Energy Efficiency Improvement Opportunities in the Global Industrial Sector

Wina Crijns-Graus and Hui Yue, Utrecht University, Utrecht, the Netherlands
Shaohui Zhang, Beihang University, Beijing, China
Katerina Kermeli and Ernst Worrell, Utrecht University, Utrecht, the Netherlands

Introduction

In 2016, the global industrial sector consumed 144 EJ final energy, which corresponded to 36% of global final energy consumption (based on IEA, 2018a). The International Energy Agency (IEA, 2018b) projects that without any further actions, by 2040, industrial energy use will increase to 206 EJ (or by 43%). Improved energy efficiency can limit industrial energy use and is considered as one of the most cost-effective ways of reducing greenhouse gas emissions (Ryan and Campbell, 2012). Although in the past decades the adoption of energy efficiency measures reduced industrial energy intensity, increased energy demand due to increased industrial production, has offset any energy gains from improved efficiency. With increasing industrial productivity, industrial energy use and associated greenhouse gas emissions are expected to grow further, increasing the importance of energy savings.

In this article we will first give an overview of past developments of energy use and greenhouse gas emissions in industries, where we look at trends in sectors and countries (Section "Energy Use and Greenhouse Gas Emissions in Industries"). In Section "Energy Efficiency Measures" we focus on four major energy consuming sectors (chemicals, iron and steel, cement and aluminum) and describe the main energy consuming processes and energy saving opportunities. Finally, conclusions are given in Section "Conclusions".

Energy Use and Greenhouse Gas Emissions in Industries

Fig. 1 shows a breakdown of global energy use in industries by sector, based on IEA (2018c). The chemical sector (including petrochemicals) is the biggest sector and is responsible for 26% of industrial energy use in 2016. This sector is followed by the iron and steel sector, which accounts for 19% and non-metallic minerals and oil refineries which both consume 9% of industrial energy

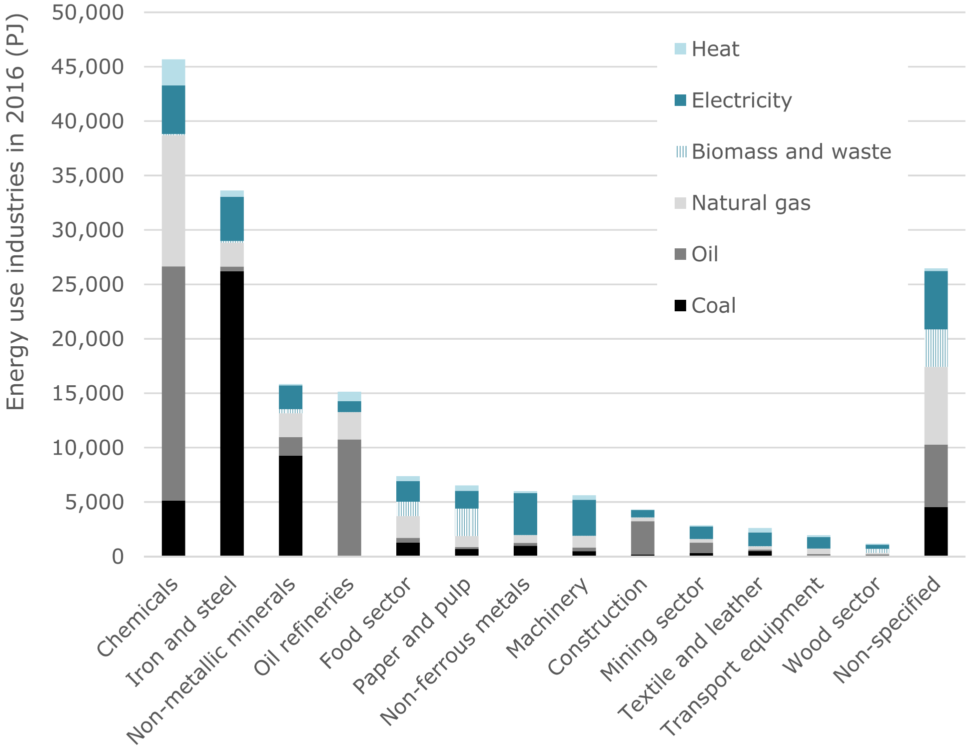

Fig. 1 Global energy use in industries in 2016 (PJ). Based on data from IEA, 2018c. Extended World Energy Balances Database. 2018 ed. Paris: International Energy Agency (IEA).

 doi:10.1016/B978-0-12-803581-8.10906-3

use. Energy use in non-metallic minerals is mainly related to cement production, which accounts for 70%–80% of the sectors energy use (Kermeli *et al.*, 2019).

Out of the energy carriers, coal is most often used in industries with 28%, followed by oil (26%), natural gas (19%) and electricity (18%). Renewable energy use, excepting biomass, is negligible so far. Coal is mainly used in the iron and steel sector (78% of total coal use in industries) and non-metallic minerals (19%), followed by chemicals (10%). Natural gas is more spread over all sectors, with its main use in chemicals (37%). Oil use is mostly occurring in chemicals (47%) and oil refining (24% of total oil use). Electricity use is also widely spread but highly consuming sectors are chemicals (14%), iron and steel (13%) and non-ferrous metals (12%). The energy use in the non-ferrous metals sector is for about 70% related to aluminum production (Kermeli *et al.*, 2015).

If we add up all sectors the total energy use in industries amounted to 174 EJ in 2016, which is 30% of total primary energy use worldwide (576 EJ). This includes:

(1) 144 EJ final energy use; of which 30 EJ is non-energy use (consisting for 26 EJ of feedstocks in petrochemicals),
(2) 14 EJ of energy use and transformation losses in coke ovens and blast furnaces and
(3) 15 EJ of energy use in oil refineries.

Indirect energy use from electricity consumption that is not produced on site is not included.

Fig. 2 shows the development of energy use in industries over time in the period 1990–2016 (based on IEA, 2018c). In this period an increase is visible of 56%, from 111 EJ to 174 EJ, mainly occurring in the 2000s. The share of iron and steel in this period increases from 15% to 19% and of chemicals from 22% to 26%. Also the non-metallic minerals sector shows an increase from 6% to 9%. Meanwhile the other sectors remain more or less constant, while the category "non-specified industries" (which is part of "others" in **Fig. 2**) decreases from 25% to 15%.

Fig. 3 shows the development of industrial energy use by country. Here it is quite visible that a large share of the increase in industries in the 2000s is related to growth in China. Excluding China, industries grow from 99 EJ in 1990 to 119 EJ in 2016 (increase of 20%). In China industries grow from 12 EJ to 55 EJ (+360%), increasing its share in global industrial energy demand from 11% in 1990 to 32% in 2016. Other fast growing countries are India (from 3.5 EJ to 10.8 EJ), South Korea (1.3–5.3 EJ), Saudi Arabia (0.8–3.2 EJ), Iran (1.0–3.2 EJ) and Brazil (2.3–4.0 EJ). The EU-28 is one of the regions with a decrease from 22 EJ in 1990 to 18 EJ in 2016. Also Russia (13 to 12 EJ), Japan (7.3 to 6.1 EJ) and the United States (20.3 to 19.7 EJ) show a decrease.

CO_2 emissions from energy use in industries (including oil refineries and non-energy use) amounted to 9.7 Gtonne CO_2 in 2016 (based on data from **Fig. 1** and typical emission factors of 94 g CO_2/MJ for coal, 73 g CO_2/MJ for oil and 56 g CO_2/MJ for natural gas (IPCC, 2006)). Including indirect CO_2 emissions by electricity consumption adds 4.8 Gtonne CO_2 in 2016 (based on **Fig. 1** and a global average emission intensity for power generation of 532 g CO_2/kWh in 2016 (based on IEA, 2018b)). Finally, industrial process emissions add another 3.2 Gtonne CO_{2eq} in 2014 (ClimateWatch, 2019). These emissions are for more than half related to process emissions from cement production, which were 1.7 Gtonne CO_{2eq} in 2012 (Janssens-Maenhout *et al.*, 2017). Together it means that total industry is responsible for about 35% of global GHG emissions, which were 50 Gtonne in 2014 (ClimateWatch, 2019).

