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Energy demand for materials in an international context

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Materials are everywhere and have determined society. The rapid increase in consumption of materials has led to an increase in the use of energy and release of greenhouse gas (GHG) emissions. Reducing emissions in material-producing industries is a key challenge. If all of industry switched to current best practices, the energy-efficiency improvement potential would be between 20% and 35% for most sectors. While these are considerable potentials, especially for sectors that have historically paid a lot of attention to energy-efficiency improvement, realization of these potentials under current 'business as usual' conditions is slow due to a large variety of barriers and limited efforts by industry and governments around the world. Importantly, the potentials are not sufficient to achieve the deep reductions in carbon emissions that will be necessary to stay within the climate boundaries as agreed in the 2015 Paris Conference of Parties. Other opportunities need to be included in the menu of options to mitigate GHG emissions. It is essential to develop integrated policies combining energy efficiency, renewable energy *and* material efficiency and material demand reduction, offering the most economically attractive way to realize deep reductions in carbon emissions.

This article is part of the themed issue 'Material demand reduction'.

1. Introduction

Materials form the fabric of our present society; materials are everywhere in our lives. Life as we know it would be impossible without them. In fact, terms such as the 'Bronze Age' and 'Iron Age' demonstrate that materials have defined our society. Today's industrialized society has become entirely dependent on materials, as it produces more of them and

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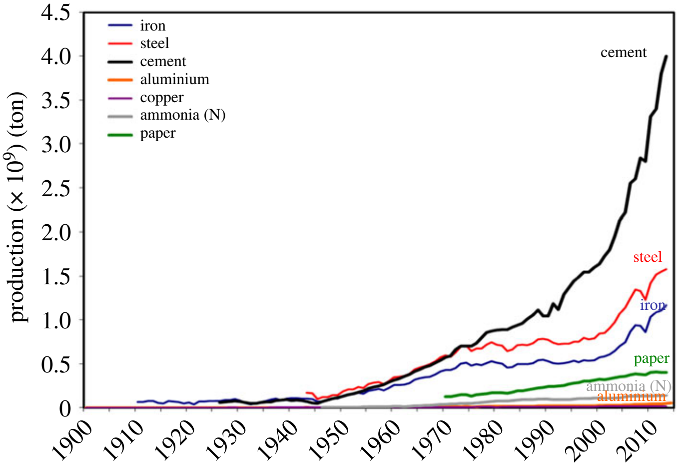

Figure 1. Global material production trends (1900–2014). Derived from US Geological Survey, UN, FAO, World Aluminium Association.

accumulates an incredible volume of materials to build an increasingly complex society. Materials will also play a key role in the transition of our society towards future sustainability, as novel (energy) technologies need (new) materials. The challenge of sustainability for the material system is rooted in the way that we now process resources to make materials and products, and in the current industrialized route towards economic development. Our growing and increasingly affluent global population, with high demands for materials and resources, is driving an exponential growth in material production and it is increasingly clear that this form of economic success story is now running into physical limits [1,2]. Figure 1 depicts the production over time of the most important materials from a volume and energy use perspective (i.e. those materials that are responsible for the largest fraction of global industrial energy use).

Mankind now dominates the global flows of many elements of the periodic table found on our planet [3]. The Earth's resources are not infinite, but, until recently, they have seemed to be. Increasingly, we realize that our society may be approaching certain limits, with respect to not only resource availability but also the wider economic system. Our society has operated as an open system on a finite planet, transforming resources to products that are eventually discarded to the environment. This, coupled with the massive increase in the use of materials, has led to growing impacts on the environment. This is especially true in relation to climate change and the use of fossil fuels. Large amounts of energy, producing greenhouse gas (GHG) emissions, are directly tied to the production and use of materials, while affecting land-use change (and related GHG emissions). In 2013, industry emitted (directly and indirectly) about 37% of global CO_2 emissions, equivalent to 10.1 $GtCO_2$ [4,5], of which an estimated 67% is from materials production (figure 2).

This development path is environmentally unsustainable. At the Paris Conference of Parties (2015) all countries pledged to limit global temperature rise to below 2°C. This implies that we have to achieve a net-zero GHG emission world by 2050. This poses an enormous challenge for the energy and materials system, as it has to transition from a fossil-fuel-dominated system to a net-zero system in 35 years. This is technically feasible for buildings, the power sector, as well as (light) transport and parts of industry. The key technical challenges will be in heavy-duty transport (including aerospace), and in the energy-intensive material-producing industries. Emissions in material-producing sectors can be reduced by improved energy efficiency, switching to low or zero carbon energy sources, carbon capture and storage (CCS), and the more efficient use of materials. Achieving the necessary deep reductions in industrial emissions will require all of the above options [2].

