Imperial College London

Grantham Institute for Climate Change
Briefing paper No 7

February 2012

Reducing CO_2 emissions from heavy industry: a review of technologies and considerations for policy makers

DR TAMARYN BROWN, AJAY GAMBHIR, DR NICHOLAS FLORIN AND DR PAUL FENNELL

Executive summary

Why is it important to address industrial emissions?

INDUSTRIAL PROCESSES ARE HIGHLY ENERGY INTENSIVE AND CURRENTLY account for one-third of global energy use. Around 70% of this energy is supplied by fossil fuels, and CO_2 emissions from industry make up 40% of total CO_2 emissions worldwide. Since the 1990s, the energy consumption of industry per unit of value added in developed countries, has fallen by around 1.3% per year on average (once adjusted for structural changes), but at a lower rate than the average reduction of 2.8% per year during the 1970s and 1980s[1]. Moreover, improvements in energy intensity have been more than offset by increased total production, such that energy consumption and CO_2 emissions have continued to rise dramatically. Demand for manufactured goods is expected to at least double by 2050 (relative to 2006 levels), and, if industrial emissions remain unchecked, total CO_2 emissions are projected to increase by up to 90% by 2050 compared to 2007[2].

Reducing emissions from industry requires a sustained and focussed effort. This Briefing Paper outlines the options for reducing industrial CO_2 emissions, concentrating on those sectors which make up the largest share (>70%) of emissions, i.e. iron and steel, cement and chemicals and petrochemicals. The paper gives an overview of industrial mitigation technologies, both those that are process-specific and those that apply broadly across the whole of industry. The abatement potential of these technologies, their cost effectiveness and barriers to uptake, as well as the policies to overcome these barriers, are discussed.

How can we reduce industrial emissions?

The industrial sector is made up of a diverse range of processes and product manufacture. There is therefore no single technology on which to focus our efforts. A piecewise approach to reducing emissions is required, which is challenging to monitor, incentivise and control. In order to significantly reduce industrial emissions, the following key actions are required:

Contents

Grantham Briefing Papers analyse climate change research linked to work at Imperial, setting it in the context of national and international policy and the future research agenda. This paper and other Grantham publications are available from **www.imperial.ac.uk/climatechange/publications**

a) Maximise energy efficiency potential by replacing older, inefficient processes with current Best Available Technologies and Best Practise Technologies.

- **Implementation of process specific technologies.** These can offer step change improvements in energy intensity unique to each industrial process, for example: improved process designs and phasing out inefficient technologies; heat recovery and integration options, such as power generation from high calorific gases in iron making. Many of these technologies require significant capital investment and the long-lived nature of current capital stock limits the rate at which new technologies can be adopted. It is therefore critical that new plants are built using current BAT so as to avoid lock-in to more carbon-intensive technologies. Furthermore, BAT standards must be regularly updated on an appropriate timescale in keeping with technological advancement.

- **Implementation of cross-cutting technologies.** These include systems and equipment that are common to a wide range of process, such as energy efficient motor and steam systems and installation of combined heating and power (CHP) units. Significant improvements can be implemented at low or even negative cost.

- **Adoption of energy efficient technologies** – specific or generic – could result in reductions of 2.1 $GtCO_2$ by 2050, against business-as-usual levels of emissions, according to IEA estimates[2].

b) Demonstrate and deploy fuel switching to low carbon energy sources.

- **Co-firing of biomass and wastes could significantly reduce fossil fuel usage.** Due to the high temperatures inside industrial reactors, co-firing is often a more environmentally friendly way of disposing of wastes. Additionally, unlike biofuels, purpose-grown crops are not required. The use of agricultural residues reduces concerns regarding land use and competition for food production.

- The share of electricity making up the industrial energy mix has increased from around 14% in the 1970s to roughly 25% today[3], but the options for further **electrification of industry** are currently limited. Increasing use of electric arc furnaces in steel manufacturing will be constrained by the availability of cheap electricity and the supply of recycled steel.

- **Fuel and feedstock switching** could provide emissions savings of 0.95 $GtCO_2$ against business-as-usual projections by 2050, according to IEA projections[2].

c) Accelerate research into industrial CO_2 capture and rapidly demonstrate integrated industrial CO_2 Capture and Storage (CCS) plants.

- CCS from industrial sources is in the R&D phase but could **reduce annual emissions by around 1.75 $GtCO_2$** against business-as-usual by 2050, according to IEA projections[2]. Less attention has been paid to CCS from industry compared to the power sector despite the crucial role that it is required to play in reducing CO_2 emissions.

- **Continued and focussed investment and R&D** is required to reduce the costs of industrial CCS if commercial deployment between 2020 and 2030 is to be realistic. CO_2 is routinely separated in ammonia production and natural gas processing. These industries offer opportunities for early demonstration of integrated CCS plants.

d) Alter product design and waste protocols to facilitate reuse and recycling in order to close the materials loop

- Taking an integrated systems approach to the management of resources in order to minimise waste and maximise value over the lifetime of the product.

How can we enable action?

A number of policies are required to achieve the abatement potential in industry, falling into four broad categories:

- **Improve benchmarking through standardised measurement and data capturing protocols** to assess the relative energy consumption and CO_2 emissions of industrial plants and identify the Best Practise Technology (BPT) and Best Available Technology (BAT) for a given industrial process. A number of industrial associations have benchmarking initiatives, but access to reliable data remains limited. Global metering standards should be introduced to ensure that emissions from different countries are comparable.

- **Identify barriers and develop approaches to improve uptake of energy efficient technologies.** Even though many energy efficiency technologies and processes are cost effective, the uptake of BAT remains low. This is known as the 'energy efficiency gap' and results from a number of barriers including lack of management focus, an absence of energy consumption and emissions monitoring systems, capital constraints and a lack of effective, targeted policies. Where necessary policy-makers should work with industries to focus their attention on energy efficiency monitoring and provide appropriate targets and incentives to support the uptake of energy-efficient practices and technologies.

- **Incentivise fuel-switching and more costly abatement options through appropriate financial incentives or regulations.** Industries in some regions (including the EU and New Zealand) are included in emissions trading schemes where they face an emissions cap and carbon price. Such schemes recognise that the globally competitive nature of many industrial products mean that a higher carbon price in one region may lead to competitiveness losses and carbon leakage to other regions, by for example allocating energy-intensive industries a number of free emissions allowances. Alternative approaches to free allowances, such as border adjustment mechanisms and sectoral approaches involving industries from a broader range of regions, are under consideration.

- **Provide government support to research, development, demonstration and deployment efforts,** crucially for industrial CCS. The main focus of CCS to date has been on the power sector, even though industrial applications are expected to play an equally important role by 2050. A concerted effort involving international collaboration is required to achieve the requisite scale and speed of research to demonstrate CCS in the broad range of industrial applications in which it is likely to be needed.

Introduction

The Industrial Revolution of the late eighteenth century sparked unprecedented economic growth. Over the last two centuries, there has been a dramatic increase in living standards and real income, predominantly in Europe, North America and the Pacific. More recently, China, India and other developing countries have entered a period of high growth[2]. As these countries undergo the rapid expansion of the infrastructure required to underpin this growth, the demand for materials such as cement and steel has risen, and will continue to rise, dramatically. During the last two decades, growth in these countries made up 80% of the increase in industrial production[2].

In OECD countries, industrial production is relatively stable (see Box 1 for a definition of 'industry'); the majority of infrastructure in these countries is established and so materials consumption is largely for maintenance and upgrade of these structures. Additionally, an economic shift to services and knowledge-based sectors has occurred and materials production has relocated abroad, with OECD countries increasingly relying on imports from countries such as China and India. Currently, China is the largest producer of ammonia, cement, iron and steel, and methanol. Some expect that production in China will follow OECD trends, likely levelling out by 2050, as its economy shifts towards the services industry[4]. By comparison, industrial activity in India, Africa and the Middle East is expected to increase by around 150% by 2030 and 300% by 2050, compared to current levels[2]. Overall, the global demand for industrial products is expected to more than double by 2050[5].

The industrial sector is highly energy intensive. The total final energy consumption of industry worldwide was 127 EJ (see Box 2 for units) in 2007. This is approximately 40% of global final energy use[7]. Figure 1a shows the share of fuels which made up this energy supply; 70% was from fossil fuels. With currently available technologies, the options for replacing fossil fuels or switching to less carbon intensive fossil fuels are limited and they will likely remain the predominant source of energy in industry at least for the remainder of this century.

Box 1. Definitions of the Industrial Sector

'Industry', very broadly, refers to economic activity producing either goods or services. Colloquially the term usually refers to the secondary sector, covering production processes such as refining, manufacturing and construction. This paper uses the conventions found in IEA publications: 'Industry' includes energy-intensive industries making up the secondary sector of the economy but excluding petroleum refineries. This sector is largely made up of the primary production of materials such as iron and steel, non-ferrous metals, non-metallic minerals (predominantly cement), chemicals and petrochemicals and pulp and paper. The remainder of the sector is made up of the manufacture and production of goods such as machinery and other equipment, food, tobacco, textiles and wood products. Mining and quarrying are also included. Petroleum use as feedstocks (raw materials) is also included[6]. A full breakdown of the industrial sector is given in the IEA's Energy Technology Perspectives 2010.

Box 2. Explanation of units used in this paper

Measuring CO_2 emissions:
1 Gigatonne of CO_2 (Gt CO_2) = 10^3 Megatonnes of CO_2 (Mt CO_2)
1 Megatonne of CO_2 (Mt CO_2) = 10^6 tonnes of CO_2

Units of energy:
1 Exajoule (EJ) = 10^3 Petajoules (PJ) = 10^9 Gigajoules (GJ)
1 Gigajoules (GJ) = 10^9 Joules (J)

Units of energy intensity:
GJ/t = the amount of energy (in gigajoules) required to produce 1 tonne of product

Around 40% of global CO_2 emissions[2] arise from industrial processes; either directly (emitted at the point of use of a fuel) or indirectly (emissions emitted prior to the use of the fuel or electricity, e.g. emissions from the generation of electricity or refining of crude oil). In 2007, total global direct emissions from industry were 7.6 Gt of CO_2. Currently, indirect CO_2 emissions make up around 32% of total industrial CO_2 emissions[8]. Indirect CO_2 emissions can be addressed by the decarbonisation of the electricity sector. In addition, demand for electricity can be reduced through improved efficiency of various electrical appliances such as refrigerators and motor-driven equipment such as fans, compressors and pumps. Assuming a largely decarbonised power sector in the future, there is an argument for switching to production processes that use electricity, in order to reduce consumption of fossil fuels in industry.

Direct CO_2 emissions can be further separated into (i) fuel combustion processes for process heating; and (ii) emissions which are the product of a chemical reaction e.g. from the conversion of limestone ($CaCO_3$) into lime (CaO). Figure 1b shows the share of direct industrial CO_2 emissions by sector. The largest contributors to emissions are iron and steel, and cement production[2]. These collectively contributed around 4.3 Gt, or 56%, of direct industrial CO_2 emissions in 2007. A further 17% was from chemicals and petrochemicals, which consist of a wide range of processes, producing both organic and inorganic chemicals. Aluminium production, and pulp and paper processes made up a further 4%. The remaining 23%, or 1.7 Gt of CO_2 emissions, arose from a large number of smaller processes such as manufacturing of textiles, machinery and equipment, and processed foods. Reducing emissions from the highly varied processes making up the industrial sector is by no means simple. Although there are a number of cross-cutting technologies, ultimately, these processes each need to be assessed individually in order to realise their full abatement potential. Since the iron and steel, cement and chemicals sectors make up around 73% of direct CO_2 emissions from industry, this paper focuses on abatement in these three sectors.

