2010 industrial energy use by major industrial sector, broken down by fuel and electricity use. Based on IEA statistics.

Energy-Intensive Industries

Iron and Steel Industry

The first record of the use of iron goes back to 2500 to 2000 bc, and the first deliberate production of iron began around 1300 bc. Small furnaces using charcoal were used. High-temperature processes started to be introduced in Germany around 1300 ad. The design of these furnaces is essentially the same of that of modern blast furnaces. The furnaces still used charcoal, and the first reported use of coke was in 1718 in the United Kingdom. The higher strength of coke allowed larger furnaces to be built with increasing energy efficiency. By 1790, coke ironmaking contributed to 90% of the British iron production. The development of the modern blast furnace after World War II resulted in an annual reduction of energy intensity of 3–4%/year due to the use of improved raw materials, ore agglomeration, larger blast furnaces, and higher air temperature. Today, the blast furnace is the main process to make iron and provides the largest raw material stream in steelmaking.

Steel is produced by reducing the carbon content in the iron to levels below 2%. This reduces the brittleness of the material and makes it easier to shape. The first steelmaking process was invented in 1855 by Bessemer. In the Bessemer converter, air was blown through the hot iron, a process that oxidizes the carbon. This principle is still followed in modern steelmaking processes. In the United States, the last Bessemer converter was retired during the 1960s. During the late nineteenth century, the Siemens–Martin or open hearth furnace (OHF) was invented. The OHF process uses preheated air to oxidize the carbon and melt the steel. This process is currently found only in developing countries and in Eastern Europe. The United States was one of the industrialized countries that phased out the OHF at a very late stage. During the 1980s, the dominant process became the basic oxygen furnace (BOF), which uses pure oxygen instead of air. The BOF process was developed in Austria during the 1950s. The productivity of this process is much higher, as is the energy efficiency. An alternative process is the electric arc furnace (EAF). The EAF process is used mainly to melt scrap. Performance of EAFs has improved tremendously, starting to use fuel and oxygen in addition to electricity. It is expected that in the future, the BOF and EAF processes will follow similar developmental paths. Liquid steel is cast into ingot or slabs and is shaped in rolling mills to the final product. Although most energy use is concentrated in the iron- and steelmaking, reduced material losses and productivity gains in casting and shaping (e.g., continuous casting, thin slab casting) have contributed to dramatic increases in the energy efficiency of steelmaking.

Today, the global iron and steel industry produced 1518 million tonnes of steel (2011). The industry is made up of integrated steel mills, which produce pig iron from raw materials (e.g., iron ore, coke) using a blast furnace and produce steel using a BOF, and secondary steel mills, which produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using an EAF. The majority of steel produced is from integrated steel mills (almost 70% in 2011), while the share of secondary steel mills (or ‘mini-mills’) has varied over the past years (29% in 2011).