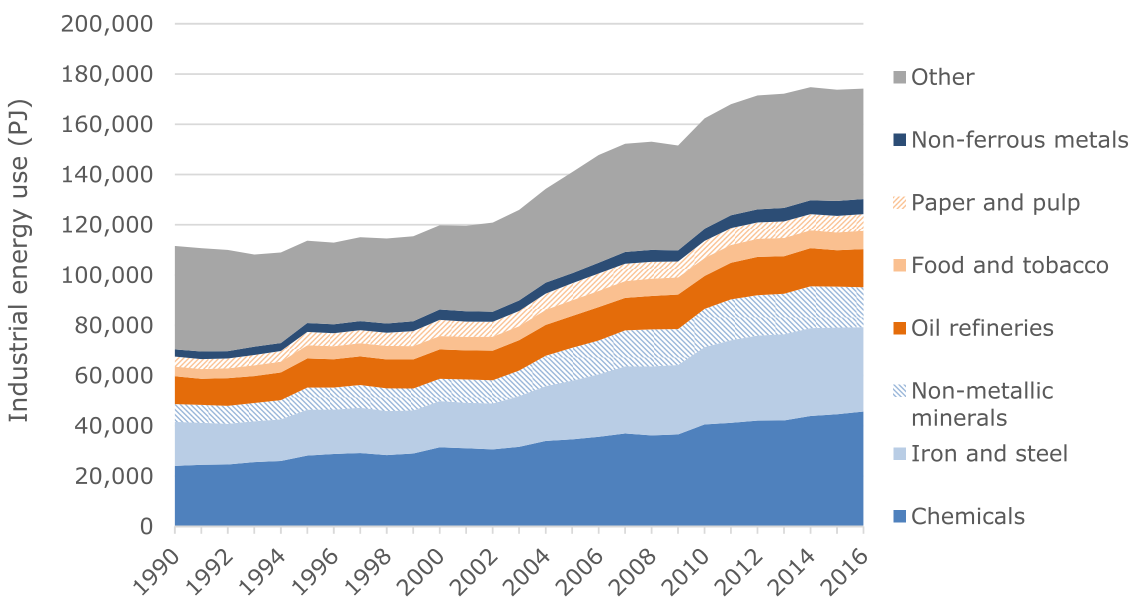

Fig. 2 Global industrial energy use per sector. Based on data from IEA, 2018c. Extended World Energy Balances Database. 2018 ed. Paris: International Energy Agency (IEA).

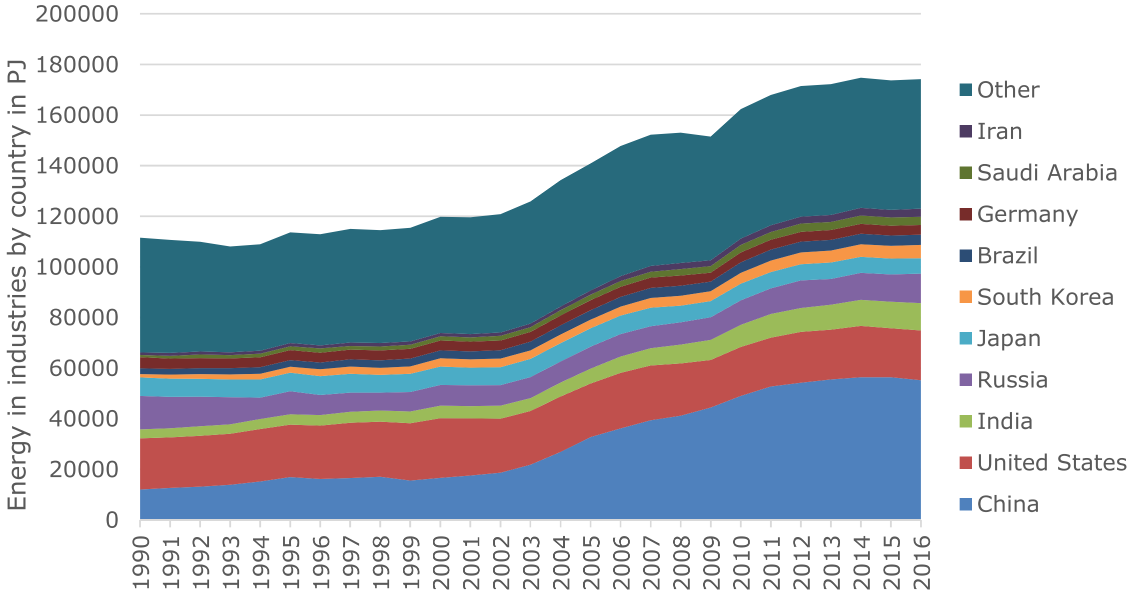

Fig. 3 Energy use in industries by country. Based on data from IEA, 2018c. Extended World Energy Balances Database. 2018 ed. Paris: International Energy Agency (IEA).

Energy Efficiency Measures

In this section we will discuss main energy saving options in the main industrial sectors which are chemicals, iron and steel and cement. Also we include aluminum production, which is the biggest electricity consuming sector, after chemicals and iron and steel.

Chemicals

The chemical industry produces many different chemical products (e.g., ammonia, caustic soda and ethylene) and is by far the largest industrial energy user. The global energy demand of the chemical industry is 19 EJ excluding feedstock and 46 EJ including feedstock, accounting for about 26% of the total industrial energy demand in 2016 (IEA, 2018a). While the chemical industry produces thousands of chemicals, only a few chemicals consume most of the energy. These are the production of light olefins (ethylene and propylene), BTX aromatics (benzene, toluene and xylenes), ammonia and methanol, which account for 73% of the total energy use of the chemical industry (IEA, 2017). Improving the energy efficiency in the energy-intensive processes is key to reduce overall energy consumption in the chemical industry worldwide.

One of the main energy consuming processes is steam cracking of hydrocarbon feedstocks, which is used in the petrochemical industry to produce ethylene and propylene and BTX aromatics. These products are further processed into polymers, solvents and resins. Steam cracking results in a large variety of products with varying energy intensities and accounts for about 20% of the final energy use (excl. feedstocks and electricity in the chemical and petrochemical industry (IEA, 2009a)). Saygin *et al.* (2011) estimate that by implementing best practice technology the average world energy intensity of 16.9 GJ/tonne High Value Chemicals (HVCs) (including ethylene, propylene, benzene, butadiene, acetylene and hydrogen) could decrease by 26% (excl. feedstocks). When implementing best available technology an improvement of 37% was estimated to be possible (Kermeli *et al.*, 2014).

The manufacture of ammonia and methanol accounts for about 32% of the energy consumed in the chemical and petrochemical sector (IEA, 2017). Ammonia is mainly used as a feedstock in fertilizer production. Saygin *et al.* (2011) estimate a global fuel savings potential for ammonia production, when implementing best practice technology, of 31% (excl. feedstock and electricity use).

Methanol is used mainly as antifreeze, solvent and fuel. The majority of methanol production (80%) is natural gas-based with the remainder, mainly taking place in China, being coal-based (Kermeli *et al.*, 2014). The world average energy use in methanol production is estimated at 10.9 GJ/tonne (excl. feedstock and electricity) (Saygin *et al.*, 2011). The worldwide adoption of best practice technology (8.5 GJ/tonne), would result in a 22% decrease of the energy intensity.