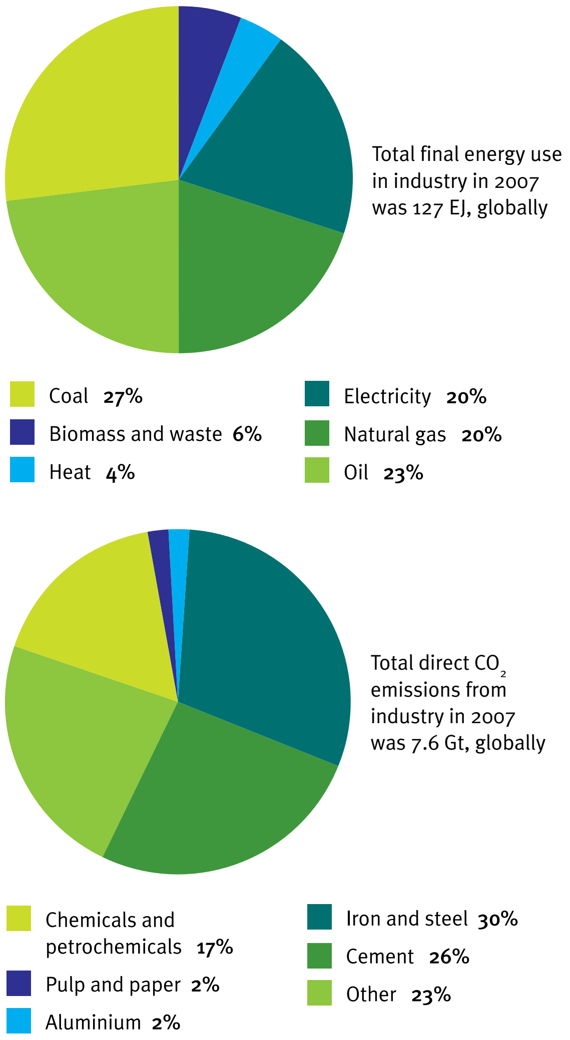


Figure 1. a) Share of final energy use in industry by fuel type. b) Share of direct CO_2 emissions from industry for 2007 by sector[8]. Note that 'Chemicals and Petrochemicals' excludes refineries but includes crude oil derived products such as plastics and fibres. Figures adapted from the IEA[8].

Key industrial sectors

This section introduces the key industrial sectors discussed in this paper and describes the typical manufacturing processes.

Iron and steel

Iron and steel are two of the most widely used materials in the world. Globally, more than 1.3 billion tonnes of crude steel are produced every year, with more than 34% being produced in China alone, making it the largest producer of crude steel in the world. IEA projections[2] indicate that global steel demand could reach around 3 billion tonnes by 2050 (Figure 2). Depending on their grade, iron and steel are used in a range of applications from building materials, automobiles and appliances to cutlery and surgical equipment. Global CO_2 emissions[2] from the iron and steel sector were 2.3 Gt in 2007.

The different manufacturing routes for producing iron and steel are shown in Figure 3. Steel can either be produced from raw iron ore (primary steel production) or from recycled steel scrap (secondary steel production). Primary steel production is essentially the conversion of the iron ore (largely iron oxide) into 'pig' iron. Pig iron has a number of impurities and a relatively high carbon content. Steel is produced by removing these impurities and lowering the carbon content, which makes steel much less brittle than the pig iron.

Today, the most commonly used process for primary steelmaking is the Basic Oxygen Process. Here, iron ore is reduced to pig iron in a Blast Furnace (BF) in which carbon monoxide (produced from the partial oxidation of coking coal) reacts with molten iron ore to remove oxygen from it. The resulting pig iron is then converted to steel in a Basic Oxygen Furnace (BOF), where high purity oxygen at high temperature is used to remove carbon and other impurities from the pig iron, forming steel of the required carbon content. The BOF has largely replaced its precursor, the Open Hearth Furnace (OHF), where pig iron is converted to steel by heating it in the presence of air. Both the BOF and OHF can be supplemented with scrap steel to produce new steel.

In the secondary steel production process, recycled steel scrap is melted by applying a very high current through to it in an Electric Arc Furnace (EAF). Steel scrap can be supplemented with an alternative to pig iron called Direct Reduced Iron (DRI) also known as 'sponge iron'. DRI is produced by reducing iron ore in the presence of coal or natural gas. As no coke is required, the energy intensive process of coke production is avoided. The direct reduction

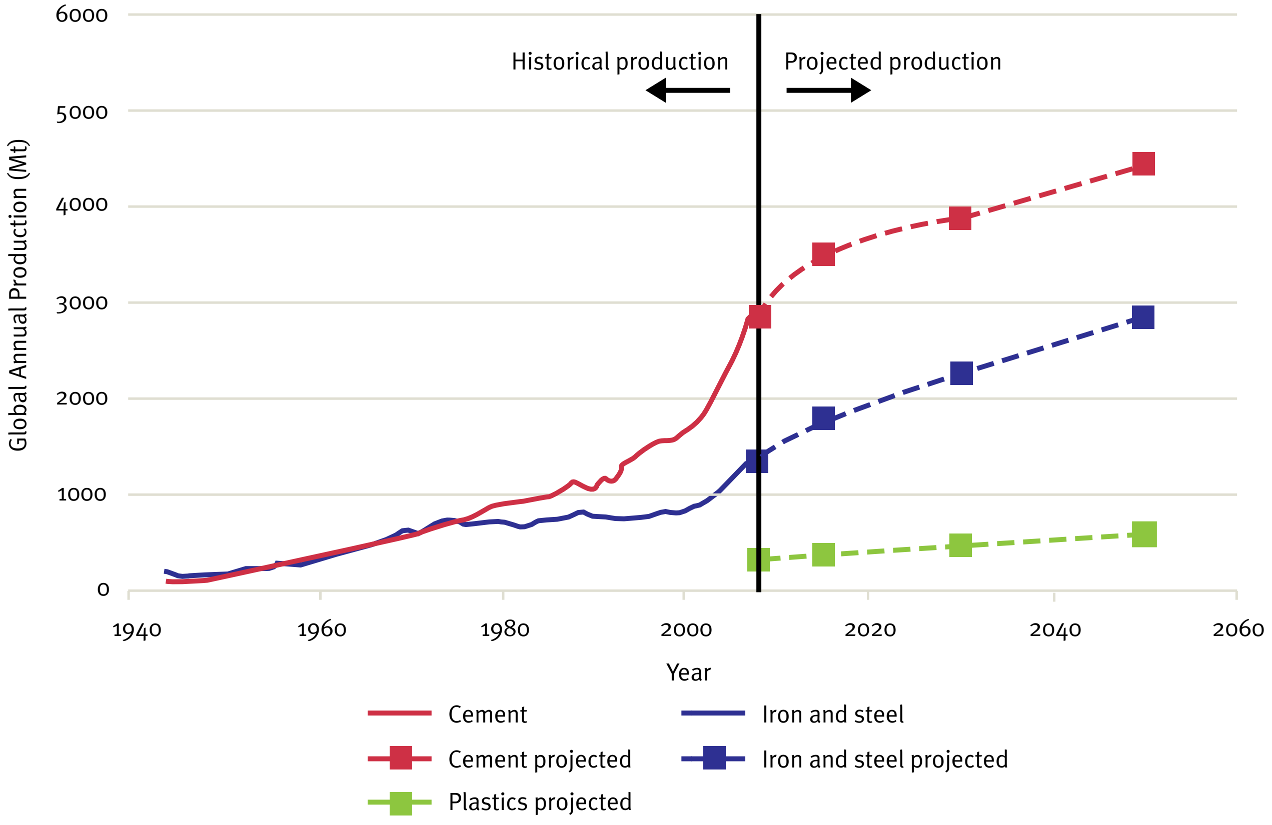


Figure 2. Historic and projected annual global production of cement, aluminium and steel. Historic production has been taken from the U.S. Geological Survey Records and the future production is taken from an average of IEA low and high demand projections[2]. Note that it is extremely difficult to forecast future production and there is a high degree of uncertainty in these projections. Actual future production of industrial products will have a crucial impact on absolute CO_2 emissions. If demand is higher than projected, more drastic actions will be required.

process operates at a lower temperature and, unlike in the blast furnace, the iron ore is not melted. The resulting iron is generally of higher purity than pig iron from the blast furnace process and is an excellent raw material for electric arc furnaces. The DRI process combined with EAF is an alternative primary steel production route to the BF-BOF process.

Once the steel has been made it must be cast into useful shapes. Traditionally, crude steel is first cast into ingots by pouring molten metal into moulds. These ingots must then be further cut or shaped into the desired final product. Today, ingot casting has largely been replaced by continuous casting. Here, molten metal is continuously poured into the top of a long mould, the metal cools as it passes down the length of the mould and is cut to the desired size as it exits the other end. Continuous casting is normally followed directly by hot rolling in order to shape the metal into the final product.

Globally, more than 55% of steel is produced in basic oxygen furnaces. Open-hearth furnaces have been phased out over the past decade and today, only around 2.4% of steel produced worldwide is manufactured in open-hearth furnaces. The majority of these furnaces are in Russia, Ukraine and India. The remaining steel is produced in electric arc furnaces. Around 9% of steel is produced from Direct Reduced Iron (DRI). Most DRI (more than 90%) is natural gas-based, largely in the Middle East and South America. Coal-based DRI facilities exist largely in India[9].

Cement

Cement is a commonly used binder, which when mixed with sand and rock aggregates, forms a strong and durable building material known as concrete. Annual cement production is currently around 3.3 billion tonnes and this is projected to increase to close to 4.5 billion tonnes by 2050, as shown in Figure 2. China is by far the world's largest cement producer, accounting for 54.5% of global cement production in 2010, of which only around 1% is for export[11]. India, the US, Japan and Korea are the next largest producers, together accounting for around 15% of global cement production[12].

The raw materials required for cement production are limestone (calcium carbonate, $CaCO_3$), clay and sand. Following crushing and milling, correct proportions of the different raw materials are mixed together and then fed to the kiln system. Modern kiln systems consist of staged pre-heaters, a pre-calciner and a rotary kiln. The pre-heaters dry and heat the raw material to the required temperature (around 900°C). The number of pre-heater

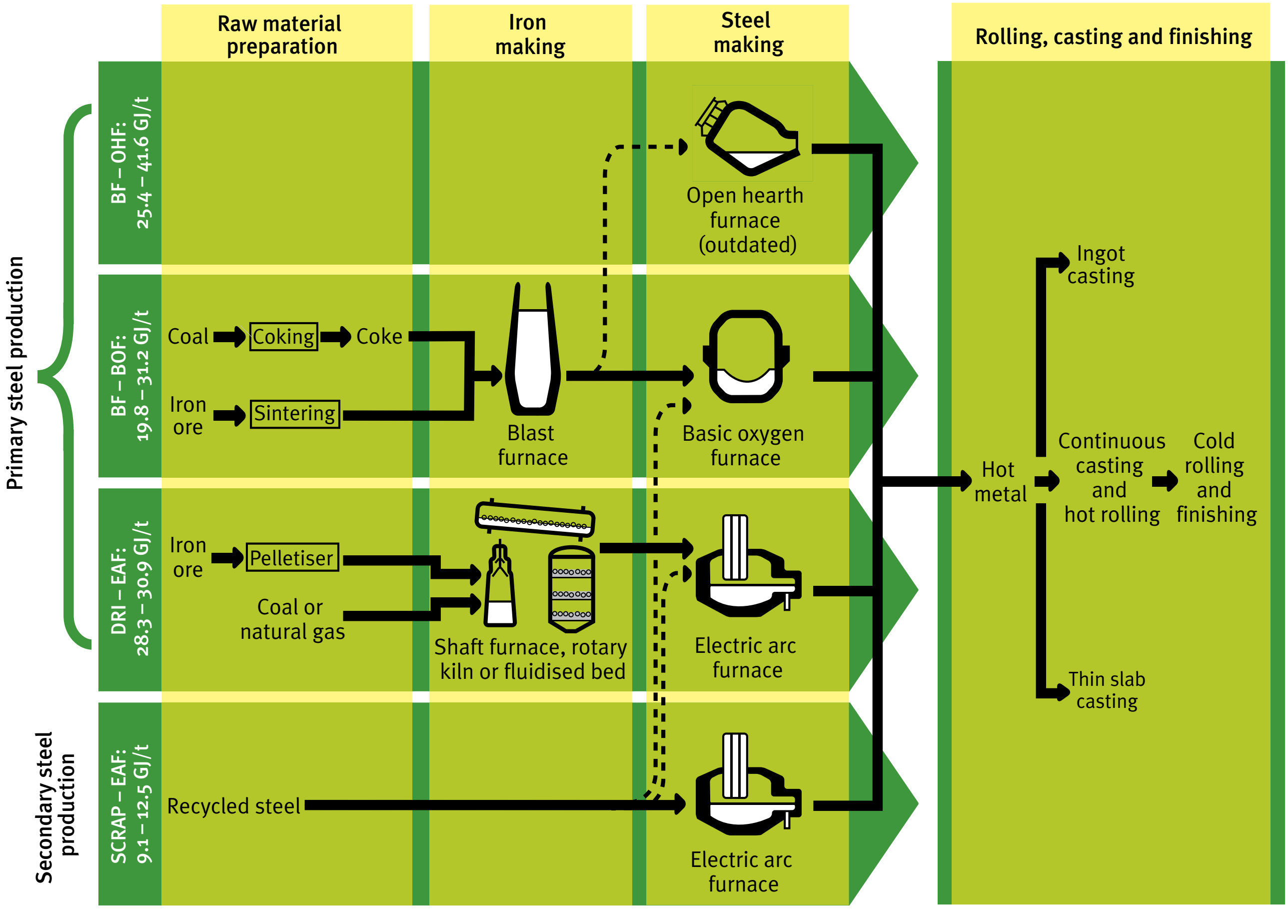


Figure 3. Steel production routes and energy intensity per route (in units of GJ per tonne of crude steel produced) taken from Worldsteel Energy Factsheet[10]. Steelmaking process can vary from one facility to another and energy intensity varies depending on steel grade produced and technology used. Energy intensity values are based on CO_2 intensity values from Worldsteel 2007 data.

stages depends on the moisture content of the raw materials. In the pre-calciner the limestone is converted into lime (calcium oxide, CaO), releasing CO_2 in a process known as calcination. The mixture is fed to the rotary kiln where it is fired with fuel burned directly in the kiln, achieving temperatures as high as 2000°C. At this high temperature, calcium oxide and silica in the sand react to form calcium silicates, forming a hard product, known as 'clinker'. On exiting the kiln, the clinker is cooled, crushed and blended with gypsum to form cement.