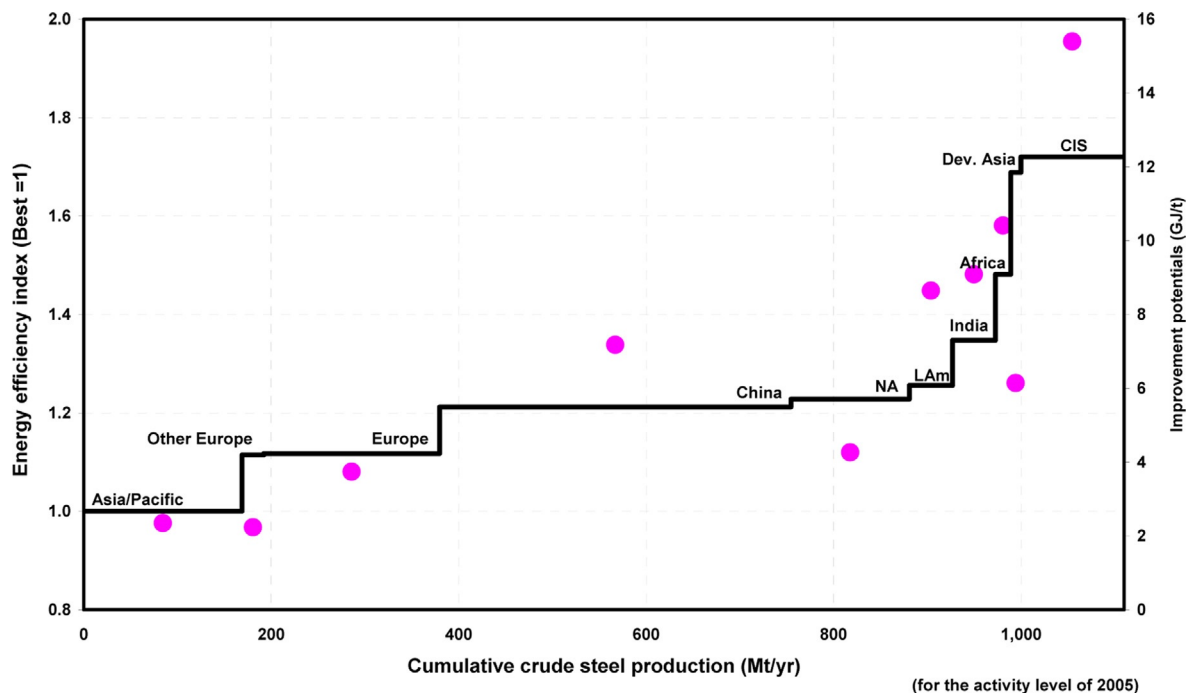


Fig. 3 Benchmark curve of the energy efficiency of the global iron and steel industry, relative to a best-practice technology (1 = best practice). The benchmark level is depicted on the left-hand y-axis. The dots represent the improvement potentials in the various regions relative to best practice energy use, and are depicted based on the right-hand y-axis.

Global final energy consumption for steelmaking is estimated at over 26 EJ (excluding conversion losses for purchased power). The worldwide average energy intensity of steelmaking is estimated at 19 gigajoules per ton (GJ tonne⁻¹), although large variations occur between countries and plants. This is roughly equivalent to a primary energy consumption of 23 GJ tonne⁻¹. Today, the most energy-efficient process would use 19 GJ tonne⁻¹ for integrated steelmaking and 7 GJ tonne⁻¹ for making steel out of scrap. Fig. 3 presents a benchmark curve of global iron and steel industry, depicting the regional variation in energy efficiency in the world.

Analyses have shown that many technologies exist that could improve energy efficiency further. A recent benchmarking study of global industrial energy use showed that if all steel plants would convert to current best-practice energy intensity, energy use can be reduced by 24%. An older study for the United States found the potential for energy efficiency improvement to be close to 18% using proven and cost-effective practices and technologies with a payback period of 3 years or less. New technologies that could considerably lower the energy intensity of steelmaking are under development. Smelt reduction in ironmaking would integrate the production of coke and agglomerated ore with that of ironmaking, leading to reductions in production costs and energy use. The development of direct casting techniques that abandon rolling would increase productivity while reducing energy use further. Combined, these technologies could reduce the energy intensity of primary steelmaking to 12.5 GJ tonne⁻¹ and could reduce that of secondary steelmaking to 3.5 GJ tonne⁻¹, reductions of 34 and 50%, respectively. In the highly competitive and globalizing steel industry, manufacturers must continuously look for ways in which to lower their energy intensity and costs.

Pulp and Paper Industry

Paper consists of aligned cellulosic fibers. The fibers may be from wood or other crops or from recycled waste paper. Starting with wood fibers, the fibers need to be separated from the wood, a process that is done by pulping the wood. The separation can be done by chemicals, by heat, or by mechanical means. In the chemical pulping process, chemicals and hot water are used to separate the cellulosis from the ligno-cellulosis. The amount of pulp produced is about half the amount of wood used. Chemical pulping results in high-quality paper. In mechanical the wood is ground under pressure, separating the fibers from each other. In mechanical pulping, the ligno-cellulosis is not removed, resulting in a lower quality paper (e.g., paper used for newsprint) but also in a higher recovery (~90% of the used wood). In chemical pulping, a lot of steam is used to heat the water and concentrate the chemical by-products. Recovery of the by-products to be recycled in the process can actually produce sufficient steam for the whole paper mill. The mechanical process uses large quantities of electricity, whereas some processes can recover steam from the grinding process. Waste paper is pulped by mixing with water, after which ink is removed and the pulp is refined. Paper recycling reduces the energy needs of the pulping process. Waste paper use in the production of paper varies widely due to the different structures of the industry in different countries.

Although energy efficiency improvement options do exist in the pulping step, greater opportunities exist in the chemical recovery step. The most common pulping process in the United States is the Kraft pulping process. Black liquor is produced as a by-product. The chemicals are recovered in a recovery boiler, combusting the ligno-cellulosis. Because of the high water content, the recovery boiler is not very efficient, and the steam is used to generate electricity in a steam turbine and steam for the processes. Gasification of black liquor would allow the use of the generated gas at a higher level of efficiency. This would make a Kraft pulp mill an electricity exporter.