Chlorine production is the main electricity consuming process in the chemical industry (Graus *et al.*, 2011). The most efficient production process for chlorine production is the membrane process which consumes 2600 kWh/tonne chlorine, which is already close to the most efficient technology considered feasible (IEA, 2008). As a comparison to commonly used mercury process has an energy intensity of around 4000–4500 kWh/tonne chlorine (Kermeli *et al.*, 2014), but is being phased out in many countries.

Table 1 gives an overview of the main energy efficiency technologies that can be implemented in the chemical industry with their main characteristics.

Table 1 List of energy efficiency technologies applied in the chemical industry

Sector	*Energy efficiency technology*	*Investment (€/tonne chemical)*	*Energy savings (%)*	*Source*
Ammonia	Adiabatic pre-reformer	17.7	7.5	Boulamanti and Moya Rivera (2017) and Kermeli *et al.* (2017)
	Heat exchange autothermal reforming	25.2	6	Boulamanti and Moya Rivera (2017) and Kermeli *et al.* (2017)
	Advanced conventional processes	31.5	10	Boulamanti and Moya Rivera (2017) and Kermeli *et al.* (2017)
	Reduced primary reforming and increased process air	29.4	5	Boulamanti and Moya Rivera (2017)
	Preheat mixed feed and efficient gas turbine	14.5	16.6	Boulamanti and Moya Rivera (2017)
	Advanced process control	6	2.3	Boulamanti and Moya Rivera (2017), Kermeli *et al.* (2017) and Yue *et al.* (2018)
	Low pressure ammonia synthesis catalysts		3.9	Boulamanti and Moya Rivera (2017) and Kermeli *et al.* (2017)
	Using hydrogen from water electrolysis	176	66.3	Boulamanti and Moya Rivera (2017)
	Improved the reforming section	37	13.3	Boulamanti and Moya Rivera (2017)
	Multi-nozzle opposed coal water slurry gasification	110	15	Yue *et al.* (2018)
	New reforming membranes[a]	348.1	17	Boulamanti and Moya Rivera (2017)
	Solid state ammonia synthesis[a]	241.1	66.3	Boulamanti and Moya Rivera (2017)
	Short contact time catalytic partial oxidation[a]	1670	11	Boulamanti and Moya Rivera (2017)
	Used new membranes for CO_2 removal[a]		<5	Boulamanti and Moya Rivera (2017)
Light olefins	Decoking activities		<5	Boulamanti and Moya Rivera (2017)
	Advanced furnace materials such as selective radiant coils and ceramic-coated tubes	2.1	10	Boulamanti and Moya Rivera (2017)
	Improving compression and separation section (ICSS) – Advanced distillation columns	0.8	1.5	Boulamanti and Moya Rivera (2017)
	ICSS – Mechanical vapor recompression	0.6	5	Boulamanti and Moya Rivera (2017)
	Adsorption heat pump[a]	10.8	12	Boulamanti and Moya Rivera (2017)
	ICSS – Membranes[a]	18.4	8	Boulamanti and Moya Rivera (2017)
	Olefin production via methanol[a]		5	Boulamanti and Moya Rivera (2017)
BTX aromatics	Energy integration – reformate based process	9.5	25 electricity and 20 thermal	Boulamanti and Moya Rivera (2017)
	Energy integration – pygas based process	9.5	9 thermal	Boulamanti and Moya Rivera (2017)
Hydrogen and methanol	Air preheat	6.8	5	Boulamanti and Moya Rivera (2017)
	Minimal steam: carbon ratio and associated measures		<5	Boulamanti and Moya Rivera (2017)
	Hydrogen from electrolysis	2211.7	35	Boulamanti and Moya Rivera (2017)
	Membrane methane reforming[a]	1978.0	20	Boulamanti and Moya Rivera (2017)
	Short contact time catalytic partial oxidation[a]	695.3	15	Boulamanti and Moya Rivera (2017)
Soda ash	Integrated design and operation	40	44.6 electricity and 17.6 thermal	Boulamanti and Moya Rivera (2017)
	Vertical shaft kiln for the production of concentrated CO_2 gas and reactive lime	16	2.7	Boulamanti and Moya Rivera (2017)
Chlor-alkali	Conversion of mercury to membrane cell plants	426.2	28.4 electricity	Boulamanti and Moya Rivera (2017)
	Conversion of asbestos diaphragm to membrane cell plants	367	7 electricity and 70.5 steam	Boulamanti and Moya Rivera (2017)
	Asbestos-free diaphragms	10	4.4 electricity	Boulamanti and Moya Rivera (2017)
	High performance bipolar membrane cells	21	13.6 electricity	Boulamanti and Moya Rivera (2017) and Yue *et al.* (2018)
	High performance electrodes and coatings		3–4	Boulamanti and Moya Rivera (2017)
	Recovered hydrogen as a chemical reagent or fuel		<5	Boulamanti and Moya Rivera (2017)
	Oxygen depolarized cathodes[a]	89	15	Boulamanti and Moya Rivera (2017) and Yue *et al.* (2018)
	Four-stage caustic evaporator in membrane plants[a]		20	Boulamanti and Moya Rivera (2017)

Table 1 Continued

Sector	*Energy efficiency technology*	*Investment (€/tonne chemical)*	*Energy savings (%)*	*Source*
Ethylene oxide & ethylene glycols	Shell OMEGA process	244.4	20	Boulamanti and Moya Rivera (2017)
PVC	Pigging system	101,568 (for 100 m pipeline)	19 electricity	Boulamanti and Moya Rivera (2017)
	High pressure distillation for calcium carbide-based PVC	1	24 electricity	Yue *et al.* (2018)
Ethylbenzene & styrene	Advanced control and optimization	6.1	5	Boulamanti and Moya Rivera (2017)
	Exelus styrene monomer process[a]	184.1	40	Boulamanti and Moya Rivera (2017)
Calcium carbide[b]	Advanced kilns such as vocarse shaft kiln, double shell shaft kiln and maerz PFR shaft kiln	37	13	Yue *et al.* (2018)
	Transforming semi-covered furnace to closed furnace (exclude the utilization of tail gas)	33	5 electricity	Yue *et al.* (2018)
	Direct current electric arc furnace	42	10 electricity	Yue *et al.* (2018)
	New conductive copper contact shoe for closed furnace	43	4 electricity	Yue *et al.* (2018)
	40.5 MVA closed furnace	50	18	Yue *et al.* (2018)
	63 MVA closed furnace	101	25	Yue *et al.* (2018)
	Low-voltage dynamic reactive power compensation	12	4.5 electricity	Yue *et al.* (2018)
	Combination electrodes	12	5.4 electricity	Yue *et al.* (2018)
	Comprehensive compensation of short-supply network	27	7	Yue *et al.* (2018)
	Electricity saving expert system for electric arc furnace	6	3 electricity	Yue *et al.* (2018)
	Automatic control system for materials feeding and batching	12	4 electricity	Yue *et al.* (2018)
	Waste heat of flue gas for power generation	33	11 electricity	Yue *et al.* (2018)

[a]Uncommercialized technology.

[b]The technologies used in calcium carbide are mainly based on China because China represents around 95% of global production and consumption of calcium carbide (SEC: 3400 kWh/t-calcium carbide).

Energy efficiency improvement through the use of best practice technologies can reach around 17% for the chemical industry. Higher potentials can be realized through process integration (4%), Combined Heat and Power (CHP) generation (10%) and recycling and energy recovery (1%) (Saygin *et al.*, 2011). From the regional perspective, IEA indicate that China has the largest potential to improve energy efficiency in the chemical industry, accounting for 40% of global energy savings potential (IEA, 2013).