An alternative to the modern rotary kiln is the older vertical shaft kiln. The shaft kiln was one of the first kilns designed to operate continuously. Although this kiln type has been largely replaced by the rotary kiln, a large number are still in operation in China today. However, these are typically small-scale plants in rural areas and are rapidly being phased out. By 2015, almost all remaining vertical shaft kilns are expected to be shut down[13]. Rotary kilns are more efficient than shaft kilns owing to economies of scale. Rotary kilns can process around 60 times more cement compared to the average shaft kiln.

Chemicals and petrochemicals

In contrast to the steel and cement sectors discussed above, the chemicals sector is highly diverse with numerous processing routes and products. However, there are a few key intermediate products, which form the building blocks for most chemicals products. These can be broadly categorised into organic and inorganic as shown in Figure 4. The key organic intermediates include: olefins (ethylene is of particular importance), aromatics and methanol. Important inorganic chemicals include: ammonia, carbon black, soda ash, chlorine and sodium hydroxide.

The chemicals sector also differs from other sectors in that fossil fuels are also used as the raw material for many chemical processes. When fossil fuels are used as raw materials, the carbon in the fuels is embodied in the final products and is only released at the end of the product's life. Around 833 Mt CO_2e is stored in plastics and fibres every year[14]. In addition, on an energy basis, fossil fuel raw materials account for more than half of the fossil fuel usage in the chemicals sector. Figure 4 shows the energy and raw material inputs for the production of key intermediates in the chemicals sector. Including fossil fuel used as raw materials, the total energy requirements for the

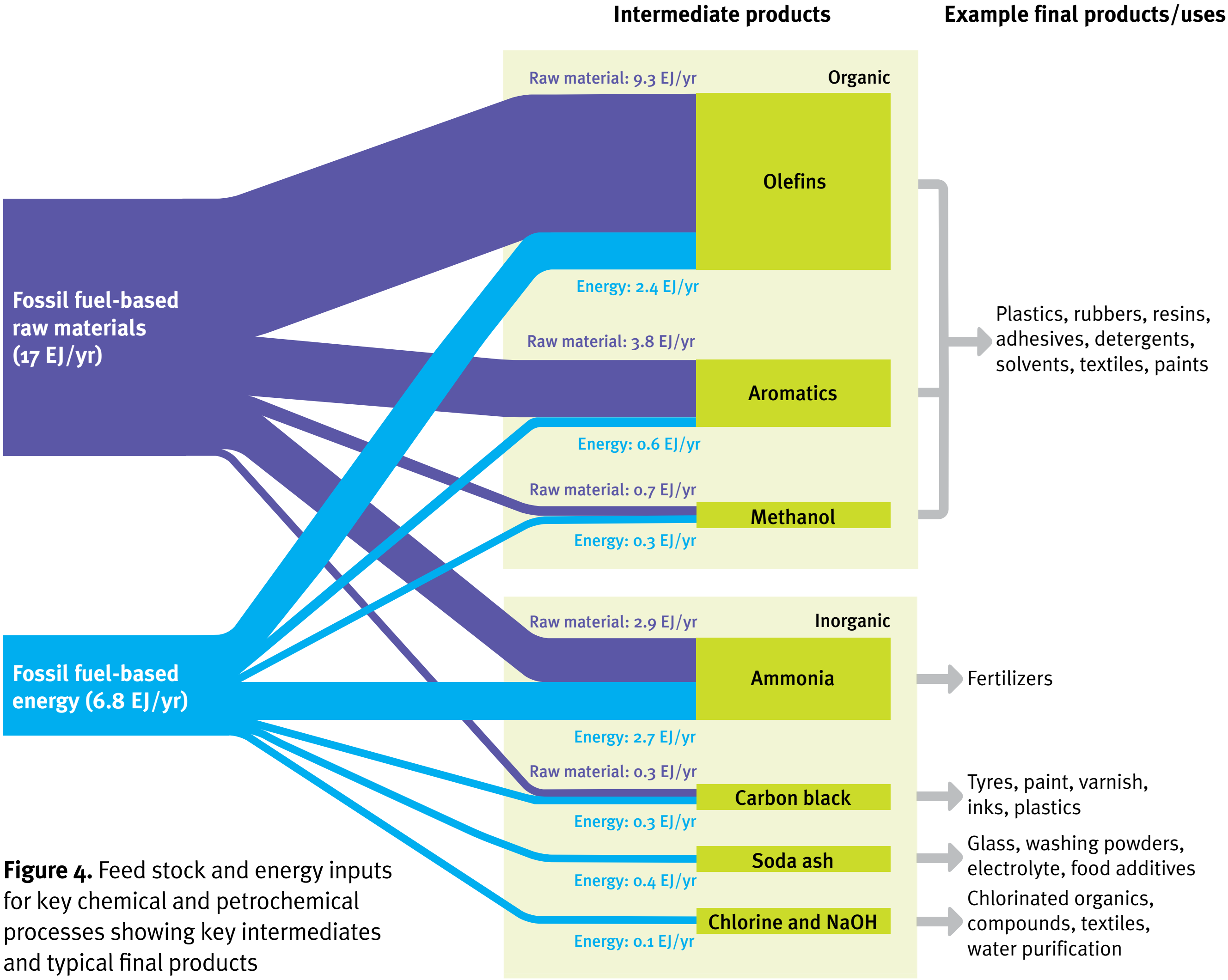


Figure 4. Feed stock and energy inputs for key chemical and petrochemical processes showing key intermediates and typical final products

chemicals and petrochemicals sector amounted to over 30% of total industrial energy usage.

In the petrochemicals industry, steam cracking is a key process whereby hydrocarbons, usually derived from crude oil, are broken down into smaller hydrocarbons. For example, naptha or ethane is converted into ethylene by the process of steam cracking. Cracking occurs when the heavy hydrocarbon raw material is heated in a furnace in the presence of steam and absence of oxygen. In some cases a catalyst is used to speed up the reaction and increase product selectivity. The product stream is immediately quenched (rapidly cooled) in order to halt the reaction. The desired product is separated, usually through a series of compression and distillation stages.

Ammonia is the key raw material for the production of fertilisers. The primary method of producing ammonia is through steam reforming of natural gas, accounting for about 77% of ammonia production[9]. However, ammonia can also be produced from coal, oil and biomass. These alternative production routes are largely based in China and India where coal is readily available.

Mitigation technology options

The options for reducing direct emissions from industry are highly varied. The technology routes are represented schematically in Figure 5. The boxes in Figure 5 represent the key categories for technology developments in abatement of industrial CO_2 emissions.

- Energy efficiency technologies, split into (a) process specific technologies and (b) industry-wide technologies;
- Fuel and raw material switching;
- Life cycle changes and recycling;
- Carbon Capture and Storage (CCS) and other novel technologies.

The term energy efficiency is often heard in the context of CO_2 mitigation and is used to describe a wide range of technologies and measures. Typically, energy efficiency refers to any process improvement, which reduces the required input of fuel whilst still producing the same product or service. New equipment designs or processing routes, for example, can result in significant step-change reductions in the energy intensity of a specific process. Similarly, improvements to steam and motor systems, which are generic to many industries, can make a contribution to improving overall energy efficiency. Energy efficiency can also refer to processes where additional products or services are generated from the same input of energy such as combined heat and power (CHP) plants or efficient heat integration. Assuming that the energy is carbon-based or derived from a carbon source (i.e. fossil-fuel power generation), improved energy efficiency should directly result in reduced CO_2 emissions. However, if a completely decarbonised electricity source is used, energy efficiency improvements do not offer CO_2 savings. Additionally, in some cases savings from improved energy efficiency are offset by increased energy use elsewhere, known as the 'rebound effect'. Thus the degree to which energy efficiency improvements are converted into economy-wide CO_2 emissions savings is not straightforward; however, for the purposes of this paper, energy efficiency is assumed to translate into CO_2 savings.

In the longer term, life cycle improvements involving the optimisation of system-wide mass and energy flows could offer additional savings, for example with increased recycling and the more efficient use of materials. However, it will be very difficult for the aforementioned technologies to provide significant reduction of CO_2 emissions from industries that are heavily dependent on fossil fuels. Assuming considerable progress in demonstration and deployment is made in the power sector over the next few years, Carbon Capture and Storage is expected to play a vital role in reducing industrial CO_2 emissions, providing it can be sucessfully demonstrated at commercial scale and at an affordable price. In the IEA's BLUE Map scenario (which aims to halve global CO_2 emissions by 2050, compared to 2005 levels), CCS reduces industrial emissions by 1.75 Gt of CO_2 or 33% of the total reduction required from industry.

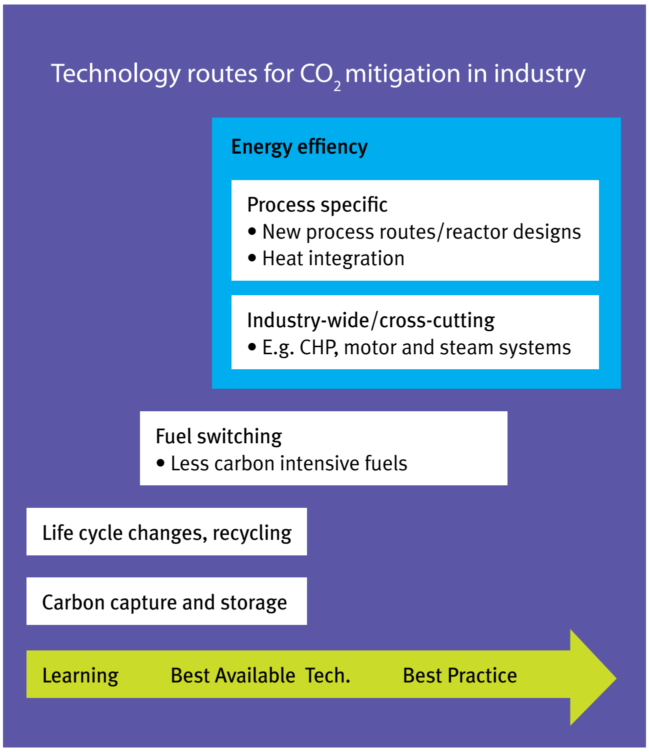


Figure 5. Schematic representation of the technology routes for CO_2 mitigation in industry showing the progression from learning to Best Practice Technology and the current status of these technology routes along this timeline.

The arrow in Figure 5 represents the development stages of new mitigation technologies. During the initial 'learning phase', new technologies undergo extensive research and development. Once a technology has proven itself to be viable and cost effective, it is deployed commercially. At this stage, when only a few plants operate with this technology, this is known as the Best Available Technology (BAT). Once the technology is proven and established, more and more companies adopt the technology, and it becomes known as the Best Practice Technology (BPT). Full definitions of BAT and BPT are provided in Box 3. If the technology is well established then BAT and BPT will essentially be the same. For emerging technologies, however, the BAT will be better than BPT. Both BAT and BPT change over time as new technologies

Box 3. Defining Best Available Technology (BAT) and Best Practice Technology (BPT)

The term Best Available Technology (BAT) is derived from the concept of best available technique defined by the European Union Directive[15] concerning integrated pollution prevention and control as: 'the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for limit emission values...'.

Here, techniques includes 'both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned' and available techniques refers to 'those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, as long as they are reasonably accessible to the operator' and best means 'most effective in achieving a high general level of protection of the environment as a whole'. Typically BAT is represented as a range, rather than a single value. Since the cost of a technology is taken into account, often the best achievable performance is not included in this range.

Similarly, Best Practice Technology (BPT) refers to technologies, processes and methodologies currently being deployed, i.e. 'proven and established' technology. If the technology is well established then BAT and BPT will essentially be the same. For emerging technologies, however, the BAT will be better than BPT.

are developed. In order to monitor these improvements and to accurately assess the full available potential, accurate records and statistics of emissions and energy usage are required; this is known as benchmarking. Figure 5 also gives an indication of the timescale of implementation of technologies for mitigating industrial CO_2 emissions. Both process specific and cross-cutting energy efficient technologies, which are already commercially proven, should be implemented over the short and medium term. Although switching to biomass and wastes has been demonstrated in some industries, this is not widespread and challenges exist depending on the fuel and process. Fuel switching is likely to be applied over the medium term. Life cycle changes and novel technologies such as CCS, which are still in the learning stage, will only be implemented in the long term.