In papermaking, the pulp is diluted with water at about 1:100. This pulp is screened and refined. The solution with the refined fibers (or stock) is fed to the paper machine, where the water is removed. In the paper machine, the paper is formed into a sheet and water is removed by dispersing over a wire screen. At the end of the forming section, 80% of the water is removed. The rest of the water is removed in the pressing and drying section. Although only a small amount of water is removed in the drying section, most energy is used in the drying section. Hence, energy efficiency opportunities try to reduce the water content by increasing the water removal by pressing. In a long nip press, the pressing area is enlarged. The larger pressing area results in extra water removal. New technologies aiming to increase the drying efficiency considerably are under development.

The pulp and paper industry uses approximately 7 EJ final energy. Because energy consumption and intensity depend on the amount of wood pulped, the type of pulp produced, and the paper grades produced, there is a great range of energy intensities among the industrialized countries of the world. If the global paper industry would convert mills to current best-practice it could save approximately 28%. The Netherlands used the least energy per ton of paper, largely because most of the pulp was imported. Countries such as Sweden and the United States have higher energy intensities due to the larger amount of pulp produced. Sweden and other net exporters of pulp also tend to show higher energy intensities. Energy intensity is also influenced by the efficiency of the processes used. Many studies have shown considerable potentials for energy efficiency improvement with current technologies such as heat recovery and improved pressing technologies. The paper industry is unique from other industries as it already uses a lot of renewable energy in the form of biomass and by-products from pulping. This reduces the carbon footprint considerably, when compared to the energy consumed by the industry.

Cement Industry

Cement is an inorganic, nonmetallic substance with hydraulic binding properties. Mixed with water, it forms a paste that hardens due to formation of hydrates. After hardening, the cement retains its strength. There are numerous cement types due to the use of different sources of calcium and different additives to regulate properties. The exact composition of cement determines its properties.

In 2011, global cement production was estimated to be 3600 million tonnes, with half of that production in China. Because of the importance of cement as a construction material and the geographic abundance of the main raw materials, cement is produced in virtually all countries. The widespread production is also due to the relatively low price and high density of cement, and this in turn limits ground transportation due to high transport costs.

The most common raw materials used for cement production are limestone, chalk, and clay. The collected raw materials are selected, crushed, and ground so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyro-processing systems. The grinding process differs depending on the pyro-processing process used. The feed to the kiln is called 'raw meal.' Clinker is produced by pyro-processing the raw meal. The raw meal is burned at high temperatures, first by calcination of the materials and then by clinkerization to produce clinker. Various kiln types have been used historically or are used around the world. Besides the rotary kiln, the vertical shaft kiln is used mainly in developing countries. In industrialized countries, the ground raw materials are processed predominantly in rotary kilns. In processing without precalcination, the decomposition (calcination) of CaCO_3 to CaO and CO_2 takes place in the kiln. The clinker is cooled. The cooling air serves as combustion air. The largest part of the energy contained in the clinker is returned to the kiln in this way. Grinding of cement clinker together with additives to control the properties of the cement is done in ball mills, roller mills, or roller presses. Coarse material is separated in a classifier to be returned for additional grinding. Power consumption for grinding depends strongly on the fineness required for the final product and the use of additives.

Cement production is a highly energy-intensive process. Cement making consists of three major process steps: raw material preparation, clinker making in the kiln, and cement making. Raw material preparation and cement making are the main electricity-consuming processes, whereas the clinker kiln uses nearly all of the fuel in a typical cement plant. Clinker production is the most energy-intensive production step, responsible for approximately 70–80% of the total energy consumed. Raw material preparation and finish grinding are electricity-intensive production steps. Final energy consumption by the cement industry is estimated at over 9 EJ, or 2% of global energy consumption.

The theoretical energy consumption to produce cement can be calculated based on the enthalpy of formation of 1 kg of Portland cement clinker (which is ~ 1.76 MJ). In practice, energy consumption is higher. The kiln is the major energy user in the cement-making process. Energy use in the kiln depends basically on the moisture content of the raw meal. Most electricity is consumed in the grinding of the raw materials and finished cement. Power consumption for a rotary kiln is comparatively low. If all cement plants would shift to modern kilns and state-of-the-art grinding technology, the global cement industry could reduce its energy use by 24%. This excludes any changes in the product mix, so blending with additives (e.g. fly ash, blast furnace slags, natural pozzolanes) could further reduce the energy consumption of this industry.