At the end of the useful life of plastics, it is possible to save energy by recycling (mechanically or as feedstock) and energy recovery. Mechanical recycling is by far the most widely used approach worldwide. The main alternatives to recycling are incineration (with and without energy recovery) and landfilling. Globally, less than 10% of the total plastic waste is recycled. In Europe and Japan, the share of recovered plastic waste (by mechanical recycling and energy recovery) is higher than global average. Around 20% of the plastic waste is mechanically recycled and 30% is combusted with energy recovery in Europe. The remaining 50% is unrecovered (disposed by landfilling or incinerated without energy recovery). In Japan the share of recovered waste is higher than in Europe (60% in comparison to 50%) (Saygin *et al.*, 2011).

As seen in Section "Energy Use and Greenhouse Gas Emissions in Industries", China is one of the main energy consuming countries in terms of industrial energy use, being responsible for 32% in 2016. This is reflected in China's chemical industry which shows a strong grown since 2000, with an annual growth rate of 9%, for main chemicals (Yue *et al.*, 2018). As the largest chemical market worldwide, China represents around 1/3 of the global chemicals production. In particular, China is the largest producer and consumer of ammonia, caustic soda, polyvinyl chloride and calcium carbide. Energy consumption of China's chemical industry increased with the growth of chemicals output from 4.1 EJ in 2000 to 14.4 EJ in 2015, accounting for 11% of China's total energy demand. The final energy consumption mix of China's chemical industry shows that electricity has increasingly become the dominant energy source, amounting to 30% in 2015. The growing energy consumption of the chemical industry has resulted in enormous emissions of air pollutants and GHGs. Energy-related CO_2 emissions of China's chemical industry account for 3.7% of global total in 2015, with 1220 Mt CO_2, which nearly doubled since 2005. As a key emitter of air pollutants, China's chemical industry emitted 2254 kt of SO_2, 1512 kt of NO_x and 808 kt of PM in 2015, contributing 12%, 8%, and 5% to the national emissions, respectively (Yue *et al.*, 2018).

Cement

In 2014, the cement industry consumed 10.6 EJ of energy (7% of industrial energy use). Due to the high level of process emissions, cement production comprises the second largest industrial emitter, following the iron and steel industry, accounting for 27% (2.2 $GtCO_2$ in 2014) of industrial emissions and 6% of global CO_2 emissions (IEA, 2017).

Main processes in cement manufacturing are raw material preparation, clinker production (limestone calcination) and cement grinding; with clinker production being the most energy intensive step (Worrell and Galitsky, 2008). Clinker is produced by burning a mixture of mainly limestone, silicon oxides, aluminum oxides and iron oxides in a kiln. Based on the moisture content of raw materials, clinker production can take place in a wet, dry, semi-dry or semi-wet kiln. The dry process has lower energy requirements due to lower evaporation needs.

The adoption of more energy efficient technologies and the decrease of the clinker content in cement can significantly reduce the energy use in cement manufacturing.

The thermal energy use for clinker production in the different world regions ranges between 3.1 and 5.0 GJ/tonne clinker (see **Fig. 4**). It differs mainly due to the kiln technology type used and the level of energy efficiency (Kermeli *et al.*, 2019). The lowest energy consumption is observed in India where cement capacity increased significantly in recent years. The highest is in CIS which still relies heavily on the wet process. Dry kilns equipped with a precalciner and several preheater stages (5–6 stages), are currently considered best available technology, and can have under optimal conditions a fuel consumption of about 2.9–3.3 GJ/tonne clinker (EIPPCB, 2010). The theoretical minimum energy requirements are about 1.65–1.8 GJ/tonne (WBCSD/CSI-ECRA, 2009). The difference in energy use between typical kilns and the theoretical energy occurs mainly due to heat losses. The energy use in state-of-the-art dry kilns is not expected to significantly decrease in the future (IEA, 2009a).

In the cement industry, electricity is mainly used for the preparation of raw materials, fuels and additives, and for cement grinding. Current state-of-the-art techniques use roller presses and vertical roller mills for grinding. The energy requirements mainly depend on raw material hardness, moisture content and the type and amount of additives used. **Fig. 5** shows the electricity use for cement making in different world regions. In 2012, electricity use ranged between 81 and 126 kWh/tonne cement. The lowest electricity use is observed in India and the highest in the North America and CIS. The implementation of best practice technology can decrease electricity use to about 70 kWh/tonne cement.

Table 2 shows main energy efficiency measures for clinker making for dry process cement plants, including fuel savings, electricity savings and payback period.

Additional energy savings can be obtained by reducing the clinker content in cement. Portland cement has a clinker to cement ratio of 95%–100% (the remaining part is gypsum). Substituting a part of clinker with other materials with similar properties (hydraulic and/or pozzolanic) reduces the clinker content in cement lowering the demand for clinker. Reducing clinker production by 1 tonne will roughly reduce CO_2 emissions by the same amount. Cements that contain clinker substituting materials in considerable quantities are known as blended cements. These materials are either interground with clinker in the final step of cement making or are ground and dried separately before being mixed with clinker. Clinker can be substituted by industrial by-products such as coal fly ash, blast furnace slag or pozzolanic materials (e.g., volcanic material). The relative importance of additive use can be expressed by the clinker to cement ratio. **Fig. 6** shows the clinker content in cement for different world region. The average clinker to cement ratio is estimated at 70% (Kermeli *et al.*, 2014).

Iron and Steel

Steel is a widely used material in modern society, which has been linked to the development of steel end use sectors, e.g., building and infrastructure, manufacturing, and transport systems. The iron and steel industry is one of the world's

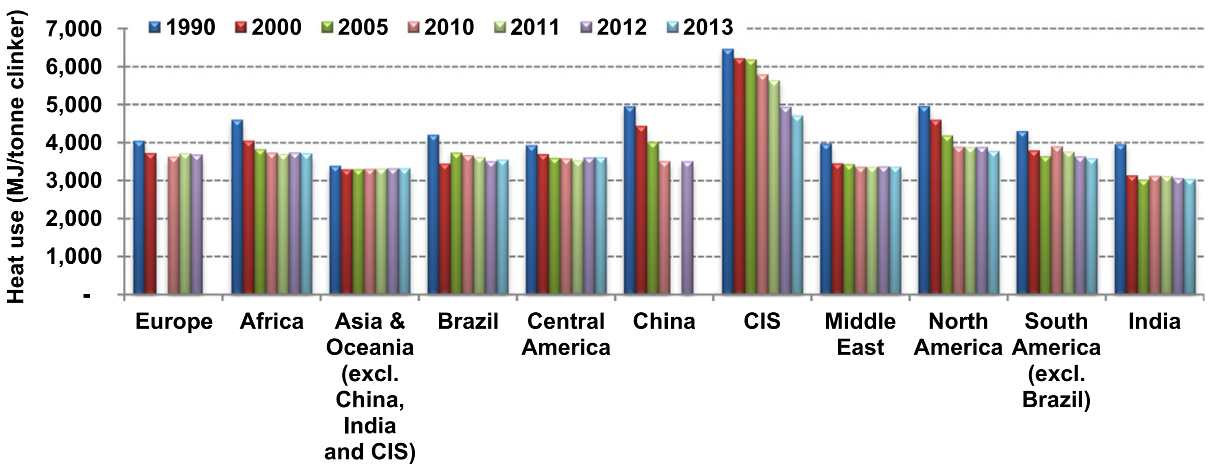

Fig. 4 Heat consumption for clinker making per world region (excluding heat loss for drying). Reproduced from Kermeli, K., Edelenbosch, O.Y., Crijns-Graus, W., *et al.*, 2019. The Scope for Better Industry Representation in Long-Term Energy Models: Modeling the Cement Industry.