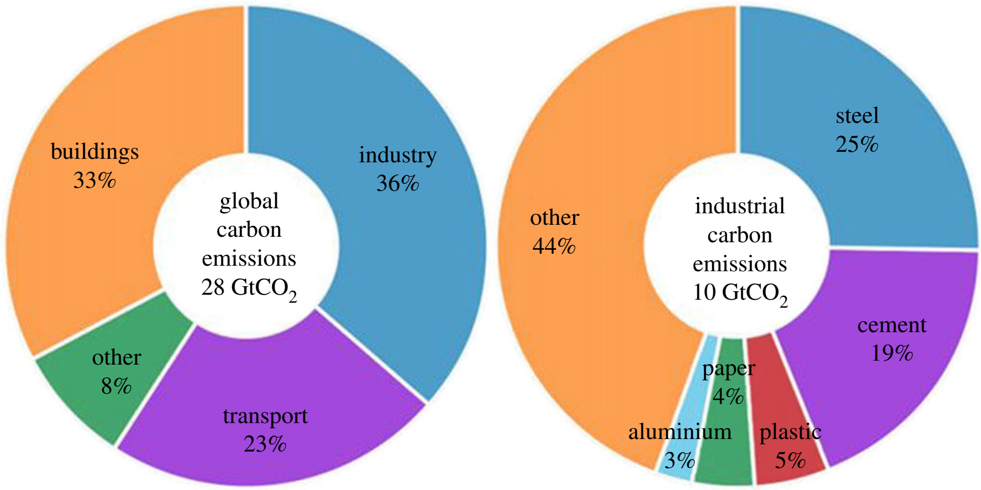

Figure 2. Distribution of CO_2 emissions among materials (2005). Source: [1]. (Online version in colour.)

In this paper, we review the energy use in a number of the key material-producing industries (i.e. iron and steel, cement, chemicals and aluminium), based on various recent studies. These industries are not only responsible for a large share of global industrial energy use, but available data allow for reliable benchmarking of energy intensity and efficiency. Differences are found in the energy intensity of these industries, which can help to determine the potentials for improvement in energy efficiency with easily available practices and technologies, when disseminated around the world. New technologies do exist or are under development that would allow for further reductions, but are not the prime subject of this paper. These technologies are explored at the end of the paper, with implications for emission reduction strategies for energy-intensive industries.

2. Comparing apples and oranges: benchmarking industrial energy intensity

Benchmarking is a powerful tool to compare the energy efficiency of industrial plants and facilities, as it allows the differences in energy efficiency between different operations to be assessed, controlling for differences in production structure. In an energy-efficiency benchmark, the energy performance of a single plant or an entire sector can be evaluated against the performance of reference technologies or plant, or several plants can be benchmarked against each other, or against historical performance of a plant, or design performance. Benchmarking is based on the concept that plants are evaluated against comparable installations and is widely used in the refining and chemical industries. Benchmarking may be applied at various levels, comparing the performance of countries and regions (as in this paper), comparing individual plants, or even comparing within processes (e.g. [6]). Plant-by-plant benchmarking is used by firms to optimize the energy efficiency of a plant, and it is also used in policy. For example, in the EU Emissions Trading System, emission allowances are distributed based on a benchmark, while benchmarking has previously been used in voluntary programmes in The Netherlands [7]. Today, benchmarking is used in the US Environmental Protection Agency's Energy Star programme to help participants in the programme to understand their potentials for energy-efficiency improvement, as well as to reward the top performers in the programme. It has shown that benchmarking can assist in improving energy efficiency, and change the distribution of a whole sector towards increased efficiency [8]. In this paper, we use regional (or national) statistical information to provide insights into the distribution of energy efficiency in different parts of the world, based on work by Saygin *et al*. [9]. We focus on the key material-producing sectors: iron and steel, cement, (selected) chemicals and aluminium (figure 2).

In this paper, we use benchmarking to compare the performance of the current efficiency with which a product is made, using energy intensity for an industry or process that produces a single product, or an energy-efficiency index (EEI) for an industry that uses multiple inputs and/or produces multiple outputs. The EEI has been used to provide an overall score for energy use in a plant or sector, accounting for differences in the product mix or the mix of processes used. The index provides a single number that scores the plant relative to the reference technology, which is easy to understand. However, the analysis methodology often allows one to assess the underlying reasons and differences in energy efficiency of the different process steps. The EEI of a plant is based on the products produced at various production steps. The relative difference between the actual specific energy consumption (SEC), which is the energy use per ton of product produced, and that of the reference of the benchmark technology is calculated for each of the key products produced by the plant and then aggregated for the entire enterprise. The aggregated EEI is calculated as follows:

$$\mathrm{EEI} = 100\frac{\sum_{i=1}^{n} P_i \cdot \mathrm{SEC}_i}{\sum_{i=1}^{n} P_i \cdot \mathrm{SEC}_{i,\mathrm{ref}}} = 100\frac{E_{\mathrm{tot}}}{\sum_{i=1}^{n} P_i \cdot \mathrm{SEC}_{i,\mathrm{ref}}}, \tag{2.1}$$

where n is the number of products to be aggregated; SEC_i is the actual specific energy consumption for product i; $\mathrm{SEC}_{i,\mathrm{ref}}$ is the benchmark or reference specific energy consumption for product i; P_i is the production quantity for product i; and E_{tot} is the total actual energy consumption for all products.

Regardless of which benchmark level is chosen, once the EEI is calculated it provides an indication of how the actual SEC of the enterprise compares with the reference SEC. By definition a plant that uses the benchmark technology in an efficient manner will have an EEI of 100. In practice, all plants will have an EEI over 100. The gap between actual energy consumption used to produce the products and the reference level energy consumption (EEI = 100) can be viewed as the energy-efficiency potential of the plant, if this plant changed towards using the benchmark technology. Several sectors regularly use benchmarking studies to compare energy-efficiency developments with those of competitors, e.g. ethylene producers, oil refineries and other parts of the international chemical industries, while other industries are starting to use international benchmark studies for energy (and other operating factors). The resulting difference between actual performance and the benchmark performance can be seen as an indication of the potential to improve energy efficiency.