Chemical Industry

The chemical industry produces many intermediate compounds that are used as the basis for many chemical products. The chemical industry produces more than 50 000 chemicals and formulations. For example, ethylene, one of the most important bulk chemicals from an energy point of view, is used to produce products varying from solvents to plastics. Also, many processes in the chemical industry produce different coproducts. Chemical industries consume fuels and electricity as energy and feedstock. This makes energy analysis of the chemical industry more complicated compared than that of other industries.

A small number of bulk chemicals are responsible for the largest part of the energy consumption in the chemical industry. These are the so-called basic chemicals that are used as building blocks for many chemicals down the production chain. The most important basic chemicals are the family of petrochemicals (ethylene, propylene, butadiene, and benzene) from the organic chemical industry as well as ammonia and chlorine/caustic soda from the inorganic chemical industry.

Ethylene and its derivatives are feedstocks for many plastics and resins as well as for fibers and detergents. Global ethylene production is estimated at more than 80 Million tons and growing. The United States is the world's largest ethylene producer, accounting for less than 30% of the world capacity. Since 1974, ethylene production has grown by 3% annually, while propylene has grown by more than 4% annually. Propylene has grown more rapidly – 5% per year – during the past decade or so. Ethylene and other coproducts are produced through cracking of hydrocarbon feedstocks. In the presence of steam, hydrocarbons are cracked into a mixture of shorter unsaturated compounds. In the cracking process, hydrocarbon feedstocks are preheated to 650 °C (using fuel gas and waste heat), mixed with steam, and cracked at a temperature of approximately 850 °C. A series of separation steps produce fractions consisting of ethylene, propylene, a C_4 fraction (e.g., butadiene), and pyrolysis gasoline (containing benzene, toluene, and xylenes). The gas mixture is rapidly cooled to 400 °C (or quenched) to stop the reaction, during which process high-pressure steam is produced. Injection of water further decreases the temperature to approximately 40–50 °C, and a condensate that is rich in aromatics is formed. The liquid fraction is extracted, while the gaseous fraction is fed to a series of low-temperature, high-pressure distillation columns. Feedstocks used are ethane, LPG, naphtha, gas oils (GOs), and (sometimes) coal-derived feedstocks. Many of the installations used today can handle different (if not all) types of feedstock.

The single most energy-consuming step in the petrochemical industry is the steam cracking of hydrocarbon feedstocks into a mixture of shorter unsaturated compounds. Recent estimates of global energy consumption for the production of ethylene and coproducts are not available. Global (final) energy use is estimated at approximately 3 EJ. Energy consumption for ethylene production can be separated in feedstock and energy use. Feedstock energy use is generally equivalent to the heating value of the product, that is, approximately 42 GJ tonne^{-1} (lower heating value [LHV]). Specific energy consumption for the energy use of the process varies depending on the feedstock, technology, age of plant, capacity, and operating conditions. In general, it varies between 14 (ethane feedstock) and 30 GJ tonne^{-1} of ethylene (gas oil feedstock), whereas older plants can use more energy.

The production of ammonia, a key component in the manufacture of nitrogenous fertilizers, is a highly energy-intensive process. Roughly 80% of ammonia production is used as fertilizer feedstock. Ammonia is produced through the high-pressure synthesis of gases. Ammonia production in 2011 was estimated at 164 Million tonnes. Growth is found mainly in developing countries, where the production expansion is also concentrated.

Ammonia is produced by the reaction of nitrogen and hydrogen, the so-called Haber–Bosch process. The main hydrogen production processes used in the United States are steam reforming of natural gas and partial oxidation of oil residues. Hydrogen is produced by reforming the hydrocarbon feedstock and producing synthesis gas containing a mixture of carbon monoxide and hydrogen. The carbon monoxide is then reacted with steam in the water–gas–shift reaction to produce carbon dioxide and hydrogen. The carbon dioxide is removed from the main gas stream. The carbon dioxide is recovered for urea production or exported as a coproduct or vented. The hydrogen then reacts with nitrogen in the final synthesis loop to form ammonia. The ammonia is often processed to different fertilizers, including urea and ammonium nitrate, whereas ammonia is also used as an input to make other chemicals.