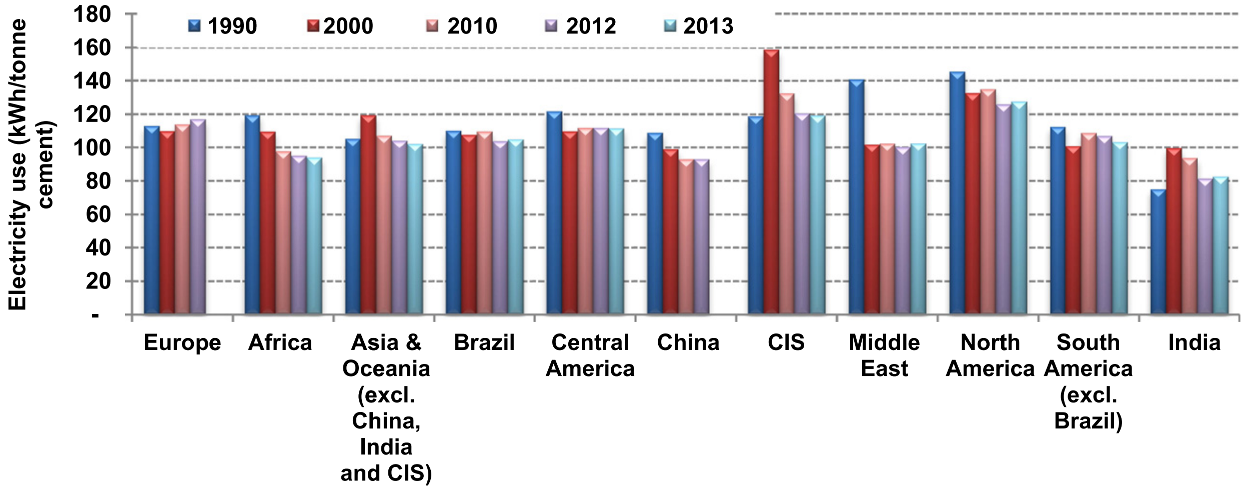

Fig. 5 Average electricity consumption for cement making per world region. Reproduced from Kermeli, K., Edelenbosch, O.Y., Crijns-Graus, W., *et al*., 2019. The Scope for Better Industry Representation in Long-Term Energy Models: Modeling the Cement Industry.

Table 2 Energy efficiency measures for clinker making – dry process plants

Energy efficiency measure	*Specific fuel savings (GJ/tonne clinker)*[a]	*Specific electricity savings (kWh/tonne clinker)*[a]	*Estimated payback period (years)*[b]
Energy management and control systems	0.1–0.2	0–4.9	<2
Kiln combustion system improvements	0.1–0.4	–	1.0–5.0
Mineralized clinker	0.0–0.2	0 to −1.0	N/A
Indirect firing	0.2	0 to −0.6	>10
Oxygen enrichment	0.0–0.2	(−)9 to (−)32	N/A
Mixing air technology (PH kilns)	0.20	(−) 0.03	2
Seal replacement	0.02	–	<1
Kiln shell heat loss reduction	0.1–0.6	–	<1
Preheater shell heat loss reduction	0.02	–	6
Refractories	0.06	–	4
Conversion to grate cooler	0.3	(−)3.00 to (−)6.00	>18
Optimize grate cooler	0.05–0.16	0.0 to (−)2.0	2.00–7.00
Low-pressure drop Suspension preheaters	–	0.6–4.4	>10
Heat recovery for power generation	–	20.0	2.00–14.00
Conversion of long dry to preheater	0.7–1.6	–	10
Increase preheater stages (from 5 to 6)	0.1	–	>7
Addition of precalciner or upgrade	0.2–0.7	–	>10
Conversion of long dry kiln to preheater precalciner	0.84–1.11	–	>10

[a]Negative values for electricity saving indicate that although the application of this measure saves fuel, it will increase electricity consumption. However, the total primary energy savings of these measures is positive.

[b]The estimated energy and expenditure savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g., clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant.

Note: Worrell, E., Kermeli, K., Galitsky, C., 2013. Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making. United States Environmental Protection Agency (U.S. EPA).

largest energy consumer and therefore a major contributor to global anthropogenic CO_2 emissions, accounting for 9% of global energy use and 4%–7% global anthropogenic CO_2 emissions (Pauliuk *et al.*, 2013). In the period 1960–2018, the historical steel production has risen fivefold. In 2018, China is the largest steel producer, accounting for 51.3% of the global total, followed by the European Union, India, USA, and Japan (World Steel Association, 2019). Many studies indicate that global steel demand is expected to more than double by 2050, depending on the industrialization in developing regions (Ruijven *et al.*, 2016).

Manufacturing steel can be divided into the following processes; raw material preparation (including coke making, iron ore extraction and sinter/pellets making), iron making, steel making, casting, rolling, forming and coating, and fabrication. Currently, two manufacturing routes have been widely used in crude steel production. The integrated route is based on iron ore and

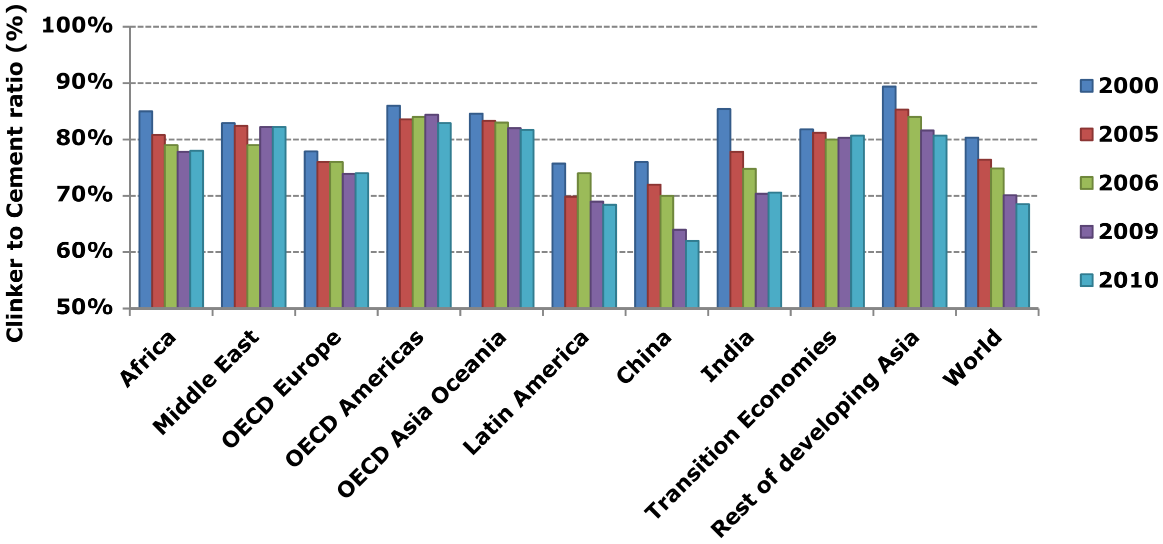

Fig. 6 Clinker content in cement in the different world regions. Reproduced from Kermeli, K., Edelenbosch, O.Y., Crijns-Graus, W., *et al.*, 2019. The Scope for Better Industry Representation in Long-Term Energy Models: Modeling the Cement Industry.

limestone and consists of coke ovens, sinter/pellets plants, blast furnaces (BF) and Basic Oxygen Furnaces (BOF) or an open-hearth furnace (OHF), while the recycling route uses scrap as main material in electric arc furnaces. For integrated steel-making, around 70% of energy is consumed in the blast furnaces, followed by sintering and coke making (Zhang *et al.*, 2014). For the recycling route, scrap is mainly coming from casting, forming and other fabrication processes in steel making and after use (Cullen *et al.*, 2012). The energy consumed in the recycling route is about 20% of the energy used for integrated steel making from iron ore, because using scrap offsets the demand for energy and natural resources in the iron making process (Kermeli *et al.*, 2014). In 2016, 74% of global crude steel production was produced by the integrated route while 25.5% came from electric arc furnaces. There are two relatively new manufacturing routes, namely direct-reduced iron (DRI) and smelting reduction, which currently together account for less than 1% of global steel production. The key advantage of these routes is that 20%–25% of CO_2 can be avoided, compared to the integrated route (Pardo *et al.*, 2012).