In this paper, the benchmark or reference is based on best practices found around the world. This is considered a valid and relatively conservative way to estimate the potential, as plants operating at best practices are in commercial use at various places in the world. This is in contrast with best available technology (BAT). Using BAT would include technologies that are technically proven, yet their current use may be limited to a small number of plants. Note that BAT is often used as the benchmark technology in environmental regulatory target setting, e.g. in air and water pollution control technologies.

3. Iron and steel industry

The global iron and steel industry is, after the chemicals industry, the largest energy-using industrial sector in the world. In 2005, it accounted for 20% of world industrial energy use and 29% of energy and process CO_2 emissions, including coke ovens and ore preparation, emitting around 2.6 $GtCO_2$ in direct and indirect emissions (2006). The four largest producers (China, the European Union, Japan and the USA) accounted for almost 70% of the CO_2 emissions.

The minimum energy consumption for making steel can be determined by thermodynamics. For the reduction of iron ore the thermodynamic minimum is 6.6 GJ t^{-1} of pig iron [10]. However, the net energy use of a modern blast furnace is in the range of 12.5–15 GJ t^{-1} of pig iron, which is about twice the theoretically lowest SEC. Recycling, using the electric arc furnace (EAF) route, uses less energy than producing steel from iron ore, as it is not necessary to reduce the iron oxides. The minimum energy use for making a steel product from scrap is negligible, as, for example, a

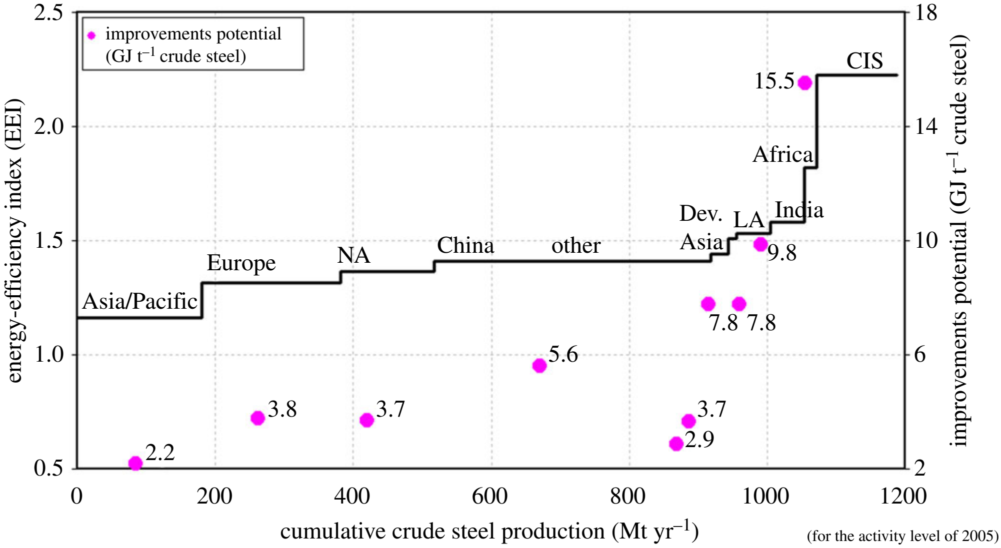

Figure 3. Estimated benchmark curve for the iron and steel industry, 2005. The benchmark curve refers to the *y*-axis on the left-hand side; the dots which represent the improvement potentials in the various regions relative to best-practice energy use refer to the vertical axis on the right-hand side. NA, North America; Dev. Asia, developing Asia; LA, Latin America; CIS, Commonwealth of Independent States. Source: [11,12]. (Online version in colour.)

discarded steel product can be re-used in a new application with minimal energy input. Scrap is melted in modern EAFs with primary energy inputs between 3 and 6 GJ t^{-1}. In theory, the potential for reduction of the SEC is 100%, compared with the theoretical minimum for making steel from scrap. In practice, the minimum energy is limited by the energy needed to melt the scrap. In practice, energy intensity depends on the production routes, production technology applied (e.g. type, age) and the operational efficiency of the plants.

The process shares of crude steel production differ between countries. The potentials for energy-efficiency improvement can be estimated, by looking at potential performance if commercially available best-practice technology would be used to produce the same mix of products and using the same raw materials. Benchmarking shows that steel production in Japan and South Korea operates with the lowest energy use, although there is still an improvement potential of 15%. This is followed by the plants in Europe (20% potential savings), North America (26%) and China (30%). Potential savings in iron and steel plants in India (35%), Africa (45%) and the Commonwealth of Independent States (CIS) (55%) are relatively high (figure 3).

A large variety of opportunities exists within the iron and steel industry to reduce energy consumption while maintaining or enhancing the productivity of plants. Studies in the iron and steel industries have demonstrated the existence of a substantial potential for energy-efficiency improvement in almost all facilities, whether primary or secondary steel producers (e.g. [13–15]). The potential will vary from plant to plant, and from country to country. The International Energy Agency estimated the total primary energy savings potential to be 9–18% through the adaptation of best-practice commercially available technologies. Improved energy efficiency may result in other benefits that outweigh the energy cost savings. Experiences of various iron and steel companies have shown that projects can be found with relatively modest investments and that savings with short paybacks can be found. However, to realize selected major energy-efficiency opportunities large investments will be needed (e.g. basic oxygen furnace gas recovery, furnace replacements). These capital investments may not be supported by energy cost savings alone. Additional productivity and product quality benefits will strongly affect the economics of such an investment.