Energy intensity of ammonia making depends on the feedstock used and the age of the process. Natural gas is the preferred feedstock and is used for more than 80% of global ammonia production. Coal is still used in countries with limited natural gas supplies (e.g., China). The use of natural gas provides not only higher production efficiency but also lower capital costs. The global ammonia industry is estimated to consume about 6.5 EJ in (final) energy. Part of the energy input is used as feedstock; that is, the hydrogen in natural gas ends up in the ammonia. This is generally equivalent to the thermodynamic minimum energy consumption for Haber–Bosch synthesis, corrected for losses. Hence, feedstock use is estimated at 19–21 GJ tonne⁻¹ of NH₃ (LHV). Energy use varies between 9 and 18 GJ tonne⁻¹. The most efficient plants in the world consume approximately 28 GJ tonne⁻¹ of NH₃ (natural gas, feedstock and energy use). If all ammonia plants in the world would meet this performance (or a comparable practice for coal-based plants), this could result in savings of 22%.

Chlorine production capacity is estimated at 63 Million tons at nearly 700 sites. Most of the chlorine is produced in Asia. The production of chlorine gas is an energy-intensive chemical process. In the process, a brine solution is converted into two coproducts, chlorine gas and sodium hydroxide (caustic soda), through electrolysis. The three main electrolysis cell types that are used to separate and produce the chlorine gas and caustic soda are the mercury flow, diaphragm, and ion-selective membrane. In the diaphragm and membrane cells, the caustic soda requires an additional step of concentrating the solution so that it can meet market specifications for most products. Chlorine production is a main electricity-consuming process in the chemical industry, as is oxygen and nitrogen production. Energy use for chlorine production depends strongly on the cell type used for the electrolysis. Typically, power consumption varies between 2800 (membrane process) and 4300 kWh tonne⁻¹ (mercury process). In addition, steam may be used to concentrate the caustic soda in the membrane process. Membrane cells require the least amount of energy to operate. The membrane process is considered the state-of-the-art process. Countries in Asia and Europe have a higher share of membrane processes than do the United States and Canada.

Cross-Cutting Energy Services

Steam Production and Use

Besides the energy-intensive industries, many smaller and less energy-intensive, or light, industries exist. Light industries can include food processing, metal engineering, and electronics industries. In light industries, energy is generally a small portion of the total production costs. There is a wide variety of processes used within these industries. In general, a large fraction of energy is used in space heating and cooling, motors (e.g., fans, compressed air), and boilers. Industrial boilers are used to produce steam or heat water for space and process heating and for the generation of mechanical power and electricity. In some cases, these boilers have a dual function such as the cogeneration of steam and electricity. The largest uses of industrial boilers by capacity are in paper, chemical, food production, and petroleum industry processes. Steam generated in the boiler may be used throughout a plant or site. For example, total installed boiler capacity (not for cogeneration) in the United States is estimated at nearly 900 TW. Total energy consumption for boilers in the United States is estimated at 9–10 EJ.

A systems approach may substantially reduce the steam needs, reduce emissions of air pollutants and greenhouse gases, and reduce operating costs of the facility. A systems approach that assesses options throughout the steam system and incorporates a variety of measures and technologies can help to find low-cost options. Improved efficiency of steam use reduces steam needs and may reduce the capital layout for expansion, reducing emissions and permitting procedures at the same time. In specific cases, the steam boiler can be replaced nearly totally by a heat pump (or mechanical vapor recompression) to generate low-pressure steam. This replaces the fuel use for steam generation by electricity. Emission reductions will depend on the type and efficiency of power generation.

Another option to reduce energy use for the steam system is cogeneration of heat and power. Based on gas turbine technology, this is a way in which to substantially reduce the primary energy needs for steam making. Low- and medium-pressure steam can be generated in a waste heat boiler using the flue gases of a gas turbine. Classic cogeneration systems are based on the use of a steam boiler and a back pressure turbine. These systems have relatively low efficiency compared with a gas turbine system. Steam turbine systems generally have a power-to-heat ratio between 0.15 (40 kWh GJ⁻¹) and 0.23 (60 kWh GJ⁻¹). The power-to-heat ratio depends on the specific energy balance of the plant as well as on energy costs. A cogeneration plant is most often optimized to the steam load of the plant, exporting excess electricity to the grid. The costs of installing a steam turbine system depend strongly on the capacity of the installation. Gas turbine-based cogeneration plants are relatively cheap. In many countries (e.g., the Netherlands,

Scandinavia), gas turbine cogeneration systems are standard in industry. The power-to-heat ratio is generally higher than that for steam turbine systems. Aero-derivative gas turbines may have a power-to-heat ratio of 70–80 kWh GJ⁻¹. Aeroderivative turbines are available at low capacities, but specific costs of gas turbines decrease sharply with larger capacities.