Specific energy consumption and the associated CO_2 emissions per ton of steel production differ widely across countries, due to the difference of production route applied, plant size, level of waste heat recovery, quality of iron ore, and operation efficiency of the plants (IEA, 2012b; Worrell and Carreon, 2017). Since 1960, the energy intensity in the global iron and steel industry improved significantly and decreased by 60%. There are still large opportunities to improve energy efficiency though. Overall, the implementation of best available technology (BAT) could save 9%–18% of energy use (Worrell and Carreon, 2017). **Table 3** lists the current best available technologies for energy-efficiency improvement in the iron and steel industry. The energy savings potential varies per country. Take China as an example, cogeneration by heat recovery, coke dry quenching (CDQ) and coal moisture control (CMC), injection of pulverized coal in BF are the most important measures to save energy and together can reduce energy use by 50% in the integrated steel making route. For the recycling route, scrap preheating and process control could contribute to one third of energy saving (Zhang *et al.*, 2014). Milford *et al.* (2013) estimate that energy efficiency alone is not enough to limit CO_2 emissions in the iron and steel sector, which would only decrease up to 20% of emissions by 2050, compared to a business-as-usual scenario. Therefore, material efficiency improvement is another key opportunity to reduce energy use and consequently lower CO_2 emissions. Strategies to improve material efficiency include reducing demand for the service, optimizing the weight of products, reducing yield losses, increasing product lifespans and recycling of end-of-life scrap (Allwood *et al.*, 2013). With the growing concern for climate change and ambitions to lower global temperature increase to well below 2°C, deeper decarbonization of the steel industry is needed, e.g., by using Hydrogen (H_2) or electricity to replace coke in the blast furnaces or the adoption of carbon capture and storage (CCS) and carbon capture and usage (CCU).

Aluminum

The primary aluminum industry is one of the top electricity consuming industries and is responsible for about 8% of global electricity consumption in industries (Kermeli *et al.*, 2014). The production of primary aluminum is a multi-stage process. Initially, bauxite ore is resolved/digested and refined into alumina in the Bayer process. Alumina is then transformed into aluminum in an electrolytic cell with the Hall-Héroult process. Molten aluminum is cast into ingots which are transferred and further processed in aluminum foundries. The most energy intensive processes in primary aluminum production are alumina refining and aluminum smelting, responsible for 27% and 70% of energy use, respectively. Anode production is responsible for about 2%, while aluminum casting for about 1.4% of the energy use (IAI, 2013a).

Table 3 Main energy efficiency measures

Process	*Measures*	*Fuel saving (GJ/ton)*	*Electricity saving (GJ/ton)*[a]	*Capital cost (2005 $/ton)*
Sintering	Small pellet sintering technology	0.26	0.00	2.06
	Low temperature sintering	0.26	0.00	2.95
	Improved charging method	0.10	0.00	1.07
	Increasing bed depth	0.10	0.00	0.00
	Heat recovery from sinter cooler	0.40	0.00	2.93
	Use of waste fuel in sinter plant	0.16	0.00	0.21
Coke making	Pressure Shift-Absorhing Technique in H_2 unit	0.05	0.00	0.00
	Programmed heating in coke oven	0.16	0.00	0.21
	Variable speed drive on coke oven gas compressors	0.01	0.00	0.32
	Coal moisture control	0.33	0.00	5.97
	Coke dry quenching (CDQ)	0.81	0.00	12.58
Iron making	Moisture Removing Blowing Technique in BF	0.23	0.00	1.86
	Dry Bag Dedusting System of Blast Furnace Gas	0.01	0.00	0.11
	Injection of pulverized coal in BF	0.64	0.00	4.99
	Injection of natural gas in BF	0.32	0.00	4.81
	Injection of oil in BF	0.48	0.00	9.10
	Injection of plastic waste in BF	0.16	0.00	4.99
	Injection of coke oven gas in BF	0.32	0.05	4.81
	Top-pressure recovery turbines (TRT)	0.21	0.00	2.40
	Cogeneration with untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas	0.23	0.00	2.61
	Recovery of blast furnace gas	0.09	0.00	1.16
	Improved hot blast stove control	0.32	0.00	0.32
	Improved blast furnace control	0.32	0.00	0.53
Steel Making_BOF	Integrated casting and rolling (Strip casting)	0.73	0.00	6.34
	Recovery of BOF and sensible heat	0.56	0.00	23.51
	Variable speed drive on ventilation fans	0.00	0.00	0.21
	Efficient Ladle preheating	0.02	0.00	0.06
	vacuum degassing from liquid iron	0.10	0.00	0.37
Steel Making_EAF	wet and heat recovery of slag	0.09	0.00	0.55
	Scrap preheating	0.36	0.00	4.26
	Adjustable speed drives (ASDs) on flue gas fans	0.00	0.05	2.14
	Oxy-fuel burners/lancing	0.00	0.05	1.38
	Improving process control in EAF	0.24	0.09	1.28
	Direct current (DC) arc furnace	0.00	0.03	0.40
	Bottom stirring/gas injection	0.00	0.01	0.07
Casting, rooling and finishing	Flameless oxyfuel burners	0.64	−0.02	2.67
	Insulation of reheat furnaces	0.16	0.00	8.00
	Hot charging	0.48	0.00	16.03
	Process control in hot rolling	0.30	0.00	0.75
	Waste heat recovery from cooling water	0.03	0.00	0.85
	Continuous annealing	0.16	−0.02	287.67
	Reduced steam use in the acid pickling line	0.24	0.01	2.88
	Preventative maintenance in integrated steel mills	0.32	0.02	0.01
	Heat recovery on the annealing line	0.24	0.01	2.88
	Recuperative or regenerative burner	0.56	0.00	2.66
	Low temperature rolling technology	0.13	0.00	1.08
	Endless Hot Rolling of Steel Sheets	0.36	0.00	6.73
	Multislit Rolling Technique on the Bar Rolling	0.15	0.00	1.22
	Energy monitoring and management systems	0.08	0.01	0.16

[a]Negative values for electricity saving indicates that although the application of this measure saves fuel, it will increase electricity consumption. However, the total primary energy savings of these measures is positive.

Note: Based on Hasanbeigi, A., Morrow, W., Sathaye, J., Masanet, E., Xu, T., 2013a. A bottom-up model to estimate the energy efficiency improvement and CO_2 emission reduction potentials in the Chinese iron and steel industry. Energy 50, 315–325. doi:10.1016/j.energy.2012.10.062. Hasanbeigi, A., Price, L., Arens, M., 2013b. Emerging Energy-Efficiency and Carbon Dioxide Emissions-Reduction Technologies for the Iron and Steel Industry. Lawrence Berkeley National Laboratory (Available at: http://china.lbl.gov/sites/all/files/6106e-steel-tech.pdf). Worrell, E., Blinde, P., Neelis, M., Blomen, E., Masanet, E., 2010. Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry. Lawrence Berkeley National Laboratory. IIP, 2013. The Institute for Industrial Productivity: Iron and Steel, Technology and Resources. Available at: http://www.ietd.iipnetwork.org/content/iron-and-steel. Mao, X., Zeng, A., Liu, S., Hu, T., Youkai, S., 2012. Assessment of SO_2, NO_x, and CO_2 co-control effects by technological reduction measures in iron & steel industry. Acta Scientiae Circumstantiae 32, 1253–1260. Xu, T.T., 2011. Development of Bottom-Up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Iron and Steel Sector. Lawrence Berkeley National Laboratory. Available at: http://escholarship.org/uc/item/8n82s7j3. Dai, Y., Xiong, H., 2013. Roadmap Study on Achieving Technical Energy Conservation Potential in China's Industrial Sector by 2020. China Science and Technology Press.