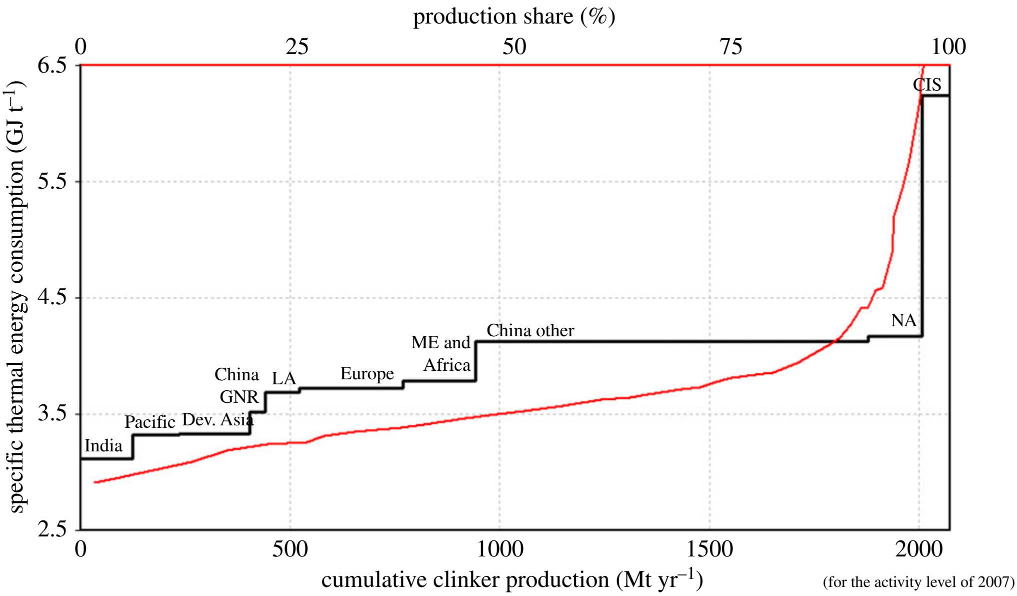

Figure 4. Benchmark curves for clinker production (2007). The black solid line is based on own estimates. The red continuous curve is based on data provided by the Cement Sustainability Initiative for individual plants. GNR, Getting the Numbers Right; ME, Middle East. Source: [9,16]. (Online version in colour.)

4. Cement industry

The cement industry is a large energy user due to the energy intensity of the process and the large volume of cement produced worldwide (an estimated 4100 Mt in 2015). Global primary energy use by the cement industry is estimated at 11 EJ, emitting about 2.3 $GtCO_2$, including direct, indirect and process emissions [13]. Regional energy use typically follows the production distribution, although considerable differences in energy intensity are found for specific countries and regions. The enthalpy of formation of 1 kg of clinker is calculated to be about 1.76 MJ [11]. This calculation refers to reactants and products at 25°C and 0.101 MPa. The enthalpy changes at the temperatures at which the reactions occur are somewhat different. A reasonable enthalpy range of the formation of 1 kg of Portland cement clinker is 1.75 ± 0.1 MJ. Additional to the theoretical minimum heat requirements, energy is required to evaporate water and to compensate for the heat losses. Heat is lost from the plant by radiation or convection, and, with clinker, emitted kiln dust and exit gases leaving the process. Hence, in practice, energy consumption is higher. Focusing on the key energy-using process, clinker production, energy use is primarily affected by the moisture content of the raw meal or slurry, and hence by the process. As the distribution of kiln types varies by region, as do the age of the plants and operational practices, variations are found in the energy intensity of clinker production. Figure 4 depicts benchmark curves for clinker production in various regions in the world. The continuous curve is based on data for individual plants that participated in the Cement Sustainability Initiative (CSI), while the step function is based on national statistical data. Most major cement companies participate in the CSI, although coverage of Chinese cement production facilities is relatively low.

Substantial differences may be found in the cement composition, as some regions (especially western Europe) favour blended cements with low clinker content. Hence, the variations in energy intensity of cement may vary more widely than those of clinker. Moreover, the energy intensity of cement grinding is affected by the composition of the cement, the fineness of the cement (affecting the strength of the cement), as well as the grinding technology and efficiency of the grinding operations. Figure 5 depicts the regional distribution of electricity intensity of cement grinding.