Process-specific energy efficient technologies

Iron and steel sector

In the iron and steel sector there are three key ways in which significant energy savings and hence also CO_2 emissions savings can be achieved. These are:

- Switching to more efficient processing routes such as phasing out open hearth furnaces and increased use of scrap with electric arc furnaces;
- Increased recovery of gases and heat integration from the blast furnace and basic oxygen furnace;
- Adoption of efficient methods for finishing the final crude steel product.

Figure 6a shows the energy intensity of the different steel manufacturing routes. The open hearth furnace is the most inefficient processing route. It is estimated that completely replacing open hearth furnaces with basic oxygen furnaces would save around 100 PJ per year (or 2% of total energy savings potential). The majority of steel is produced using the BF-BOF route. BAT has an energy efficiency of 19.8 GJ per tonne of crude steel. The energy intensity of the scrap-EAF secondary steel production route is much lower than the BF-BOF route. Switching from BF-BOF to scrap-EAF can make significant energy savings (implications for the overall lifecycle emissions are discussed in the section on lifecycle and systems approach). The limiting factor is the supply of cheap electricity and scrap steel. Steel scrap comes from vehicles, machinery, packaging, white goods and buildings, which can take 10–100 years to be discarded and become available for scrap. As economies mature, the supply of scrap increases and the recycling rate can increase. According to 2007 statistics, for example, the steel recycling rate[16] in Germany was 91%.

Blast furnace improvements make up the largest potential share of energy savings in the iron and steel sector. The main reducing agent in both the blast furnace (BF) and basic oxygen furnace (BOF) is coke. Coke is a highly energy intensive fuel which is produced from speciality coking coal (known as metallurgical coal) by heating it slowly in an oxygen-free environment. The gases leaving the BF, BOF and the coke oven have a high calorific value and so can be used as fuels elsewhere in the plant or to generate steam or electricity. BOF gas recovery is on the increase[9]. In China, BOF gas recovery increased from 55% in 1995 to 89% in 2003. Coke oven gas recovery depends on the location of coke manufacturing. In an integrated steel plant, typically 97% of coke oven gas is recovered. However, coke oven gas recovery is less common for coke ovens situated near mines as there are fewer uses for the gas; gas flaring is still the common practice here. Additional waste heat can also be recovered from the coke and used to raise steam in a process known as 'coke dry quenching'. Coke dry quenching is widely applied in Asia (95% of Japanese plants). The EU and the USA are lagging behind.

More efficient continuous casting has largely replaced traditional ingot casting. Following casting, the steel is usually further shaped by either hot or cold rolling. More recently, thin slab casting has been introduced which reduces the need for hot rolling. Currently, less than 10% of production uses this method.

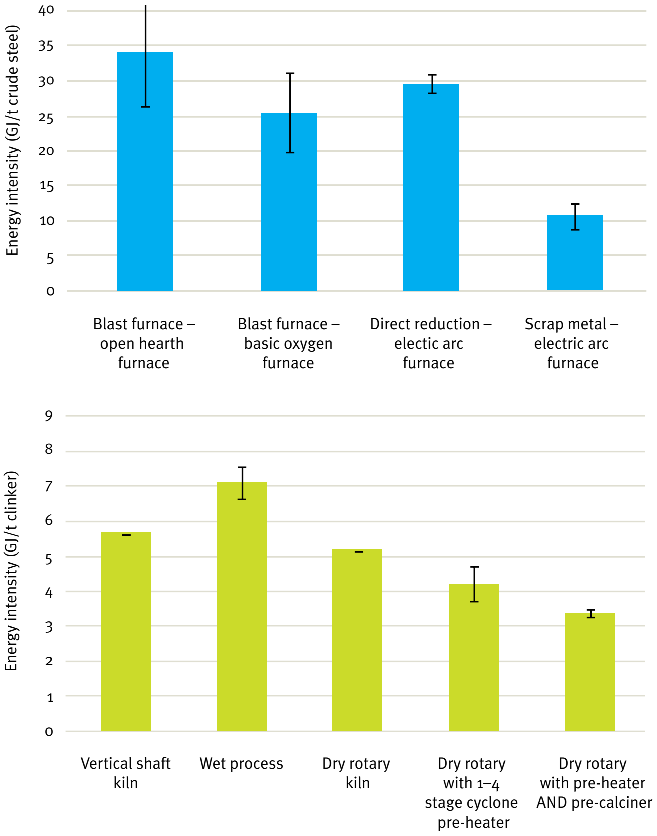


Figure 6. a) Comparision of the global average energy intensity of different steel manufacturing routes.
b) Comparision of the global average energy intensitites of different cement kiln types[17]. Error bars represent the range of energy intentsities of these processes in different countries.

Overall, the specific energy savings potential in the iron and steel sector is estimated at 4.1 GJ per tonne of crude steel. The specific energy savings potential of the four largest iron and steel producing countries are, in order of production, China (6.2 GJ per tonne), Japan (1.4 GJ per tonne), United States (2.4 GJ per tonne) and Russia (6.1 GJ per tonne).

Cement

The main ways in which energy usage and CO_2 emissions can be reduced in cement manufacturing are as follows:

- Phase out inefficient kilns and add pre-heaters and a pre-calciner to the efficient modern rotary kiln;
- Increase the ratio of clinker substitutes in order to decrease process emissions arising from calcination; and
- Introduce efficient milling and grinding equipment.

Figure 6b shows the energy intensity of the different kiln types in operation today. Current BAT is the dry rotary kiln with a six stage preheater and a pre-calciner. Most new cement kilns are BAT, however the lifetime of a cement plant can be up to 50 years and so capital stock turnover limits the rate at which these savings potentials can be realised.

As for steel, China makes up the largest share (41%) of total energy savings potential in the cement sector. China has made significant progress in closing down vertical shaft kilns. The share of vertical shaft kilns has decreased from 90% in 2000 to 40% in 2008[18]. Modern rotary kilns, some of them fitted with preheater and pre-calciner technologies, make up the remaining 60%. A recent study of the energy savings potential of 16 cement plants in the Shandong province showed that there is potential for primary energy savings of 12% and 23% compared to domestic and international best practices, respectively[18].

The production of clinker is the most energy intensive stage in cement manufacture. Additionally, large amounts of CO_2 are emitted owing to the calcination reaction. If less clinker is used per tonne of cement, significant savings in both energy and CO_2 emissions can be achieved. There are three main types of cement: Ordinary Portland Cement, Portland Cement blends and non-Portland Cements, with Ordinary Portland Cement being the most commonly used type, owing to its high compressive strength. Table 1 shows the typical composition of different cement types. Ordinary Portland Cement contains the highest percentage of clinker. Fly-ash (waste residues from coal-fired power stations), the non-combustible parts of the fuel, and slag (mineral waste from iron production from iron ore) from blast furnaces can be mixed with clinker to produce blended cements. This has the added advantage of avoiding the need for disposal of ash or slag waste. The global average clinker-to-cement ratio (this is the fraction of clinker in the cement) is 78%, however there is quite a wide spread depending on the location of manufacture.

Around 40% of electricity used in cement manufacture is used for grinding and milling[19]. Ball mills are the traditional method of grinding, accounting for around 60% of cement mills[19]. The remaining mills are made up of more modern mills, namely: vertical roller mills, roller presses and horizontal mills. These mills are more efficient and use between 30 and 40% less energy compared to the ball mill[19]. The choice of mill depends on the required grain size, clinker properties and final product quality.

The total specific energy savings available in the cement industry is estimated to be 1 GJ per tonne of cement.

Chemicals

Across the scope of varied chemical processes there are a number of ways in which to improve the energy efficiency of these processes. These can be generalised as follows:

- Adoption of best practice reactor designs and processes with best practice heat integration and energy recovery;
- Design of new catalysts to increase yield and selectivity of desired products; and
- Design and development of novel membrane separation technologies.

	Ordinary Portland Cement (%)	Portland fly-ash cement (%)	Blast-furnace cement (%)	Pozzolanic cement mixes (%)
Clinker	95–100	65–94	5–64	45–89
Fly-ash (waste residues from coal-fired power stations)	–	6–35	–	–
Blast furnace slag	–	–	36–95	–
Pozzolana (volcanic ash)	–	–	–	11–55
Other constituents (e.g. clinker dust, other mineral additives)	0–5	0–5	0–5	0–5

Table 1. Typical composition of different cement types[17]. Note percentages exclude gypsum which is typically 5%.

Of all the intermediates shown in Figure 4, olefin production consumes the greatest energy. World average energy intensity of the olefin production process (conventional steam cracking) is 22.5–24 GJ per tonne of product compared to state of the art (16–17 GJ per tonne of product)[17]. Some new biomass-based production processes produce ethylene from lignin, starches and sugars. Together with combined heat and power (CHP) these processes can generate energy in excess of the energy required to produce ethylene, making them net energy producers. This energy can be exported for use elsewhere. Continued research in catalysis can increase both product yield and selectivity, resulting in significant energy efficiency improvements. The development of new catalytic conversion routes, such as direct conversion of alkenes to petrochemicals without the intermediate ethylene, reduces the number of process operations and energy requirements[2].

Industry-wide energy efficient technologies

Industrial processes have a number of equipment and systems in common, such as steam systems, motor systems and opportunities for CHP, which offer a useful target for energy efficiency programmes.

Motor and steam systems

Driving motors and raising steam consumes a significant portion of energy in industrial processes. Around two thirds of electricity consumption in the industrial sector is used to drive motors[2,20]. Steam generation consumes 30% of global final industrial energy use[9]. Together, these systems account for 41% of total final energy consumed in industry. Globally, the energy savings potential of industrial motor and steam systems remains largely untapped. It is estimated that the worldwide efficiency of motor systems and steam systems can be improved by 20–25% and 10%, respectively[9]. In the US, the estimated total energy savings potential through applying BAT in motors and motor systems[20] is between 15–25%.

Motor systems comprise a number of components. Principally, there is the motor itself and the motor-driven equipment e.g. a pump, compressor or fan. The correct motor speed is of particular importance since the power consumption of the drive is approximately dependent on the cube of the motor rotation speed, i.e. small changes in motor speed can result in large energy savings. Adjustable speed drives (ASD) can be used to control the motor speed in response to changes in demand loads. Energy savings of 10–20% and, under certain conditions, even as high as 60% can be achieved through ASDs. Over-design of driven equipment, resulting in equipment operating below peak performance efficiency, is another major source of wasted energy. Additionally, improved maintenance practices are essential for reducing system losses. For example, leaks in compressed air systems can account for 20–30% of compressor output[20].

Similar improvement options exist in steam systems. These can be divided into energy efficiency measures for (i) boilers and (ii) heat distribution. The efficiency of steam boilers depends on the design and fuel. In China, for example, average boiler efficiency is 60–65%, largely due to poor quality coal and incomplete combustion (by comparision, a well-designed coal-fired boiler can achieve an efficiency of around 84%)[9].

Improvements	Measure	Fuel savings	Implementation Potential	Payback period (years)
Boilers	Improved process control	3%	59%	0.6
	Reducing flue gas quantities	2–5%	–	–
	Reducing excess air	1% per 15% less excess air	0%	–
	Improved insulation	6–26%	–	?
	Improved maintenance	10%	20%	0
	Heat recovery from flue gas	1%	100%	2
	Recovery of steam from blowdown	1.3%	41%	2.7
Distribution systems	Improved insulation	3–13%	100%	1.1
	Improved steam traps	Unknown	–	?
	Steam trap maintenance	10–15%	50%	0.5
	Automatic steam trap monitoring	5%	50%	1
	Leak repair	3–5%	12%	0.4
	Flash steam recovery/condensate return	83%	–	?
	Condensate return	10%	2%	1.1

Table 2. Summary of improvements to steam systems[21]

Table 2 summarises the potential measures for improving energy efficiency in steam systems. Measures such as improved insulation and steam trap maintenance can offer large energy savings and are easy to retrofit, relatively cost effective with estimated payback periods of less than 1.1 years (assuming a discount rate of 30%)[21]. It has been estimated that, in the USA in 2001, there existed cost effective improvements to steam systems which could provide annual energy savings of up to 1258 PJ per year[21]. This is equivalent to 7% of final energy consumption in US industry and would result in CO_2 emissions reductions of 45–48 Mt CO_2 per year (around 5% of current USA CO_2 emissions from industry). More recently, the IEA[9] gives a more conservative estimate of energy savings in the USA of around 500 PJ per year, possibly indicating that some opportunities for savings in steam systems have been realised.