Motors and Motor Systems

Motor systems are used throughout any industrial operation. A motor system generally consists of an appliance, the drive train, and the motor. Motor systems consume more than 65% of industrial electricity use in the United States, Europe, and China. The share of motor electricity use varies by sector. For example, in the cement industry, as much as 90% of electricity is used in motors to grind raw materials and final products and to drive the kiln. Motors themselves are efficient, and well-designed and -maintained motors have conversion efficiencies of more than 90%. However, older and inefficient motors may have much lower efficiencies, and the efficiency losses are even higher in the total motor system.

Motors range from less than 1 kW to a few megawatts in size. The largest motors are found in kiln and mill drives in the cement industry or as compressors in the chemical industry. Smaller motors may be found in many locations and are often installed as a whole system (e.g., a packaged pump). Small motors account for more than half of the motors installed in U.S. industry but represent a much smaller share of electricity use because these motors are generally used for fewer hours, whereas the large motors may run continuously. The most important uses of motors are for pumps, compressed air, and fans. In the United States, nearly 25% of industrial motor electricity is used for pumping systems, 14% for fans, 16% for compressed air systems, and 23% for material processing. Other uses (e.g., material handling, refrigeration) represent more than 23% of motor electricity use.

There are many opportunities to improve efficiency in motor systems. Overall, the cost-effective potential for motor system efficiency measures is estimated at 15–30% of overall motor electricity use. The most important element of any motor efficiency effort is a systems approach, that is, to optimize the whole system and not focus on a single element (the motor). The most important opportunities are found in optimizing the system driven by the motor, managing the motor system through adjustable speed drives (ASDs), and improving the efficiency of the motor. Compressed air systems use approximately 16% of industrial motor electricity. However, the overall efficiency of compressed air systems is often less than 10%. There are large opportunities for reduction of energy use by reducing leaks, improving air intake, and abolishing inappropriate use of compressed air as an energy source (and replacing, e.g., by direct drives). ASDs have revolutionized motor systems by allowing for affordable and reliable speed control using rugged conventional induction motors. ASDs work by varying the frequency of the electricity supplied to the motor, thereby changing the motor's speed relative to its normal supply frequency. This is accomplished by rectifying supplied alternating current to direct current and then synthesizing an alternating current at another frequency. This is accomplished with an inverter, which is a solid-state device in modern ASDs.

Energy Intensity Trends

In aggregate terms, studies have shown that technical efficiency improvement of 1–2% per year has been observed in the industrial sector in the past. During and after the years of the oil shock, U.S. industrial energy intensity declined by 3.5% per year (between 1975 and 1983). However, since the mid 1980's energy prices came down, and industrial energy intensity declined by less than 1% on average.

The trends demonstrate the capability of industry to improve energy efficiency when it has the incentive to do so. Energy requirements can be cut by improved energy management and new process development. In addition, the amount of raw materials demanded by a society tends to decline as the society reaches certain stages of industrial development, leading to a decrease in industrial energy use. At the same time, the mix of fuels used by industry changes over time, affecting energy intensity as well as emissions. Overall changes in the manufacturing fuel mix are driven by price changes, availability and reliability of supply, efficiency gains, and sector structure. For example, in the U.S. manufacturing industry, a general trend toward a reduced use of coal and oil since 1958. Although coal consumption remained fairly constant after the oil price shock of the early 1970s, it has declined further since. This change is partially a reflection of the decline of the energy-intensive industries in the U.S. economy. Natural gas, an easier and more efficient fuel to use, shows a dramatic increase in its share of the fuel mix over time. Also important is the increased use of electricity throughout industry, reflecting an overall trend in society of increased penetration of electric devices and equipment. Light industries tend to consume relatively more electricity than do energy-intensive industries.

The accounting of trends in structural shift, material intensity, and technical energy efficiency, as well as their interactions, can be extremely difficult. To understand trends in energy intensity, it is important to analyze the structure of the industrial sector. Reduction of energy intensity is linked closely to the definition of structure, structural change, and efficiency improvement. Decomposition analysis is used to distinguish the effects of structural change and efficiency improvement. Structural change can be broken down into intrasectoral (e.g., a shift toward more recycled steel) and intersectoral (e.g., a shift from steel to aluminum within the basic metals industry). A wide body of literature describes decomposition analyses and explains the trends in energy intensities and efficiency improvement. Decomposition analyses of the aggregate manufacturing sector exist mainly for industrialized countries but also for China, Taiwan, and selected countries such as those in Eastern Europe. The results show that different patterns exist for various countries, possibly due to specific conditions as well as differences in driving forces such as energy prices and other policies in these countries. More detailed analyses on the subsector level are needed to understand these trends better.