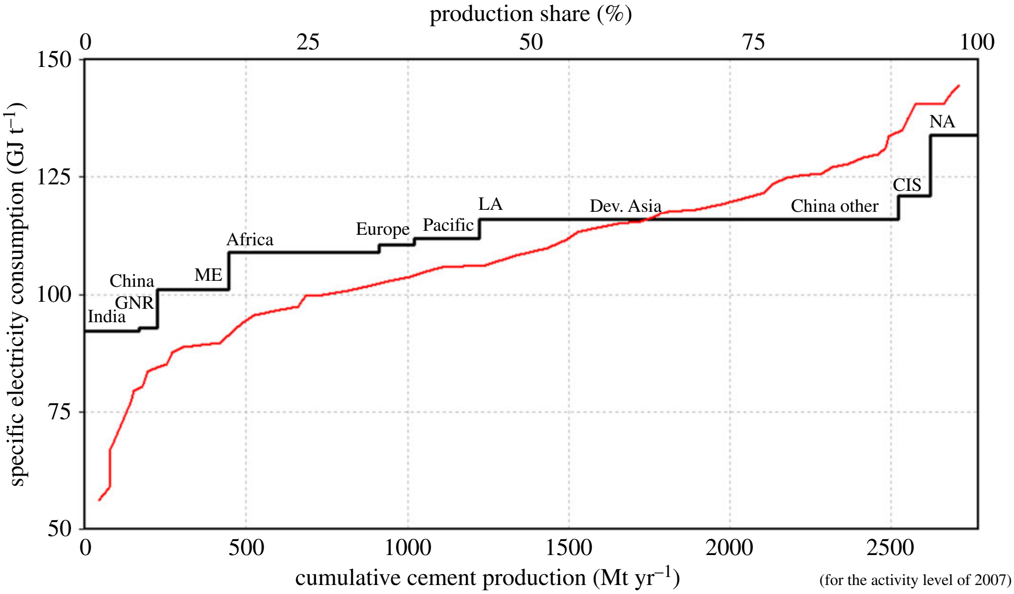

Figure 5. Benchmark curve for cement production (electricity for grinding only, 2007). The red continuous line is based on data provided by the CSI, representing data from individual plants. The black (regional) line is based on the average CSI data and national data (including China) for various global regions or countries. Source: [9,16]. (Online version in colour.)

The benchmark curves show that there is still potential to shift production capacity to the more efficient kiln types (i.e. preheater/pre-calciner kilns), as well as modern grinding technology (e.g. roller presses) to reduce energy use further. In addition to energy efficiency, the overall energy intensity for cement can be reduced by adding (more) additives to the cement in so-called blended cement, reducing the clinker content. Additives can be ground limestone, fly ash from coal-fired power stations, blast furnace slag, or natural pozzolans [11]. Currently, the use of additives may be limited by the lack of appropriate cement or building standards, or building practices that limit the use of blended cement. In the end, the availability of slag and fly ash is limited by the production of iron and coal-fired power production, respectively. However, today large volumes of slag or ash are still not used for high-quality applications, such as cement production.

5. Chemical industry

The chemical industry is an important part of the global economy, and its products are found in virtually every part of our lives. The chemical industry is complex and highly diverse, with thousands of companies producing tens of thousands of products in quantities varying from a few kilograms to thousands of tons. Because of this complexity, reliable data on energy use are not available. This makes energy analysis of the chemical industry more complicated than that for other industries. The chemicals and petrochemicals sector is the largest industrial consumer of energy and the third largest industrial emitter of CO_2. In 2005, it accounted for 29% of world industrial energy use (including feedstocks) and 10% of energy and process CO_2 emissions [14]. More than half of the energy used in the chemical industry is used as feedstock. Three-quarters of all feedstock is from oil (e.g. naphtha, gasoil), which is used for the production of petrochemicals (i.e. olefins and aromatics). Natural gas, the other major feedstock, is used for the production of ammonia, methanol and other products, while natural gas rich in ethane, propane and butane is used to produce olefins (especially in the USA, Middle East and Africa). A significant part of the carbon from the (fossil) feedstock is contained in the final products, such as plastics, solvents, methanol or urea. Some of the feedstock energy is recovered at the end of the life of the product, if it is recycled or incinerated. Incineration will result in CO_2 emissions, but may

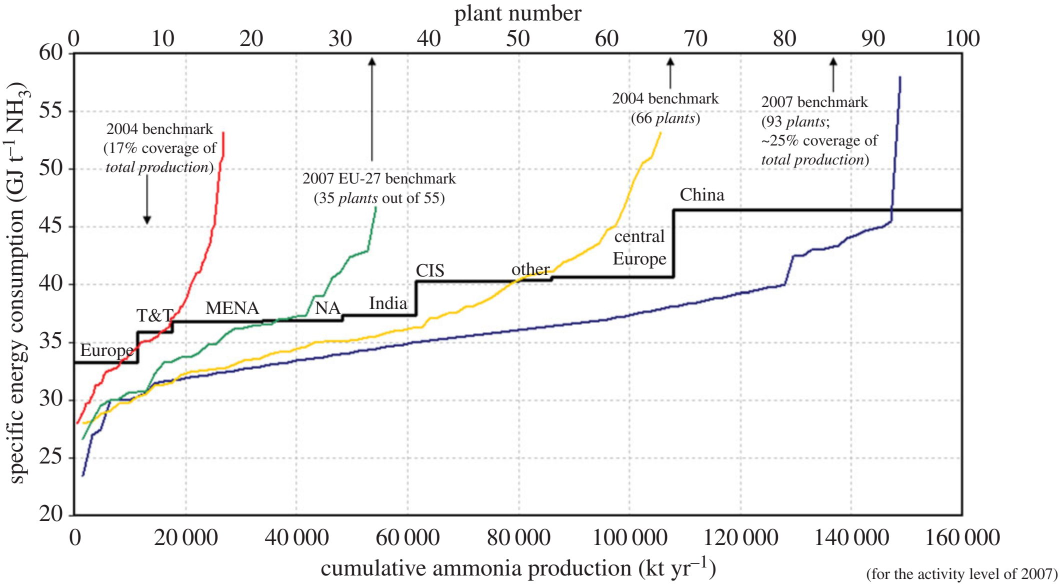

Figure 6. Benchmark curves for the ammonia industry from the International Fertilizer Association (2004 and 2007) and the estimated regional distribution for the ammonia industry (2007). Note that China mainly operates coal-based plants that have a higher energy use than gas-based steam-reforming plants. Black solid line and red line refer to the cumulative production (primary *x*-axis); all other curves refer to the plant number (secondary *x*-axis). MENA, Middle East and North Africa; T&T, Trinidad and Tobago. Source: [9,16].