The advantages of efficient motor and steam systems include: increased competitiveness and reduced consumption of fossil fuels[22] as well as improved system reliability and control, and reduced maintenance costs through reduced wear. One reason these apparently obvious potentials remain unrealised is that achieving these energy savings requires a system-wide approach, which optimises the process as a whole; this is often difficult in large organisations. High efficiencies have been reached for individual components such as motors (85–96%) and boilers (80–85%) but the efficiency of the overall system is often much lower. Essential to improving overall efficiency is designing a system where supply and demand are properly matched. Highly efficient pumping of fluids, compression of air and generation of steam is wasted if these are in excess of the plant requirements. Often this requires hiring an expert to analyse and optimise the overall system. Losses occur at every stage in the process, however with careful design and management these can be minimised. In particular, proper operation and maintenance procedures must be established.

Combined heat and power

Thermal generation of electricity always results in the production of some waste heat. Depending on the efficiency of the plant, between 40% and 80% of the energy generated in power plants is dissipated in the form of hot air or water. Instead of wasting this energy, the heat can be used to raise steam for industrial processes or hot water for district heating, depending on the temperature. This simultaneous production of heat and power (electricity) is known as Combined Heat and Power (CHP), sometimes also referred to as 'co-generation'. Most combustion-based power generation technologies, as well as Concentrated Solar Power processes and biomass combustion, can form part of a CHP system[23]. Flexibility, cost, scale and the type of heat required are the typical factors defining which technology to use. Steam turbines and gas turbines are typically large scale and can produce high temperature steam but they are inflexible. Piston engines and micro-turbines by comparison are smaller scale and flexible but produce low-medium temperature steam[23]. In terms of fuel efficiency, CHP is always an improvement on conventional power generation. Energy savings of at least 10%, and typically higher are achievable[23]. CHP can reach overall efficiencies in excess of 80%[24]. This decreased energy intensity has significant advantages beyond CO_2 emissions reduction: reduced fuel usage can have cost savings of between 15–40% compared to grid-sourced electricity and heat generated by onsite boilers[25]. This translates into improved competitiveness for industry and businesses, alleviates fuel poverty and lowers the cost of delivery of public services. In addition, reduced demand from centralised power stations decreases the stress on the grid.

The idea behind CHP is not a new one. The technology is proven and reliable and has an established supplier base. It is also versatile and can be applied to a wide range of industries. In some countries, such as Finland, CHP is used widely, with 90% of urban buildings linked to a district heating system and 38% of the country's electricity generated in CHP plants. CHP has penetrated certain industries more than others. The Chemicals and Petrochemicals industry and the Pulp and Paper industry are particularly well suited to CHP, and together account for 20–40% of industrial CHP capacity. The estimated mitigation potential of CHP in industry is 150 Mt CO_2 in the USA and 334 Mt CO_2 in Europe[7]. However, although the benefits of CHP are widely recognised, the global implementation of CHP is still low. This is largely due to the fact that a suitable use for the generated heat needs to be found within reasonable proximity to the power generation plant; for example, to date the longest district heating pipeline exists in Sweden and is 28 km[26]. In addition, the current preference for large central power stations to generate electricity means that there is often no easy local use for waste heat energy.

Owing to the increased complexity of the process, the capital cost of a CHP plant is higher than a conventional power plant[27]. In drawing up CHP projects, there are often regulatory requirements which increase the commercial and operational complexity. Typically, a long-term heat and power contract is required with the host site, which often means that there is an increased risk of deal collapse. Once the project is in progress, there is also the risk that the heat user goes out of business leaving the CHP plant without a buyer for the heat. In general, lack of awareness of the opportunities and insufficient training on how to implement them hinder the penetration of CHP technologies. A system-wide perspective on the development of CHP plants is often lacking.

Fuel switching

Fuel switching includes the following:

- Switching to less carbon intensive fuels such as replacing coal with natural gas;
- Co-firing with, or switching to waste and biomass;
- Switching to decarbonised electricity; and
- Switching to hydrogen (provided the hydrogen is produced via a low CO_2 process, for example using decarbonised electricity to electrolyse water).

Switching to less carbon intensive fuels. Of the fossil fuels, coal has the highest emissions factor relative to its available energy: 96 kg CO_2e per GJ. The emissions factor of natural gas by comparison is just over half that of coal: 51 kg CO_2e per GJ. Thus replacing coal with natural gas can significantly reduce emissions. This does, however, depend on the gas source and method of production. One recent lifecycle study indicated that the CO_2 intensity of shale gas 'fracking' is higher than for conventional gas and possibly even higher than that of oil and coal. This is owing to fugitive emissions of methane released during the shale fracturing process[28]. However this does not take into account the higher efficiency of gas-fired power generation (combined cycle) compared to a typical coal-fired plant. When this is considered, another study found that the greenhouse gas footprint of shale gas may be similar to that of coal over a 20 year timeframe and between 0.61 – 0.88 of that of coal over a 100 year timeframe[29]. A subsequent Briefing Paper will assess the mitigation implications of shale gas.

In the iron and steel process, CO_2 emissions can be reduced through the direct reduced iron process, which uses natural gas or coal as a fuel, thus eliminating the need for coke production. This process has the added advantage that it is well suited to include CCS, as will be explained in the section below. In the conventional blast furnace process, coal is increasingly being injected into the furnace to reduce coke requirements. The coal injection rate is limited by the quality of the coke. The current world average is 125 kg per tonne hot metal, however a maximum injection rate of 160 kg per tonne hot metal has been achieved under certain conditions. China and South Korea are leading in coal injection whilst Russia and the USA are currently lagging behind.

The steam reforming process for ammonia production is usually gas-based, however both coal and oil can be used as raw materials; such plants are based predominantly in India and China and are much more energy intensive. The final energy requirement for coal- and oil-based ammonia production is 50% and 30% higher, respectively, compared to the natural gas-based process. Switching from coal or oil to gas can make significant energy and emissions savings. Similarly, oil is the conventional raw material for the steam cracking process for olefin production; researchers are investigating an alternative process based on natural gas[14].

Co-firing with, or switching to waste and biomass. Switching to biomass can offer further emissions savings; biomass is considered carbon neutral under the European Emissions Trading Scheme (ETS), i.e. it has a net emission factor of zero (whether or not biomass is carbon neutral depends on its production and transportation). The transition from fossil fuels to waste and biomass is not a simple switch. Careful consideration must be given to the properties of the substitute fuel. The high content of alkali metals, typically found in biomass ash, can pose problems at high temperature resulting in agglomeration and fusing of the solid material. Waste fuels such as municipal solid waste often contain high concentrations of heavy metals such as mercury and lead. In the EU, the regulations for the combustion of waste are set out in the Incineration of Waste Directive[30]. Of course, the use of a waste fuel in one context eliminates its potential for use in another – it may be that some wastes would be better used to produce liquid fuels via pyrolysis or potentially gasified; these are regulated to ensure the safe combustion of waste.

Cement kilns are particularly suited to the incineration of waste; the high incineration temperature, alkaline environment, residence time and good mixing of gases and products ensure that the waste is safely disposed of with minimal environmental impact. Since the 1990s, various waste fuels such as waste tyres, plastic/fibres in municipal solid waste, chemical waste, waste pallets, demolition wood and wood waste, and sewage sludge[8] have been co-fired in cement kilns. In 1990, fuel substitution in cement kilns was around 3% in EU countries, equivalent to 1.7 Mt CO_2 avoided. This increased to around 17% in 2004, or 9.7 Mt CO_2 avoided[31]. There is still a large potential for waste co-firing in China, where currently very little waste fuel is burned in cement kilns. Since the energy costs account for around a third of cement production, substituting expensive fossil fuels with wastes has the added advantage of reducing the cost of cement production. Japan has increased its use of waste plastic in the iron and steel industry from 0.46 Mt in 2005 to 1 Mt in 2010. Germany and Austria also make use of their waste plastics[8].

In Brazil, charcoal is used in small-scale blast furnaces instead of coke. World charcoal production in 2009 was around 45 Mt per year. Charcoal is mechanically unstable compared to coke[8]. The disadvantage of replacing fossil fuels with biomass fuels such as charcoal is that they can compete with the agricultural sector for food production (although this can be addressed, at least in part, by using only agricultural residues and certain crops which do not compete). Additionally, converting virgin rainforest into arable land releases large amounts of CO_2 and also reduces biodiversity.

Switching to decarbonised electricity or hydrogen. With increased use of electric arc furnaces in the iron and steel sector, a shift from diesel motors to electric ones and increased instrumentation and controls, the share of electricity making up the industrial fuel mix has increased from about 14% in the 1970s to roughly 25% today[3]. The current process routes in most industrial sectors give limited options for increased electrification of industry. For example, steel manufacturing in an electric arc furnace is limited by the availability of cheap electricity and the supply of steel scrap. Research is currently underway to develop a method of primary iron production using electrolysis; however, at present the energy requirement is extremely high. In the future, a process that uses hydrogen as a reducing agent in the blast furnace could also be envisaged[32], provided the hydrogen is produced using a low-CO_2 method. Hydrogen can also be used to directly reduce steel. Reduction can take place in direct reduction reactors or more advanced flash reactors.

Resource Efficiency

Waste reduction	Reduced waste during processing, directly reduces material requirements
Recycling	Increased recycling reduces depletion of natural reserves and decreases energy consumption
Leaner production	Reduced material inputs through the design of lighter leaner products without compromising on quality
Material/product substitution	Substitution of highly carbon intensive materials with low carbon intensive materials
Strategies for sustainable building	Improving construction efficiency through modern methods
Industrial synergies	One company's waste can be a valuable raw material or energy source for another

Resource Sufficiency

Extended product lifetime	Products should be designed to last and be routinely maintained
Efficient use of existing infrastructure	Reduce demand for construction materials through retrofit rather than new build
Shift from goods to services	Reduce requirement of individual ownership, instead needs can be met by the service industry and government
Lifetime optimisation	Change consumer behaviour such that products are used for their full lifetime
Public sector procurement	Government should lead the way in sustainable procurement

Figure 7. Summary of lifecycle strategies for reducing emissions in the manufacturing industry. Adapted from the WRAP report on 'Meeting the UK climate change challenge: The contribution of resource efficiency'.

Lifecycle and systems approach

Whilst the above sections highlight a wide range of available technologies for reducing emissions from industry, approaching 'zero-carbon production' is difficult, if not impossible without taking a lifecycle and system-based approach to production and consumption in industry. The Waste and Resources Action Programme (WRAP) highlights 'resource efficiency' and 'resource sufficiency' as two complementary approaches for achieving sustainable manufacturing; Figure 7 summarises these strategies. Resource efficiency means producing a product with the same functionality, whilst minimising the resource inputs and environmental impact over the lifecycle of the product. Resource sufficiency involves reducing the demand for the product. These two approaches and their application to industry are discussed in turn below.

Resource efficiency in industry

Recycling of products such as metals, plastics and paper can offer significant energy savings. The level of recycling, which can be achieved depends on the lifecycle of the product and material flows. Once manufactured, steel and aluminium can take around 100 years before becoming available as scrap. This is particularly relevant for developing countries, which are still building up their infrastructure and have not reached a steady state of material flow. Currently, the EU is increasingly exporting significant amounts of scrap to China and other Asian countries. This has arisen due to strict EU environmental and health rules making waste disposal and recycling expensive, combined with cheap transport (container ships might otherwise return empty to China) and high demand in China. The UK government funded research programme, WellMet2050[33], is suggesting going one step further and encourages 'reuse without melting' of scrap rather than recycling. Although the production of aluminium and steel from recycled scrap is much less energy intensive compared to production from ore (around 40% less for the case of steel and 20 times lower for that of aluminium), the high melting temperatures of these metals mean that recycling is still an energy intensive process (around 10 GJ/t). By comparison, reusing metals without melting them has negligible energy requirements. Three sources of metal that offer immediate savings of 2 Mt CO_2 in the UK with minimal investment costs are the reuse of (i) structural steel in construction, (ii) manufacturing scrap (leftovers and offcuts) and (iii) aluminium swarfs (shavings and chippings of metal resulting from cutting, grinding and milling) bonded together at low temperature.

The Worldsteel Association[34] is actively promoting 'designing for purpose', such as the use of advanced and ultra high-strength steels in the manufacture of cars and trains. In doing so, automotive manufacturers can reduce the mass of the vehicle by 17–25%, while maintaining safety standards. This means reduced steel requirements and hence reduced emissions from steel production. In addition, the lighter vehicle requires less fuel. If all vehicles worldwide (approximately 71 million produced in 2008 alone) were made of high-strength steels this would result in total lifetime emission saving of 156 Mt CO_2e[35]. Many energy intensive construction materials will play a key role in a low carbon future through their role in building renewables. Around 45 t of cement and 120 t of steel is required per MW of onshore wind power[17]. This increases the urgency for reducing the emissions intensity of these materials. Wind turbines built from high emissions intensive cement and steel take around 6 to 8 months of operation before they 'cancel out' the CO_2 embodied in their manufacture[36].