The typical energy use for alumina refining with the Bayer process is 12 GJ/tonne (Henrickson, 2010). China and Russia due to their poor quality bauxite reserves have used alternative processes to produce alumina; the Combined Bayer-Sinter and the Sinter processes with typical energy consumptions of 26 and 38 GJ/tonne alumina, respectively (Li *et al.*, 2008; Smith, 2008). Other processes that have been only recently widely used in China are the Floatation-Bayer and the Lime-Bayer processes (Gu and Wu, 2012). If China and Russia would use good quality bauxite and adopt the more energy efficient Bayer process, the energy consumption would significantly decrease. In 2009, the world average energy use for alumina refining, excluding China, is estimated at 12.5 GJ/tonne alumina. Energy efficient alumina refineries (Bayer process) can have an energy use of 8–11 GJ/tonne (Wischnewski *et al.*, 2011; Worrell *et al.* 2008; Henrickson, 2010) while the theoretical minimum energy requirement is 0.24 GJ/tonne (BCS, 2007).

As mentioned, the production of primary aluminum from alumina (aluminum smelting) is the most energy intensive step in primary aluminum production. Aluminum is produced by passing a direct current through a bath with alumina dissolved in a molten cryolite electrode. The electricity intensity in the various world regions ranged between 13.5 and 15.6 MWh/tonne aluminum in 2014 (IEA, 2017). The theoretical minimum energy requirement for electrolysis is 6.0 MWh/tonne (IEA, 2009a) while best practice is 13.5 MWh per tonne (IEA, 2017).

The primary aluminum industry is a large energy consumer and also a major greenhouse gas (GHG) emitter, as next to the emitted greenhouse gas emissions during fuel combustion and electricity generation, perfluorocarbons (PFCs) are emitted. PFCs are gases with a high global warming potential (GWP), ranging from 6500 times for tetrafluoromathenane (C_2F_4) and 9200 times for hexafluoromethane (C_2F_6) the GWP of carbon dioxide (CO_2) (IPCC, 2006). In 2007, the primary aluminum industry emitted a total of about 400 Mt CO_2-equivalent of GHGs (including indirect CO_2 emissions from electricity consumption and process emissions from aluminum smelting); equivalent to about 1% of global greenhouse gas emissions (IEA, 2009b). In the same year, IAI estimates global PFC emissions from aluminum smelting at about 29 Mt CO_2-eq (IAI, 2013b).

Tables 4 and **5** show main measures for energy efficiency improvement for alumina refining and smelting, respectively. Besides these measures cogeneration of heat and power can be implemented in alumina refineries which could lead to 15% energy savings (Moya Rivera *et al.*, 2015). Furthermore waste energy from smelter off gases could be recovered (3–5 GJ/tonne aluminum accessible heat) (Moya Rivera *et al.*, 2015). The adoption of this technology depends on the proximity of heat demand in the surroundings of the smelter. Few currently available technologies can reduce the energy use in aluminum smelters. Innovative technologies such as wetted cathodes and inert anodes, although promising, are still being developed.

Aluminum can also be produced from scrap, in the secondary production route. Only 5% of the energy needed to produce primary aluminum is required to produce aluminum from scrap (IEA, 2012a). Around 30.5 Mtonnes of aluminum scrap was used in 2017 globally, which contributed to around 32% of aluminum production (World Aluminum, 2019). Out of the total scrap, 12.5 Mtonne consists of new scrap (e.g., from casting) and 18 Mtonne is from end-of life scrap. Total end-of-life scrap is estimate to be 25 Mtonne, implying that absolute scrap use can be increased up to 23% by higher recycling rates, thereby increasing the share of scrap used up to 39%. Aluminum products can be recycled repeatedly; cans, aluminum foil, and automotive components can be melted down to make

Table 4 Energy efficiency improvements for alumina refining

Measures	*Electricity savings (kWh/tonne alumina)*	*Fuel savings (GJ/tonne alumina)*	*Investment costs ($/tonne alumina)*
Sweetening	N/A	0.9	8
Tube digestion + indirect heating	–	4.4	36–97
High rate thickeners – HT Plants	N/A	0.2	6
High rate thickeners – LT Plants	N/A	0.15	6
Seed filtration – HT Plants	N/A	0.9	14
Seed filtration – LT Plants	N/A	0.7	14
Inter-stage cooling – HT Plants	N/A	0.4	5
Inter-stage cooling – LT Plants	N/A	0.35	5
Direct cooling – HT Plants	N/A	0.3	4
Direct cooling – LT Plants	N/A	0.2	4
Kiln retrofit	–	1.4	43
Optimized cyclone operation	3	0.2	0.1
“Hydrate-by-pass” system	–	0.1	3.3
Improved waste heat recovery	–	0.1	6.5
Advanced process control	14	0.6	3.0
Combined Bayer-Sinter→ Bayer-flotation	N/A	10.4	160
Sinter→ Bayer-flotation	N/A	22.0	230
Combined Bayer-Sinter→ Bayer	N/A	16.0	100
Sinter→ Bayer	N/A	27.0	170
Bayer-flotation, Lime-Bayer→ Bayer	N/A	5.0	20

Note: Kermeli, K., Ter Weer, P.H., Crijns-Graus, W., Worrell, E., 2015. Energy efficiency improvement and GHG abatement in the global production of primary aluminium. Energy Efficiency 8 (4), 629–666.

Table 5 Energy efficiency improvements for aluminum smelting, anode production and ingot casting

Measures	*Electricity savings (MWh/tonne aluminum)*	*Fuel savings (GJ/tonne aluminum)*	*Investment cost ($/tonne aluminum)*
VSS → Point fed pre baked	2.8	–	2600
HSS → Point fed pre baked	2.8	–	2600
SWPB → Point fed pre baked	0.8	–	620
CWPB → Point fed pre baked	1.7	–	260
Optimize cell operation	2.0	–	240–410
Optimum combustion air flow	–	0.2–0.8	2.2–3.0
Efficient operation of burners	–	0.2–0.3	1.6–2.0
Furnace pressure control	–	0.2–0.3	1.4–1.8
Furnace insulation	–	0.1–0.2	0.4–0.6
Waste heat recovery	–	0.3–1.0	8–12
Sensor and control systems	–	0.2–0.3	0.2–1.0
Optimized motor system operation	0.1	–	7

Note: Kermeli, K., Ter Weer, P.H., Crijns-Graus, W., Worrell, E., 2015. Energy efficiency improvement and GHG abatement in the global production of primary aluminium. Energy Efficiency 8 (4), 629–666.

again similar products. The share of secondary aluminum production cannot be increased infinitely, as product quality is affected by the use of scrap as a feedstock. Certain high quality products will still require the use of new aluminum.

Conclusions

The industrial sector is a major energy consumer, responsible for 36% of the global final energy consumption and about 35% of global greenhouse gas emissions. Main energy consuming sectors are chemicals, iron and steel and cement.

The implementation of best available technologies can lead to reduced energy use and greenhouse gas emissions. Energy savings depend on the current level of efficiency, sector and production characteristics, but are typically in the range of 20%–40%.

In the coming twenty years industrial energy use is expected to increase by about 40%. This means that in light of 2° scenarios, besides energy-efficiency measures, other measures are needed to reduce greenhouse gas emissions. Crucial in this regard is material efficiency in a broad sense, including limiting material use by product design, re-use of materials, recycling of materials and substitution of materials. For longer term and further greenhouse gas emission reduction, measures such as carbon capture and storage are needed or fossil fuel substitution by hydrogen or electricity (produced from renewable energy) and biomass.