offset CO_2 emissions from power generation. Hence, chemicals emit more CO_2 over their life cycle than the above share of CO_2 emissions suggests. The major energy-consuming processes in the chemical industry are (steam) cracking to produce the key platform chemicals and monomers (e.g. ethylene, propylene), ammonia production (for nitrogenous fertilizer), and the production of chlorine/caustic soda and methanol [17].

Benchmarking has been an established technique in petroleum refining and the petrochemicals industry for some time now, with commercial companies servicing the industry. In figure 6, the results of various benchmarks (of different regions and for different years) for the ammonia industry are depicted. Ammonia is the key energy-intensive ingredient for nitrogenous fertilizer production. Almost 90% of global ammonia production is used in fertilizer manufacture, and by itself is responsible for an estimated 1% of global energy use. The curves show that participation rates vary. Based on the various curves an estimate has also been made of the regional distribution.

Studies by several companies in the chemical industries have demonstrated the existence of a substantial potential for energy-efficiency improvement in almost all facilities [17]. Improved energy efficiency may result in co-benefits that far outweigh the energy cost savings, and may lead to an absolute reduction in carbon dioxide and other fuel-related emissions. Major areas for energy-efficiency improvement in the petrochemical industry are utilities (30%), fired heaters (20%), process optimization (15%), heat exchangers (15%), motor and motor applications (10%), and other areas (10%) [12]. Of these areas, the optimization of utilities, heat exchangers and fired heaters offer the most low-investment opportunities, whereas in other areas low-cost opportunities will exist or other opportunities may need investments.

6. Aluminium industry

Next to the steel industry, the non-ferrous metals industry is a large energy-consuming sector. Of all non-ferrous metals aluminium is by far the most relevant material with respect to production

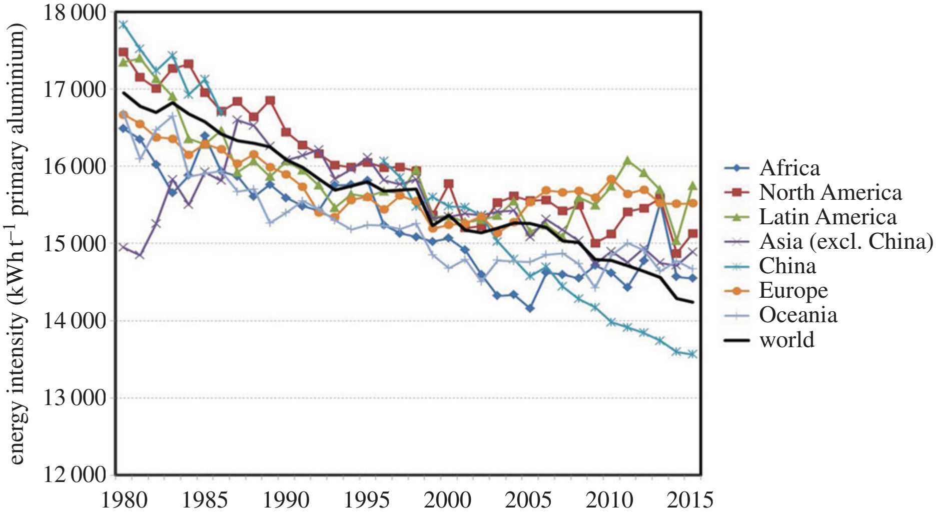

Figure 7. Specific electricity consumption for aluminium smelting for the period 1980–2005, expressed in kWh t^{-1} primary aluminium (including transformer losses). Energy consumption is given for various regions and a global average. Based on data from the International Aluminium Institute.

volumes and energy use. Aluminium production can be split into primary aluminium production and recycling. Aluminium is a strongly versatile metal and has found many applications in transportation, construction, information technology and packaging. Today, about 49 Mt of primary aluminium is produced worldwide. The global figures for aluminium recycling are not available and hard to estimate. Primary aluminium production is one of the most energy-intensive processes in the world, consuming large amounts of electricity (in the smelter and the Bayer process) as well as fuel (in the Bayer process). The electricity used in aluminium smelters in 2015 is estimated at 763 GWh, equal to 3.5% of global electricity consumption, making the aluminium industry the largest purchaser of electricity. The total GHG emissions in 2005 were 391 $MtCO_2$-eq (including direct perfluorocarbon (PFC) emissions, and direct and indirect CO_2 emissions), accounting for nearly 1% of the global GHG emissions [18]. Direct GHG emissions from primary aluminium production are responsible for 0.4% of the global GHG emissions, whereas indirect emissions for the electricity consumed in the smelters account for 0.6%. The direct emissions in the form of PFCs have declined, and in 2010 were estimated at 52 $MtCO_2$-eq. The theoretical minimum energy consumption for the (electro-) chemical reaction of alumina to aluminium is estimated at 6 MWh t^{-1} aluminium. However, in practice, inefficiencies occur in all process steps, resulting in a three to four times higher energy consumption than that determined by thermodynamics. The Hall–Héroult process is the key smelting process and is electricity intensive. Nearly one-third of primary aluminium costs are attributed to electricity consumption, thus research interest in energy-efficiency improvements is substantial. Electricity intensity ranges from less than 13 MWh t^{-1} of aluminium in state-of-art smelters to 17–20 MWh t^{-1} of aluminium in Söderberg smelters [18]. According to the International Aluminium Institute, the world average electricity intensity, in 2015, was just over 14.3 MWh t^{-1} aluminium. Figure 7 depicts the development of the energy intensity of smelting for different regions and the global average for the period 1980–2015, based on data from the International Aluminium Institute.