In many applications, conventional materials can be replaced with alternative low-carbon or renewable materials such as biomass. In the construction industry, wood is a strong and versatile material for replacing conventional materials such as cement and steel. There is a rising trend of using straw as an insulating material in buildings. In many cases, plastic packaging can be replaced with paper or card. The bio-plastics industry has grown rapidly in recent years[37], increasing by around 40% per year to 0.36 Mt in 2007. This is still only 0.2% of global petrochemical plastics production. It is estimated that the technical potential for substitution (considering application only and not resource availability or economics) is around 240 Mt or 90% of global consumption of plastics and fibres in 2007[37]. However, for bio-plastics production to reach these levels, challenges such as high production costs and low performance need to be overcome. Furthermore, as with biofuels, biomass sources must be carefully selected to avoid competing with agricultural land for food production.

A number of synergies between industries exist. One tonne of steel produces between 200 kg (EAF route) and 400 kg (BF/BOF route) of by-products. These slags, dusts and sludges contain a mixture of silica and oxides of calcium, magnesium, aluminium and iron. Over recent years, the usefulness of these supposed waste streams has been identified and a large percentage is recovered and used either within the steelmaking process or sold to other industries. The uses of these by-products include as a construction aggregate, concrete products, clinker raw material, road bases and surfaces and roofing. Use of waste materials in connection with Carbon Capture and Storage is also possible; for example, Carbon8 Systems has developed an accelerated carbonation process to sequester CO_2 and at the same time treat hazardous wastes such as slags and contaminated soils[38]. A novel synergy between the cement industry and power plants with CCS using solid sorbents will be discussed in detail below. High electricity users such as steel EAFs and aluminium smelters might also play a role in dealing with intermittency from renewable power generation. Provided that these plants are sufficiently flexible, they could be run when there is excess supply from renewable generation sources and powered down during supply shortages.

Resource sufficiency in industry

In the long-term, continued consumption of manufactured goods at current rates raises serious sustainability concerns. In addition to CO_2 emissions, industrial activity places strain on the environment through extraction of natural ores, disposal of wastes and consumption of other precious natural resources such as water. Resource sufficiency aims to reduce consumption of manufactured goods through various means, such as: designing products to last, ensuring products are used for their full lifetime, encouraging the hire of equipment rather than private ownership and making best use of existing infrastructure. Achieving the goals of resource sufficiency is likely to require a major shift in industry structure and focus, as well as in consumer behaviour. There are still huge uncertainties as to how a resource sufficient world would operate and how to reach this goal.

Summary of the abatement potential

The IEA has performed a comprehensive study of the potential gains from the adoption of best available technologies and best practice within the different industrial sectors. In doing this study, the IEA has found that the energy intensity of most industrial processes is at least 50% higher than the theoretical minimum[39]. In reality, achieving the theoretical minimum is impossible. However, there is still significant potential for improvement in most processes, as summarised in Table 3.

Potential savings are grouped into (i) sectoral improvements, which are process specific and (ii) system/lifecycle improvements and crosscutting technologies, which include system optimisation and technologies which apply to all sectors. There is a significant overlap between sectoral improvements and system improvements. In order to account for this the IEA has made adjustments (see notes below table for details), which result in a conservative estimate of the industrial savings potential.

Taking sectoral and system/lifecycle improvements together, the total annual energy savings potential in the industrial sector is between 25–37 EJ. This amounts to savings of 1.9–3.2 Gt per year of CO_2, equivalent to 7.4–12.4% of total global annual CO_2 emissions in 2004. Improvements to motor systems offer the largest potential energy savings (6–8 EJ per year). Process specific improvements in the chemicals and petrochemicals sector offer the next highest primary energy savings of between 5–6.5 EJ per year. Changes specific to the cement sector offer the largest potential reductions in CO_2 emissions. It is important to note that Table 3 represents the technical potential rather than what is currently economically feasible at a regional level. The adoption of Best Available Technology (BAT) and Best Practice Technology (BPT), is strongly dependent on the economic attractiveness of the technology. This is based on the capital cost of the technology, relative energy costs and current regulations[8]. In addition, the availability and quality of raw materials, the age profile of the current capital stock and ease of retrofitability can create technical barriers.

A key step in the implementation of best practice technologies on a global scale is the transfer of expertise and knowledge between countries, often referred to as technology transfer. In modern steel plants, for example, advanced technology has allowed manufacturers to operate close to the theoretical limits of efficiency. However, particularly in developing countries, there are still a large number of plants operating well below these limits. The Industrial Energy-related Technologies and Systems Programme[40] is an IEA initiative with the goal of cultivating international co-operation between both OECD and non-OECD countries. The IEA recommends that all new plants should be at BAT between 2006 and 2020[8].

	Total primary energy and CO_2 emissions (direct and indirect)		Low – High Estimates of Technical Savings Potential (Primary energy, excludes overlap)	
	EJ per year	**Mt CO_2 per year**	**EJ per year**	**Mt CO_2 per year**
Sectoral improvements*			11.9–16.9	
Chemicals/petrochemicals	33.8	1500	5.0–6.5	370–470
Iron and steel	25.3	2211	2.3–4.5	220–360
Cement	10.1	2000	2.5–3.0	480–520
Pulp and paper[f]	6.9	400	1.3–1.5	52–105
Aluminium[f]	4.1	375	0.3–0.4	20–30
Other (Non-metallic min. and non-ferrous)	59.7	3514	0.5–1.0	40–70
System/life cycle improvements and cross cutting technologies[†]			13.5–20.8	
Motor systems			6–8	340–750
Combined heat and power			2–3	110–170
Steam systems			1.5–2.5	110–180
Process integration			1–2.5	70–180
Increased recycling			1.5–2.5	80–210
Energy recovery			1.5–2.3	80–190
Total	140	10000	25–37	1900–3200
Share of industrial energy use and emissions			18–26%	19–32%
Share of total energy use and emissions[‡]			5.4–8.0%	7.4–12.4%

Table 3. Savings from adoption of BAT and BPT. Data Source: IEA analysis[9].

Savings data are compared to reference year 2004. Primary energy savings are given, which include both the energy used at the production facility and the energy used to produce the electricity consumed at the facility as well as the efficiency losses and transmission and distribution losses. * Sectoral primary savings exclude recycling and energy recovery. ƒ Primary energy columns exclude CHP and electricity savings for chemicals and petrochemicals. Primary energy columns exclude CHP for pulp and paper. † Only 50% of the estimated potential system/life cycle improvments have been credited except for motor systems. ‡ The total energy use and emissions includes only energy and process CO_2 emissions; deforestation is excluded from total CO_2 emissions.

Carbon capture and storage (CCS)

The previous section highlights that the adoption of best available and best practice technologies and efficiency measures alone are not sufficient to reach the ambitious targets necessary to avoid dangerous climate change. Beyond these measures, CCS is an essential option for achieving large impact reductions in emissions where very limited alternatives exist. In the cement sector for example, 50% of CO_2 emissions arise from calcination of limestone. Capturing the CO_2 and sequestering it is the only option for avoiding these CO_2 emissions to atmosphere. A detailed description of capture and storage technologies can be found in previous Grantham Institute Briefing Papers number 3 and 4, respectively, and so the discussion here will only cover matters relevant to the specific application of CCS to industrial processes.

To date, the focus of CCS research has been on CO_2 capture from power plants and little attention has been given to its application in the industrial sector. However, industrial emissions, largely from iron and steel, cement and refineries, make up a significant portion of those CO_2 emissions, which can be addressed by CCS. In the EU alone, around 25% of emissions which are addressable by CCS are from industrial sources. This amounts to 0.5 Gt of CO_2, based on 2007 figures[41].

Table 4 compares the properties of large emitters of CO_2 in both the industrial and power generation sectors. Industry provides some unique opportunities for the early demonstration of CCS. These include:

1) Separation of CO_2 is a routine process in some industries. Examples of such processes include the production of hydrogen, ethylene, ethanol and ammonia, natural gas processing and coal-to-liquids. These processes typically

Source	Average emissions/source (Mt of CO_2 per source)	Number of sources in 2005	CO_2 concentration of the stream for capture (dry volume %)
Power station flue and fuel gas			
– Natural gas fired boilers	1.01	743	7–10
– Gas turbines	0.77	985	3–4
– Oil fired boilers			11–13
– Coal fired boilers	3.94	2025	12–14
– IGCC: after combustion			8 – 20
– IGCC: synthesis gas after gasification			12–14
Upstream processes – Natural gas sweetening	NA	NA	2–65
Chemical and petrochemical			
– Refineries	1.25	638	3–13
– Ammonia	0.58	194	18
– Hydrogen			15–20
– Methanol			12
– Ethylene oxide	0.15	17	8
Iron and steel			
– Blast furnace gas before combustion	3.5	180	20
– Blast furnace gas after combustion			27
Cement			
– Cement kiln exhaust gas (using air)	0.79	1175	14–33
– Cement kiln exhaust gas with oxyfuel			more than 80

Table 4. Properties of candidate gas streams for application of capture technologies. Comparison of industry and power sources, demonstrating the transferability of CCS technology developed for the power sector to industry. Data sourced from from the IEA, IPCC and the ECRA [17,42,43].

produce streams with a high concentration (30–100%) of CO_2, lowering the cost of separation to about half that of capture from a power plant. Although the emissions from these processes make up a small share of total emissions from industry, due to lower costs, these processes could play an important role in the early demonstration of CCS technology.

2) Industrial sites are some of the largest stationary sources of CO_2 emissions in the world. This results in improved economies of scale for CO_2 capture. Large steel plants can consist of up to five blast furnaces each with a production capacity of 3 Mt of steel per year and each emitting around 3.5 Mt CO_2 per year, a total of 17.5 Mt CO_2 per year. This compares to a 500 MW coal-fired power plant, which emits around 3.8 Mt CO_2 per year.

According to the IEA, CCS will make up 33% of emissions reduction in industry by 2050. More than 80% of the CO_2 captured will be from iron and steel and cement. The remaining will be from chemical and petrochemical processes, mostly from refineries and ammonia production, and the pulp and paper industry. Continued research in CO_2 capture processes from industrial sources will be essential to meet this target. The specifics of the capture technologies depend on the industrial process and the properties of the candidate gas streams. Box 4 discusses the current research into different capture technologies for specific industrial processes.

The Cement Sustainability Initiative recommended in 2009 that there should be demonstrations of CCS applied to cement kilns by 2015 and that by 2050, 50% of all new cement kilns should be equipped with CCS[45]. Table 5 shows the current and proposed demonstration projects for industrial CCS.

Box 4: Capture technologies from iron and steel and cement

Research in the area of CCS from iron and steel production is being carried out by the Ultra-Low CO_2 Steel (ULCOS) research programme[32]. A number of alternative iron and steel production processes, which enable the capture of CO_2, are currently under investigation.

The gas exiting a conventional blast furnace (BF) contains around 20% CO_2, 21% carbon monoxide (CO) and the balance nitrogen (N_2) and hydrogen (H_2) and some water (H_2O). The CO_2 concentration can be doubled by using the so-called 'shift reaction' to convert CO and H_2O to CO_2 and H_2. This allows physical solvents, already developed for pre-combustion capture in the power sector, to become technically feasible. Alternatively, oxygen, rather than air, can be injected into the BF. The gas exiting the BF would be nitrogen free and the CO_2 can be separated more easily. The remaining CO and H_2 are recycled and injected at the bottom of the blast furnace, where they act as reducing agents. This technology is known as Top Gas Recycling (TGR) and has the additional benefit of reducing the coke requirements of the BF. Natural gas-based DRI can also be modified to include CO_2 capture. Prior to entering the DRI reactor, natural gas enriched with H_2 from the CO_2 capture process, is partially oxidised to synthesis gas (CO and H_2) by reacting it with oxygen. This reducing gas is then fed to the DRI reactor. The gas exiting the DRI reactor contains a mixture of CO_2, CO and H_2 and H_2O. As with TGR, the CO_2 concentration is increased via the shift reaction and the CO_2 can then be separated using solvents.

The European Cement Research Academy is currently conducting research on the application of CCS technology to the cement industry. Additionally, CEMEX was a partner in the EU-funded C3-Capture project and was working together with academics to further develop this process. The company has US DOE funding for a calcium-looping pilot plant in Monterrey to investigate the economical and technological feasibility of this process[44].