References

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2013. Material efficiency: Providing material services with less material production. Philosophical Transactions of the Royal Society A 371, 20120496. doi:10.1098/rsta.2012.0496.

BCS, 2007. U.S. Energy Requirements for Aluminium Production, Historical Perspective, Theoretical Limits and Current Practices. Report Prepared for the U.S. DOE Industrial Technologies Program.

Boulamanti, A., Moya Rivera, J., 2017. Energy Efficiency and GHG Emissions: Prospective Scenarios for the Chemical and Petrochemical Industry. Publications Office of the European Union. doi:10.2760/20486.

ClimateWatch, 2019. Historical GHG Emissions. Available at: https://www.climatewatchdata.org/.

Cullen, J.M., Allwood, J.M., Bambach, M.D., 2012. Mapping the global flow of steel: From steelmaking to end-use goods. Environmental Science & Technology 46, 13048–13055. doi:10.1021/es302433p.

EIPPCB, 2010. Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries. Brussels: The European IPCC Bureau.

Graus, W., Blomen, E., Worrell, E., 2011. Global energy efficiency improvement in the long term: A demand- and supply-side perspective. Energy Efficiency 4, 435–463.

Gu, S., Wu, J., 2012. Review on the energy saving technologies applied in bayer process in China. In: Proceedings of the 9th International Alumina Quality Workshop 2012.

Henrickson, L., 2010. The need for energy efficiency in bayer refining. Light Metals 2010, 173–178.

IEA, 2008. Energy Technology Perspectives 2008 - Scenarios and Strategies to 2050, Paris: International Energy Agency (IEA).

IEA, 2009a. Energy Technology Transitions for Industry – Strategies to the Next Industrial Revolution, 2009, Paris: International Energy Agency (IEA).

IEA, 2009b. Chemical and Petrochemical Sector: Potential of Best Practice Technology and other Measures for Improving Energy Efficiency, Paris: International Energy Agency (IEA).

IEA, 2012a. Energy Technology Perspectives 2012 – Pathways to a Clean Energy System. Paris: International Energy Agency (IEA).

IEA, 2013. Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes. Paris: International Energy Agency (IEA).

IEA, 2017. Energy Technology Perspectives 2017: Catalysing Energy Technology Transformation. Paris: International Energy Agency (IEA).

IEA, 2018a. World Energy Balances Database, 2018 ed. Paris: International Energy Agency (IEA).

IEA, 2018b. World Energy Outlook, 2018 ed. Paris: International Energy Agency (IEA).

IEA, 2018c. Extended World Energy Balances Database, 2018 ed. Paris: International Energy Agency (IEA).

IEA, 2012b. CO_2 Abatement in the Iron and Steel Industry. ISBN No. 978-92-9029-513-6.

International Aluminium Institute (IAI), 2013a. Global Life Cycle Inventory Data for the Primary Aluminium Industry – 2010 Data. London, United Kingdom.

International Aluminium Institute (IAI), 2013b. Results of the 2012 Anode Effect Survey. London, United Kingdom.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. International Panel on Climate Change. Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., *et al.*, 2017. Global Atlas of the Three Major Greenhouse Gas Emissions for the Period 1970–2012, Earth System Science Data, essd-2017-79, submitted, 2017. Available at: http://edgar.jrc.ec.europa.eu/overview.php?v=432_GHG&SECURE=123.

Kermeli, K., Graus, W.H.J., Worrell, E., 2014. Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector. Energy Efficiency 7 (6), 987–1011.

Kermeli, K., Ter Weer, P.H., Crijns-Graus, W., Worrell, E., 2015. Energy efficiency improvement and GHG abatement in the global production of primary aluminium. Energy Efficiency 8 (4), 629–666.

Kermeli, K., Worrell, E., Crijns-Graus, W., Corsten, M., 2017. Energy Efficiency and Cost Saving Opportunities for Ammonia and Nitrogenous Fertilizer Production. Utrecht: U.S. Environmental Protection Agency and Utrecht University.

Kermeli, K., Edelenbosch, O.Y., Crijns-Graus, W., *et al.*, 2019. The Scope for Better Industry Representation in Long-Term Energy Models: Modeling the Cement Industry.

Li, W., Liu, J., Liu, Z., Wang, Y., 2008. The most important sustainable development issues of chinese alumina industry. Light Metals 2008, 191–195.

Milford, R.L., Pauliuk, S., Allwood, J.M., Müller, D.B., 2013. The roles of energy and material efficiency in meeting steel industry CO_2 targets. Environmental Science & Technology 47, 3455–3462. doi:10.1021/es3031424.

Moya Rivera, J.A., Boulamati, A., Slingerland, S., *et al.*, 2015. Energy Efficnecy and GHG Emissions: Prospective Scenarious for the Aluminium Industry. Luxembourg: Publications Office of the European Union, doi:10.2790/9500.

Pardo, N., Moya, J.A., Vatopoulos, K., 2012. Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron & Steel Industry. Joint Research Centre of the European Commission. (No. JRC74811).

Pauliuk, S., Wang, T., Müller, D.B., 2013. Steel all over the world: Estimating in-use stocks of iron for 200 countries. Resources, Conservation and Recycling 71, 22–30. doi:10.1016/j.resconrec.2012.11.008.

Ryan, L., Campbell, N., 2012. Spreading the Net: The Multiple Benefits of Energy Efficiency Improvements. IEA Energy Paper. Paris: International Energy Agency.

Saygin, D., Patel, M.K., Worrell, E., Tam, C., Gielen, D.J., 2011. Potential of best practice technology to improve energy efficiency in the global chemical and petrochemical sector. Energy 36 (2011), 5779–5790.

Smith, P., 2008. Economic Processing of High Silica Bauxites – Existing and Potential Processes.

van Ruijven, B.J., van Vuuren, D.P., Boskaljon, W., *et al.*, 2016. Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries. Resources, Conservation and Recycling 112, 15–36. doi:10.1016/j.resconrec.2016.04.016.

WBCSD/CSI-ECRA, 2009. Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead. Dusseldorf: World Business Council for Sustainable Development (WBCSD)/Geneva: Cement Sustainability Initiative-European Cement Research Academy (CSI-ECRA).

Wischnewski, R., de Azevedo Jr., C.M., Moraes, E.L.S., Monteiro, A.B., 2011. Alunorte Global Energy Efficiency. In: Lindsay, S.J. (Ed.), Light Metals 2011. Cham: Springer, pp. 179–184.

World Aluminium, 2019. Available at: http://www.world-aluminium.org/statistics/massflow/ (accessed 12.03.19).

World Steel Association, 2019. Global Crude Steel Output Increases by 4.6% in 2018. Available at: https://www.worldsteel.org/media-centre/press-releases/2019/Global-crude-steel-output-increases-by-4.6–in-2018.html (accessed 03.08.19).

Worrell, E., Galitsky, C., 2008. Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making. Berkeley: Lawrence Berkeley National Laboratory (LBNL).

Worrell, E., Carreon, J.R., 2017. Energy demand for materials in an international context. Philosophical Transactions of the Royal Society A 375, 20160377. doi:10.1098/rsta.2016.0377.

Worrell, E., Price, L., Neelis, M., Galitsky, C., Nan, Z., 2008. World Best Practice Energy Intensity Values for Selected Industrial Sectors. Berkeley: Lawrence Berkeley National Laboratory (LBNL).

Yue, H., Worrell, E., Crijns-Graus, W., 2018. Modeling the multiple benefits of electricity savings for emissions reduction on power grid level: A case study of China's chemical industry. Applied Energy 230, 1603–1632. doi:10.1016/j.apenergy.2018.09.078.

Zhang, S., Worrell, E., Crijns-Graus, W., Wagner, F., Cofala, J., 2014. Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry. Energy 78, 333–345. doi:10.1016/j.energy.2014.10.018.