As suggested by the variations found in the energy use for the different processes and also by the identified 'best-practice' energy consumption values, there is considerable potential to be found in each of the production steps for making aluminium. Figure 8 depicts the benchmark curve for primary aluminium production, accounting for the regional production of aluminium. The continuous line is based on benchmarking data for individual plants, while the step function is based on statistical information. Data for both curves were provided by the International Aluminium Institute.

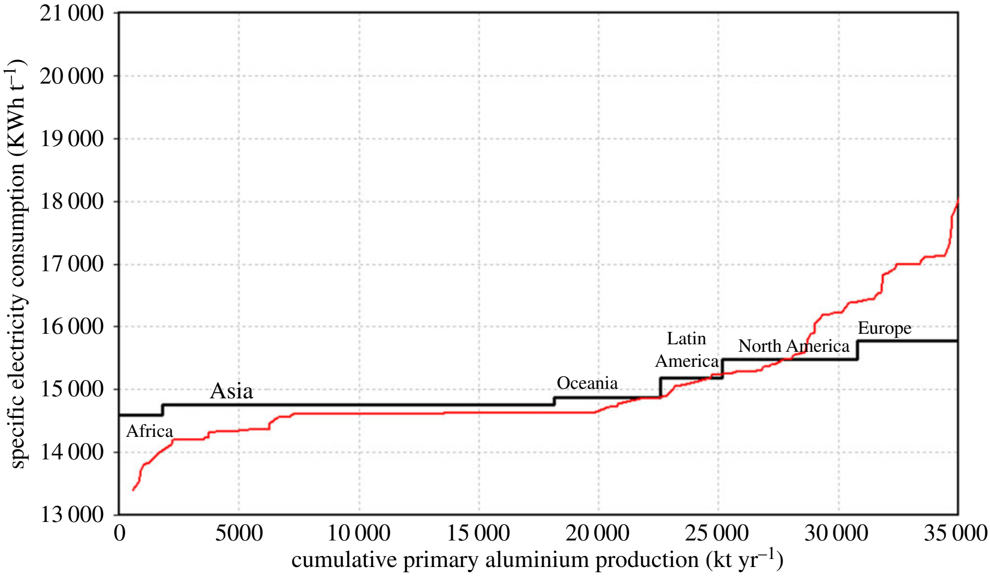

Figure 8. Benchmark curve for the aluminium industry (2007). The black solid line represents the average specific energy consumption for world regions. The red line is the specific energy consumption on the basis of individual plants. Source: [9,16]. (Online version in colour.)

7. Potentials for energy-efficiency improvement

In the discussion above the average performance of the selected industries in various regions was benchmarked against current best practices, assuming the same industry structure, e.g. product mix. The best-practice technology is used commercially, so the difference between the current average and best practice provides a relatively reliable estimate of today's potential for energy-efficiency improvement. As energy prices and economic circumstances may vary, the potential may not always be economically attractive under local circumstances. Yet, it is generally considered to provide a good estimate of what can be achieved with today's technology.

Based on the data presented above, the total potential for energy-efficiency improvement is estimated at about $27 \pm 9\%$ [9]. The uncertainty range is due to uncertainties in energy statistics, aggregation levels in available energy statistics, as well as variations in the definitions of best practices in relationship to definitions in statistics. The potential varies considerably for the selected sectors, as is shown in the figures above. The potentials for energy-efficiency improvement in the steel industry vary from 9% to 30% for different regions, with an overall potential of 20%, while the potential for the primary aluminium industry is limited to only 4–7% (with the larger potential in the industrialized countries) (figure 7). In the cement industry the energy-efficiency improvement potential varies between 20% and 25%. In the chemical industries the potentials vary with the different segments of the industry. In steam cracking the potential is estimated to be 23–27%, while in ammonia production the potential varies between 11% and 25%. In steam cracking the potential will depend a lot on the mix of feedstocks and the product mix, and the resulting cracking severity needed. Hence, potential energy savings in steam cracking are more uncertain than those of other sectors.