Post combustion capture of CO_2 from the cement industry uses the same technologies as those in the power sector and can easily be retrofitted to existing plants, albeit at high cost. Oxy-combustion is a highly promising capture technique for the cement industry. However, oxy-combustion results in increased kiln temperatures, which can damage the kiln lining. This can be avoided by dilution with recycled CO_2; the effects on the chemistry of the process need to be investigated. The prevention of air intrusion is another difficulty, which must be overcome. A promising alternative to organic solvents for post combustion capture is the use of calcium oxide as a solid CO_2 sorbent. Flue gas from a cement kiln is reacted with calcium oxide (CaO) to produce calcium carbonate ($CaCO_3$) at around 680°C. In a second reactor, the calcium carbonate is calcined at around 900°C, producing a pure stream of CO_2 for sequestration. The resulting calcium oxide is recycled back to the first reactor. The overall efficiency penalty of this process is lower than for conventional post combustion capture using amines. Additionally, there is a unique synergy with cement manufacture: the spent CaO from the capture plant can be used to make cement clinker, reducing the need for limestone calcination and saving around 50% of the emissions of cement manufacture by this substitution alone.

Cost of abatement in industry

A useful metric for comparing the abatement potential of different technologies and assessing their cost-effectiveness is the marginal abatement cost curve (MACC). McKinsey defines the marginal abatement cost as the 'annualised cost of different abatement measures in a given year per tonne of carbon dioxide saved compared with the business-as-usual technology'[47].

A MACC for the iron and steel, cement and chemicals sectors in 2030 is shown in Appendix 1; a discount rate of 7% was assumed[47]. Around 360 Mt CO_2e per year can be abated in the iron and steel sector at a negative overall cost. These economically attractive savings are provided through co-generation and coke substitution. In the cement sector around 760 Mt CO_2e per year has a negative overall cost. Clinker substitution offers the greatest emissions savings and is the most economically attractive.

The introduction of efficient motor systems and CHP and switching from oil to gas could abate around 600 Mt CO_2e of emissions from the chemicals sector at negative cost.

At the high end of the MACC is carbon capture and storage. Appendix 2 compares the cost of different capture processes across different industries. MAC curves are highly country specific and depend on the discount rate assumed. Bloomberg New Energy Finance[48] and AEA consultancy[49] have studied the cost of abatement from heavy industry in the EU and UK, respectively. There are some marked differences between these studies and the McKinsey's global study[47].

For example, AEA claims that cement fuel switching will be very expensive: 150 £/tCO_2e (172 €/tCO_2e) compared to -8 to 2 €/tCO_2e (McKinsey) and 2 €/tCO_2e (Bloomberg). Bloomberg's abatement cost curves use a higher discount rate. The level of discount rate chosen by firms for judging investment options is therefore likely to be a major determinant in the adoption or otherwise of abatement/energy efficiency technologies.

Industry	Company	Technology	Specs	Year	Location
Iron and steel	LKAB	Top gas recycling	Pilot plant	2007	Lulea, Sweden
Iron and steel	ArcelorMittal	Top gas recycling Top gas recycling with CCS	Demonstration	2010 2015	Eisenhuttenstadt, Germany Florange, France
Refinery	Shell	Pre-combustion	Pilot project (0.4 Mt CO_2 per year)	2012	Barendrecht, Netherlands
Urea ammonium nitrate	Coffeyville Resources	CCS (Pet coke gasification)	0.6 Mt CO_2 per year	Proposed	Kansas, USA
Fertilisers	Enid Fertilizer	Pre-combustion	CO_2 will be used for EOR	2003	USA
Ethanol	Archer Daniel Midland Co.	Amine post combustion capture	1 Mt CO_2 per year. Storage in a saline aquifer	2012	Illinois, USA
Steam-methane reformers	Air products and chemicals, Inc.	Sorption enhanced Water gas shift (pre-combustion	1 Mt CO_2 per year. CO_2 will be used for EOR	2012	Port Arthur, Texas
Methanol	Leucadia Energy, LLC	Rectisol (Pre-combustion)	4.5 Mt CO_2 per year to be used for EOR	2014	Lake Charles, La.

Table 5. Industrial CCS demonstration projects proposed or in operation[46]

In addition, for any future year it is debatable how much abatement potential will be taken up as a matter of business-as-usual, particularly if it is cost-saving.

Roadmap and research agenda for industry

A simplified roadmap is provided in Figure 8, showing the key actions that need to be taken in the industrial sector over the coming decades. An indication of the abatement potential, cost, time frame of implementation and barriers for each action is given. Even where the implementation timeframe is long term, action is required in the short term to ensure that technologies are commercially deployable at a later date.

The mitigation actions range from those that are (i) already widely used in certain sectors or (ii) commercially viable but not yet widely applied, to (iii) those that are as yet unproven. Depending on the current state of the technology, different policy instruments and research are required. Based on the roadmap, the sections below outline the research agenda for the industrial sector in order to improve our knowledge of different technologies, identify methods for overcoming barriers and reliably inform policy decisions.

Benchmarking and measurement studies. Access to high quality and detailed data on energy and materials flows in industrial processes is still limited, particularly for developing countries, which often lack the resources for such activities. In addition, antitrust laws prevent the sharing of data, which could result in uncompetitive activities such as price-fixing. Industrial membership organisations can play an important role in overcoming these confidentiality issues in order to build reliable, accurate and current databases, which would provide a solid baseline for setting emissions benchmarks. Details of some industrial institutions are given in Box 5. Furthermore, currently, individual countries and companies are responsible for their own statistics and hence there is a wide variation in metering methodologies. Global standards need to be set in order to ensure consistency across the data.

Identifying and overcoming barriers to uptake of energy efficient technologies. Despite their obvious benefits, energy efficient technologies continue to be overlooked. More research needs to be carried out in order to better understand why this is. The barriers to uptake should be clearly identified as well as trials carried out to test approaches to overcome these barriers.

New low-carbon processes. Many of the best available technologies for current industrial processes described earlier in this paper are approaching efficiency limitations prescribed by the laws of thermodynamics. Beyond this point, significant further improvements in energy efficiency are not possible with current processes. New radical production processes must be developed in order to achieve the required large CO_2 reductions[55]. CCS is one possible advanced technology; the current research in CCS for industrial processes has been described in detail earlier in this paper. The urgent need to demonstrate CCS at a commercial scale in order to minimise

Action	Abatement potential	Cost	Time frame of implementation	Barriers
Measurement and benchmarking	Low	Low (0 – 50 \$/tCO_2)	Short (now–2020)	• Requires international co-operation to ensure consistency • Confidentiality laws • Can be resource intensive
Adoption of cost-effective energy efficiency options	Low–medium	Neg. – low (neg. – 50 \$/tCO_2)	Short–medium (2020–30)	• Management and operational barriers • Lack of awareness
Adoption of BAT	Medium–high	Medium (50 – 100 \$/tCO_2)	Medium–long (2030–50)	• Slow capital turnover • Relative energy costs and current regulations may reduce economic attractiveness • Depends on ease of retrofittability
Novel low carbon processes (other than CCS)	High	Medium–high (50 – >100 \$/tCO_2)	Medium–long (2030–50)	• Unproven technologies
CCS	High	High (> 100 \$/tCO_2)	Medium–long (2030–50)	• Expensive • Complex integration of different technologies
Resource efficiency measures	Low–high	Low–high (0 – >100 \$/tCO_2)	Medium–long (2030–50)	• Requires systems-based approach with many players
Resource sufficiency measures	Low–high	Low–high (0 – >100 \$/tCO_2)	Long (beyond 2050)	• Requires restructuring of economy and drivers • Requires major shift in consumer behaviour and societal values

Figure 8. Summary of abatement potential, cost and time line of key mitigation actions in the industrial sector

risks associated with scale-up and cost uncertainties, cannot be stressed enough.

There are a number of other options besides CCS, which should also be investigated. For example, advanced smelt reduction technologies are being investigated by ULCOS. In smelt reduction reactors, iron ore reduction takes place in a molten iron bath. This has the advantage that low quality coal and other fuels can be used instead of coke since mechanical stability is not an issue. The coal is typically preheated just prior to entering the reactor, which avoids cooling and reheating inefficiencies associated with coke produced in a coke oven. Powdered iron ore can be used, eliminating the need for raw material preparation and the iron ore is pre-reduced in order to improve efficiencies. Smelt reduction has the further advantage that CCS can be easily integrated. Currently, smelt reduction is in the demonstration phase and up scaling projects are planned.

Researchers are investigating electrolysis as a method of primary iron production using electricity. This process is attractive from an environmental point of view since no direct CO_2 emissions are generated. The electrolyte can either be a water-based solution such as sodium hydroxide solution or molten iron oxide itself. In this process, iron ore (Fe_2O_3) is

Box 5. Industrial institutions committed to benchmarking and reducing CO_2 emissions

In the cement industry, the Cement Sustainability Initiative (CSI) has set up the ‘Getting the Numbers Right’ system[53] to collect CO_2 emissions and energy usage data within the industry. A total of 23 members, operating in more than 100 countries are contributing to the database, which requires independent assurance of the submitted statistics. This covers 40% of global cement production. The majority of production in the EU, North America, Latin America and India is covered, as well as around 20% of Chinese production. In April 2008, the World Steel Association launched a project to collect CO_2 emissions data for all steel plants. To begin with, Worldsteel aims to collect data from 400 steel plants. This accounts for 50% of the steel production of Worldsteel members. The International Aluminium Institute carries out an annual assessment of the energy consumption in 70% of the world’s primary production facilities in order to provide a benchmark for best practices[54]. The International Council of Forest and Paper Associations has developed a CO_2 calculation tool to standardise emissions reporting in the pulp and paper industry.

broken down into iron and oxygen ions which collect at the cathode and anode respectively. Currently, no suitable anode material exists and the energy required is prohibitively high[17].

A long-term possibility for the cement industry is that of so-called 'low-carbon cements'. These cements are typically based on alternative inorganic minerals to calcium carbonate-based limestone, which is used in the traditional Portland Cement manufacturing process. Although these cements are purported to have similar properties to Portland Cement, these products are still in the development phase and there are still many questions that must be answered before they are likely to gain acceptance in the wider construction industry, which will require satisfactory demonstration of performance in order to meet stringent building standards and codes of practice. In particular, the economic viability and long term stability of these products must be established. It may be that they will first find a role in non-structural applications such as paving.

Analysis of material flows in order to meet the goals of resource efficiency and sufficiency. Closing the material loop in order to reach the ultimate goal of sustainable materials usage is a complex problem and one which requires integration across supply chains, manufacturing sectors and geographical locations. Systems research into material flows, combined with investigation into the barriers to recycling and reuse, could assist in policy-making in this area and encourage industrial synergies.

Policies to unlock the industrial mitigation potential

As already discussed, several technology options at a range of costs exist to mitigate CO_2 emissions from the iron and steel, cement and chemicals industries. Moreover, these energy- and carbon-intensive industries are likely to face increased costs as a result of taking up some of the available mitigation technologies (although measures such as certain energy efficiency improvements can be cost-reducing), and their products are in general traded in globally competitive markets, so increased production costs in one region compared to others with less stringent mitigation policies could have unfavourable competitiveness impacts. Together these considerations mean that careful policy planning and implementation are required in order to realise these industries' mitigation potential whilst avoiding adverse economic impacts. Industry mitigation policies fall into four key categories:

- Establishing energy and emissions monitoring systems;
- Overcoming barriers to the take-up of cost-saving energy efficiency measures;
- Incentivising the uptake of fuel-switching and lower-cost abatement measures through carbon pricing, subsidies or other economic instruments;
- Supporting Research, Development and Demonstration efforts to establish new, pre-commercial mitigation technologies.

Industrial energy and emissions monitoring

A policy priority in many countries is to establish a robust basis for monitoring industry energy consumption and emissions (both in absolute terms and per unit product). Many developed countries already have detailed industrial energy consumption statistics as part of their greenhouse gas monitoring and policy frameworks, for example the UK's Digest of UK Energy Statistics (DUKES), whilst many developing countries are working towards improved monitoring. For example India's new Perform, Achieve and Trade (PAT) energy efficiency scheme for energy-intensive industry requires detailed energy audits of included installations[56]. In addition, international initiatives exist to implement better energy and emissions reporting, as discussed in the roadmap section of this paper. Such initiatives are an important component for informing policy makers of current energy and emissions data and establishing benchmarks for the best practice standards against which industries can aim to improve their efficiency.

Energy efficiency policies

In all world regions, energy efficiency in manufacturing industries has improved over recent decades, driven largely by the improved economics of more efficient technologies as new plants have replaced old ones, and as plants have increased in size (which often improves efficiency)[9].

Nevertheless, a range of policies have been implemented with the aim of accelerating such efficiency improvements.