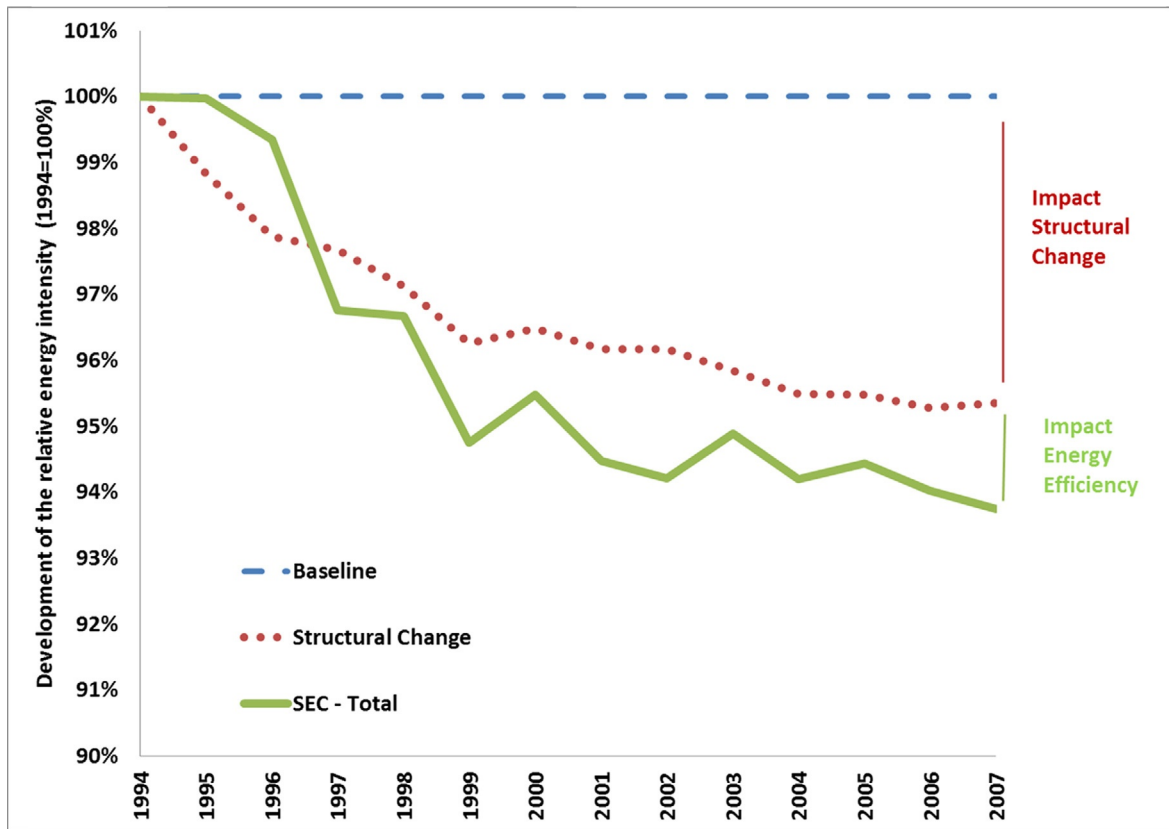


Fig. 4 Development of the specific energy consumption of the German Iron and Steel Industry between 1994 and 2007, and the contribution of structural change (i.e. shift towards more EAF) and energy efficiency improvement. Note that the German iron and steel industry during this period was one of the most energy-efficient in the world. Arens et al. (2012).

Changes in energy intensities can also be disaggregated into structural changes and efficiency improvements at the subsector level. In the iron and steel industry, energy intensity is influenced by the raw materials used (e.g., iron ore, scrap) and the products produced (e.g., slabs, thin rolled sheets). For example a recent study of the German iron and steel industry showed a steady decline in energy intensity, as the effect of a decreasing share of primary steelmaking and energy efficiency improvement (see Fig. 4).

Potential for Energy Efficiency Improvement

Much of the potential for improvement in technical energy efficiencies in industrial processes depends on how closely such processes have approached their thermodynamic limit. There are two types of energy efficiency measures: (1) more efficient use of existing equipment through improved operation, maintenance, or retrofit of equipment; and (2) use of more efficient new equipment through the introduction of more efficient processes and systems at the point of capital turnover or expansion of production. More efficient practices and (new) technologies exist for all industrial sectors. Table 2 outlines some examples of energy efficiency improvement techniques and practices.