The above results are based on older data, and, especially in countries like China, developments have been rapid in some sectors, due to closing of old inefficient capacity (e.g. in the cement and steel industries) or addition of state-of-the-art capacity (e.g. petrochemicals, aluminium smelting) (e.g. [18]). In most industrialized countries developments in energy efficiency have been slower, as shown, for example, by an analysis of the steel industry in Germany (the largest steel producer in the European Union) [19], with structural change towards more recycling being the most important driver (as also observed in other industrialized countries such as the USA and the UK). Hence, today some of the potential identified above may have already been realized. On the other hand, the results of the benchmarking exercise are limited by the system boundaries of the processes, plants (and statistical data). Hence, system improvements beyond the system boundaries may result in additional savings. These include technologies such as combined heat and power (or co-generation), and also thermal integration beyond individual processes, e.g. integrating different plants at a single site or different plants at different sites (also called industrial symbiosis). It is hard to estimate the additional potential on a global level, as these potentials are affected by many local factors (e.g. integration in larger plants, climate, capacity).

Technology development is continuous. New technologies become continuously available that further improve energy efficiency. These so-called BATs are slowly integrated in plant designs, depending on the speed with which innovations are integrated in commercial designs (as some customers are risk averse), as well as the rate of stock turnover. These BATs are not yet included in the above potential estimates. The full potential of applying BATs may further boost energy efficiency, albeit varying by sector. For example, in the steel industry application of BATs may result in a further 10% improvement in energy efficiency, while this is lower for the cement industry and aluminium smelting. In the petrochemicals sector, this may result in an additional 15%.

The theoretical potential for energy-efficiency improvement can be calculated based on the thermodynamics of the chemical conversions involved in the processes. Most sectors are still a factor of 2 or more removed from the thermodynamic optimum, suggesting a strong potential for long-term energy-efficiency improvements. Yet, this thermodynamic potential may be elusive [20], as it will be difficult to reach, if attainable at all, due to practical constraints in process design or materials for reactor construction.

Carbon emission reductions may also be achieved by shifting to renewable energy and feedstocks (e.g. [21]), or the use of CCS technology, but these have not been included in the potential estimates. CCS may actually lead to increased energy use, but may result in strong emission reductions. Development and application of CCS in industry is still limited, and has mainly been applied to capture CO_2 for enhanced oil recovery projects.

8. Implications for deep decarbonization

The results above show that there is still a considerable potential to achieve reductions in energy use and associated carbon emissions in virtually every industry and every country or region. We estimated the energy-efficiency improvement potential for industry at $27 \pm 9\%$. This assumes that all industrial production facilities around the world perform at the level of current best-practice plants. Furthermore, technology developments and options beyond the individual processes may offer additional future potential for energy efficiency and emission reductions. The energy savings represent an estimated CO_2 emission reduction of 2.5 ± 0.8 $GtCO_2$-eq. at current production levels, with the key savings found in the large and carbon-intensive industries such as the iron and steel and cement industries. This potential excludes the potential reductions due to BATs and other technologies under development. It also excludes changes in fuel mix and changes in the raw material mix (e.g. for cement) in the production process. Including these would increase the potential further, but it is hard to provide global estimates.

Taken together these opportunities provide significant potential for GHG emission reduction in the energy-intensive industries. Given the challenge of a net-zero emission world by 2050, energy efficiency can only provide part of the solution, but is an essential and significant contributor to achieving the long-term target. While these are considerable potentials, especially for sectors that have historically paid a lot of attention to energy-efficiency improvement, realization of these potentials under current 'business as usual' conditions is slow due to a large variety of barriers and limited efforts by industry and governments around the world. Hence, realization of the potential would require a strongly improved drive for energy-efficiency improvement and climate action, both within companies as well as in policymaking.

Energy efficiency alone is not sufficient to achieve the deep reductions in carbon emissions that will be necessary to stay within the climate boundaries as agreed in the Paris Conference of Parties (December 2015). In some industries, bio-based feedstocks may result in further carbon emissions, as the integration of renewable energy, theoretical limits on energy use and the very nature of the chemical conversions in some of these industries will ultimately limit the overall reduction that can be achieved, due to the need for carbon inputs or process emissions. CCS can offer a way to achieve deep reductions for these processes, but at the cost of increased energy consumption. Its use will also be limited to sites with access to storage capacity or an infrastructure to transport the CO_2 to storage sites further away (which currently does not exist, except for a few dedicated pipelines in a few locations).

Moreover, the energy transition to a renewable energy supply system needs large investments in materials such as steel and others to build new generation and distribution technologies and networks. For some industries (e.g. steel) this will lead to increased demand, and hence increased energy use. This may offset some of the energy savings due to energy-efficiency improvement. On the other hand, in most regions (including China) demand for traditional applications of these materials is stabilizing or declining, resulting in the availability of production capacity for these new energy-sector markets. For example, in the current Chinese 5 year plan, the closure of 170 Mt steel production capacity has been announced, reducing global excess capacity.

Hence, to realize these significant reductions, the above options need to be augmented by other strategies, with increased material efficiency [1,2] and material demand reduction as prime options. For example, the 2015 World Energy Outlook included material efficiency in one of its scenarios for future global energy demand [4]. As discussed above, increased recycling of steel is already affecting the structure of the steel industry in key producing countries like Germany [19], the UK and the USA, making this already the most important contributing factor for energy savings (which is not necessarily equivalent to energy-efficiency improvement) in recent years.

We end with a plea to develop integrated policies that combine not only energy efficiency and renewable energy forms, but also material efficiency and material demand reduction. This will offer the most economically attractive way to realize deep reductions in carbon emissions. In some sectors, CCS may still be needed to come to close to zero emissions, due to the nature of the chemical conversions in these industries (e.g. iron and clinker making).

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