A large number of energy-efficient technologies are available (Table 2) in the steel industry, including continuous casting, energy recovery, and increased recycling. Large technical potentials exist in most countries, ranging between 15 upto 50% even in industrialized countries, and estimated at 24% globally. New technologies that are under development (e.g., smelt reduction, near net shape casting) will reduce energy consumption as well as environmental pollution and capital costs. In the chemical industry, potentials for energy savings in ammonia making are estimated at up to 35% in Europe and between 20 and 30% in Southeast Asia. Energy savings in petroleum refining are possible through improved process integration, cogeneration, energy recovery, and improved catalysts. Compared with commercially used state-of-the-art technology, the savings in industrialized countries are estimated at 15–20% and are higher for developing countries. Large potentials for energy savings exist in nearly all process stages of pulp and paper production (e.g., improved dewatering technologies, energy and waste heat recovery, new pulping technologies). Technical potentials are estimated at up to 40%, with higher long-term potentials, while the global average for currently available commercial technology is estimated at 28%. Energy savings in cement production are possible through increased use of additives (replacing the energy-intensive clinker), use of the dry process, and a large number of energy efficiency measures

Table 2 Examples of energy efficiency improvement measures in energy-intensive industry

| | |
|--------------------|---|
| Iron & Steel | Heat recovery for steam generation, preheating combustion air, high-efficiency burners |
| | Adjustable speed drives, heat recovery coke oven gases, dry coke quenching |
| | Efficient hot blast stove operation, waste heat recovery for hot blast stove, top gas power recovery turbines, direct coal injection |
| | Recovery BOF–gas, heat recovery of sensible heat BOF–gas, closed BOF–gas system, optimized oxygen production, increased scrap use, efficient tundish preheating |
| | UHP process, oxy-fuel injection for EAF plants, and scrap preheating |
| Pulp & Paper | Use of continuous casting, thin slab casting, recuperative burners |
| | Heat recovery, efficient burners annealing and pickling line, continuous annealing operation |
| | Continuous digester, displacement heating/batch digesters, chemi–mechanical pulping |
| | Black liquor gasification, cogeneration |
| | Oxygen predelignification, oxygen bleaching, displacement bleaching |
| Cement | Tampella recovery system, falling film black liquid evaporation, lime kiln modifications |
| | Long nip press, advanced paper machines, closed hood papermachine |
| | Improved boilers, cogeneration, improved controls |
| | Improved grinding media and linings, roller mills, high-efficiency classifiers |
| | Multistage preheating, precalciner, kiln combustion system improvements, kiln shell loss reduction, optimize heat transfer in clinker cooler, use of alternative fuels |
| Chemicals | Modified ball mill, improved grinding media and linings, high-pressure roller press and mills, high-efficiency classifiers |
| | Blended cements |
| | Process management and integration (e.g., optimization of steam networks, heat cascading, low and high-temperature heat recovery, heat transformers), mechanical vapor recompression |
| | Improved and more selective catalysts |
| | Motor system optimization, adjustable speed drives, improved pumps and compressors |
| Petroleum Refining | Selective steam cracking, membrane separation |
| | High-temperature cogeneration |
| | Autothermal reforming (ammonia) |
| | Cogeneration, steam system optimization |
| | Process management and integration |
| | Reflux overhead vapor recompression, staged crude preheat |
| | Fluid coking to gasification, turbine power recovery train at the fluid catalytic cracker and hydrocracker, hydraulic turbine power recovery, membrane hydrogen purification, unit-to-hydrocracker recycle loop |
| | Improved catalysts (reforming) |
| | Cogeneration, steam system optimization |
| | |

(e.g., reducing heat losses, using waste as fuel). Energy savings potentials of up to 50% exist in the cement industry in many countries through efficiency improvement and the use of wastes, such as blast furnace slags and fly ash, in cement making.

However, barriers may partially block the uptake of those technologies. Barriers to efficiency improvement can include unwillingness to invest, lack of available and accessible information, economic disincentives, and organizational barriers. The degree to which a barrier limits efficiency improvement is strongly dependent on the situation of the actors (e.g., small companies, large industries). A range of policy instruments is available, and innovative approaches or combinations have been tried in some countries. Successful policy can contain regulation (e.g., product standards) and guidelines, economic instruments and incentives, voluntary agreements and actions, information, education and training, and research, development, and demonstration policies. Successful policies with proven track records in several sectors include technology development and utility/government programs and partnerships. Improved international cooperation to develop policy instruments and technologies to meet developing country needs will be necessary, especially in light of the large anticipated growth of the manufacturing industry in this region.

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