For example in the UK the Climate Change Levy (CCL) was introduced in 2001, as a tax on energy use by businesses. Energy-intensive industries covered by the CCL (including iron and steel, cement and chemicals manufacturers) are eligible for entering into Climate Change Agreements (CCAs), whereby they agree with Government two-yearly targets for improving their energy efficiency or lowering their carbon emissions – if they meet the targets they receive a significant discount on the CCL[57]. There is evidence that the introduction of the CCL with CCAs led to energy efficiency improvements in many of the industries covered fairly quickly, with the steel, cement and chemicals sectors all outperforming their energy efficiency targets in 2002[58]. Similar evidence comes from experience in other countries, for example Denmark in the 1990s, where an energy tax with energy efficiency agreements produced notable (in excess of 10%) reductions in industry energy usage[59]. More recent evidence, however, suggests that in the UK the CCL alone has been responsible for a more pronounced increase in energy efficiency than the CCL combined with CCAs, indicating that the energy efficiency targets of the CCAs have provided a weaker incentive to decrease energy use compared to the price incentive of the CCL alone[60]. More policy evaluation is needed here.

Product energy intensity (GJ / tonne)*	2005 (China)	2009 (China)	Advanced level (International)
Crude steel	21.4	20.4	17.9
Cement	4.9	4.1	3.5

Table 6. Industry product energy intensity in China. *Adapted from CPI (2011)[66] using IEA energy conversion factors

In spite of these policies having achieved a degree of success, a range of non-financial and financial barriers can hamper the uptake of cost-saving measures such as energy efficiency. For example the UK Committee on Climate Change has identified significant cost-saving emissions abatement potential in the UK iron and steel industry (through increased use of recycled steel), cement industry (through clinker substitution), and chemicals industries (for example through less energy-intensive chemical distillation processes) by 2030[61], but notes that long refurbishment cycles and capital constraints could hamper the uptake of these measures. It recommends that the latest CCAs, to be agreed in 2013, should include a rigorous assessment of industry abatement options with a focus on achieving longer term abatement throughout the 2020s (the CCAs will run until 2023), as well as dedicated access to capital for mitigation investments, through mechanisms such as the UK's new Green Investment Bank[62].

Outside the UK, the Greenhouse Gas Emission Reduction from Industry project in Asia and the Pacific (GERIAP) identified several barriers to the uptake of energy efficiency measures, the most important being: focus of management on production volume and turnover as opposed to production costs; lack of information on energy saving options (compounded by the absence of energy management information systems); lack of capital for even relatively short payback (e.g. two or three years) investments; and lack of clear, effectively enforced energy efficiency policies[63]. In response, Governments should enforce clear energy efficiency policies, supported by economic instruments such as fuel/emissions taxes, removal of fossil energy subsidies but provision of subsidies such as tax breaks for energy efficiency investments, improved monitoring and reporting of progress made by companies, and promotion of research and development into energy efficient technologies[64]. Governments should also where possible provide information on energy efficiency options for industries.

One example of such recommendations put into practice is China's 11th Five Year Plan (2006–10) energy efficiency programmes for the industry sectors. The Top 1000 Energy-consuming Enterprises Programme targeted specific energy savings in the 1000 most energy-consuming firms in China (of which around half are in the iron and steel, chemicals and cement sectors) with supporting policies including energy audits, benchmarking, monitoring, information dissemination, and financial incentives[65]. The Ten Key Energy Conservation Projects provided Government funding for energy-intensive industries for projects such as coal-fired industrial boiler retrofits, district CHP projects, waste heat and pressure utilization projects, petroleum conservation and substitution projects, motors energy efficiency projects, and energy system optimization projects. The Small Plant Closure Programme targeted the closure of smaller, less energy-efficient process plants including a significant capacity of smaller vertical shaft kilns in the cement industry, and smaller blast furnaces in the steel industry[66]. In aggregate these policies have contributed to a notable reduction in the energy intensity of steel and cement, though compared to international advanced levels there remains room for further improvements (see Table 6). In addition to such programmes, a number of countries are in the process of phasing out fossil fuel subsidies which discourage the uptake of energy efficiency measures in energy-intensive industries. For example China abolished preferential electricity tariffs for certain energy-intensive industries (including steel, cement and some chemicals sectors) in 2010, and India removed regulations on natural gas prices, more than doubling the price in 2010[67].

In summary, a range of energy efficiency opportunities are gradually being unlocked through a variety of targeted policies. Nevertheless, as discussed in the roadmap section of this paper, further research is required in order to more completely understand the range of barriers to the uptake of seemingly cost-effective energy efficiency measures, and how to overcome these barriers.

Subsidies and carbon pricing for more expensive abatement options

Whilst the policies outlined above can drive largely cost-effective mitigation, for measures such as fuel-switching and more expensive options, some form of financial incentive (through a carbon price or subsidy) or direct regulation is needed. For example to drive the uptake of fuel-switching away from carbon-intensive coal and gas, the UK iron and steel, cement and chemicals industries are (as of 2011) eligible for a Renewable Heat Incentive (RHI), a Government payment for each unit of renewable heat generated, thereby subsidising the installation of technologies such as biomass and biogas combustion to produce high-grade heat (which together could meet three quarters of total industrial heat demand by 2030)[61]. Payments are intended to compensate installations for the additional cost of renewable over fossil fuel heat, for their initial capital investment in the technology, and for any non-financial barriers to the uptake of the technology[68].

Since 2005 the EU iron and steel, cement and chemicals industries have been included in the EU Emissions Trading System (EU ETS), which caps the quantities of CO_2 emissions from installations in these sectors, and allows emissions permits to be traded with other installations across the EU, establishing a common carbon price. There is evidence (both anecdotally and from statistical analysis) that industrial firms within the EU ETS have undertaken mitigation measures as a result of the policy[69]. However, the iron and steel, cement and chemicals industries have until this point had their emissions largely covered by free allowances[70]. There is some evidence that the extent to which firms in the EU ETS undertake production process and product innovations is related to their expectations of their future allocation of free allowances, rather than on expectations of the carbon price[71], which might imply that free allowances could dampen incentives to invest in emissions-reducing technologies. Free allowances have been allocated to these industries in response to concerns over the competitiveness impacts and 'carbon leakage' that could result from asymmetric climate policies (i.e. where a region imposes more stringent regulations on energy-intensive industries than other regions, thereby giving an incentive to those industries – and their emissions – to relocate abroad). A number of studies have been undertaken to assess the size of carbon leakage for particular energy-intensive industries, with the leakage rate defined as 'the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries'[72].

Estimated leakage rates for iron and steel range from as low as 0.5% to as high as 26%[73], and cement as low as 5%[74] to as high as 70%[76]. Such large ranges reflect difficulties in measuring leakage empirically from historical data, due to the limited time in which the EU ETS has been operational. There is also uncertainty in estimating leakage theoretically in models of production and trade, due to the many parameters (for example abatement costs, transport costs, and market structure) that must themselves be estimated in order to do this. This has contributed to ongoing disagreements between industry groups and the European Commission over free allocation policies. A current example concerns the methodologies used to benchmark the emissions intensity of different industry installations in each sector across the EU, with installations due to receive free allowances during the 2013–20 period of the EU ETS based on the emissions intensity of the 10% best performers. The benchmarking methodology has led to a number of challenges, including a lawsuit from the European Confederation of Iron and Steel Industries (EUROFER) claiming that the benchmark level for hot metal is technically unachievable[77].

Free allowances based on a benchmarked emissions-intensity for the iron and steel, cement and chemicals sectors are also in use in New Zealand's ETS, which has included these industries since 2010. Nevertheless, alternative policies to tackle competitiveness and leakage concerns are under consideration, such as border adjustment mechanisms, which could place costs on imports into (or provide rebates on exports from) the EU, thereby levelising the carbon price across regions, and global sectoral agreements, which could in theory set a common emissions standard across products regardless of where they are produced[74]. Free allowances and border adjustment mechanisms are likely to be targeted towards compensating industries for increased costs from direct emissions. In addition, competitiveness loss and carbon leakage could in theory also result from increased indirect costs, most notably through raised electricity prices as a result of low-carbon policies in the electricity sector. With this in mind, in Autumn 2011 the UK's Chancellor announced in his budget statement that the UK Government would compensate key electricity-intensive businesses to help offset the increased costs of electricity resulting from carbon-pricing policies, as well as increasing the discount on the Climate Change Levy for electricity for those businesses with Climate Change Agreements[75].

As already discussed, some industry associations have already taken sector-wide initiatives towards establishing energy and emissions monitoring data for their members, thereby making more viable a move towards sectoral mechanisms. Such mechanisms could in theory take many forms, such as technology and best practice sharing agreements, or specific 'no-lose' emissions targets for whole sectors within countries or groups of countries, with the possible development of the Clean Development Mechanism (CDM) from a project-based approach to a sector-wide approach (depending on international negotiations). The latter approach could exacerbate competitive distortions, however, as the CDM can lead to energy-intensive industrial firms in emissions-capped regions purchasing CDM credits from uncapped regions, thereby subsidising the mitigation of their international competitors[17].

Research, development and demonstration support for pre-commercial technologies such as CCS

The carbon price levels in the EU ETS (currently less than €10/tCO_2) are insufficient to incentivise the development of a number of the breakthrough technologies in the iron and steel, cement and chemicals sectors discussed in the roadmap section of this paper. These technologies will require further research, development, demonstration and deployment before they can be commercialised. In particular, given that the vast majority of CCS research, development and demonstration funds are currently aimed at the power sector, a policy priority is to increase the research, development and demonstration funding for industry CCS with a view to commercialisation (for cement, for example, deployment should aim to begin as early as the 2020s and full commercialisation by the 2030s[6]). Recognising the wide range of processes across different industries to which capture equipment will need to be integrated, this indicates the need for significant international collaboration in order to achieve the speed and scale of research required. In addition, it will be important for policy makers to recognise the spatial planning as well as legal and regulatory requirements around CO_2 transport and storage networks, including their integration with power sector CCS networks[46].

After some five years of discussion, the UNFCCC adopted a decision at the Cancun climate change summit in December 2010 to include CCS in the Clean Development Mechanism (CDM)[78]. However, the CDM currently only provides a price incentive of less than \$10/tCO_2. In the absence of a sufficiently high carbon price (which according to current cost curve estimates may need to be more than \$50/tCO_2 even by 2030 when costs are expected to have fallen) the short term economics of such demonstrations are likely to be improved by the re-use of captured CO_2 in Enhanced Oil Recovery (EOR), where the price paid in the US for CO_2 is in the range \$15–30 /tCO_2[46]. Following successful demonstration of a range of CCS and other breakthrough technologies it will be important for policy makers to consider the correct balance of continued research, development and deployment support (for example through deployment subsidies) in order to help drive reductions in technology costs and make them commercially viable[79], taking into account future carbon price levels, the stage of maturity of the technologies and the degree to which further cost improvements may be possible.

In addition to the four policy areas described above, it will in time be critical to build on the research into material flows and recycling discussed in the roadmap section, as this could provide further emissions reductions from the industry sector as a whole. This will require the design and implementation of new and innovative policies that incentivise and/or require the re-use of materials wherever possible, learning from international best practice in countries such as Germany with relatively higher recycling rates. One of the greatest challenges in designing effective policies for mitigating industrial emissions is to ensure their longevity and credibility, since they are likely to affect very long-term capital investments (for example, cement plants have a lifetime of 30 to 50 years[53]). If policies are too stringent in the short term, this could result in the early scrappage or mothballing of capital assets before they have achieved an economic payback, at potentially very high costs. If policy signals for the longer term look insufficiently stringent or credible, however, this could result in a lock-in to long-lived, higher carbon assets, again potentially leading to eventual scrappage when policies strengthen in the future.

Given the protracted and uncertain nature of international climate negotiations, implementing credible policies over a long timeframe may prove difficult, as national and regional political and economic cycles are likely to bring with them a changing level of priority towards enforcing stringent climate change policies, especially where competitiveness concerns are significant. Nevertheless, longer term industry agreements have been achieved through close cooperation between regulators and industry associations, as for example in the Netherlands energy management long-term agreements (LTAs), which began in 1989 and whose third phase (LTA3) covers energy-intensive industries to 2020, including energy and life-cycle efficiency roadmaps[80] to 2030. As discussed in the section on energy efficiency policies, the UK's proposed introduction of longer term Climate Change Agreements to 2023 covering a wide range of industry mitigation options is a development along these lines.

Conclusions

Limiting industrial CO_2 emissions is crucial to reduce the risks of climate change, but this looks very challenging and more deserving of policy attention. Owing to energy intensive, fossil-fuel dependent processes, CO_2 emissions from heavy industries form a large segment of global emissions. Production and associated CO_2 emissions are predicted to continue to rise, as developing countries grow and seek to improve their standards of living.

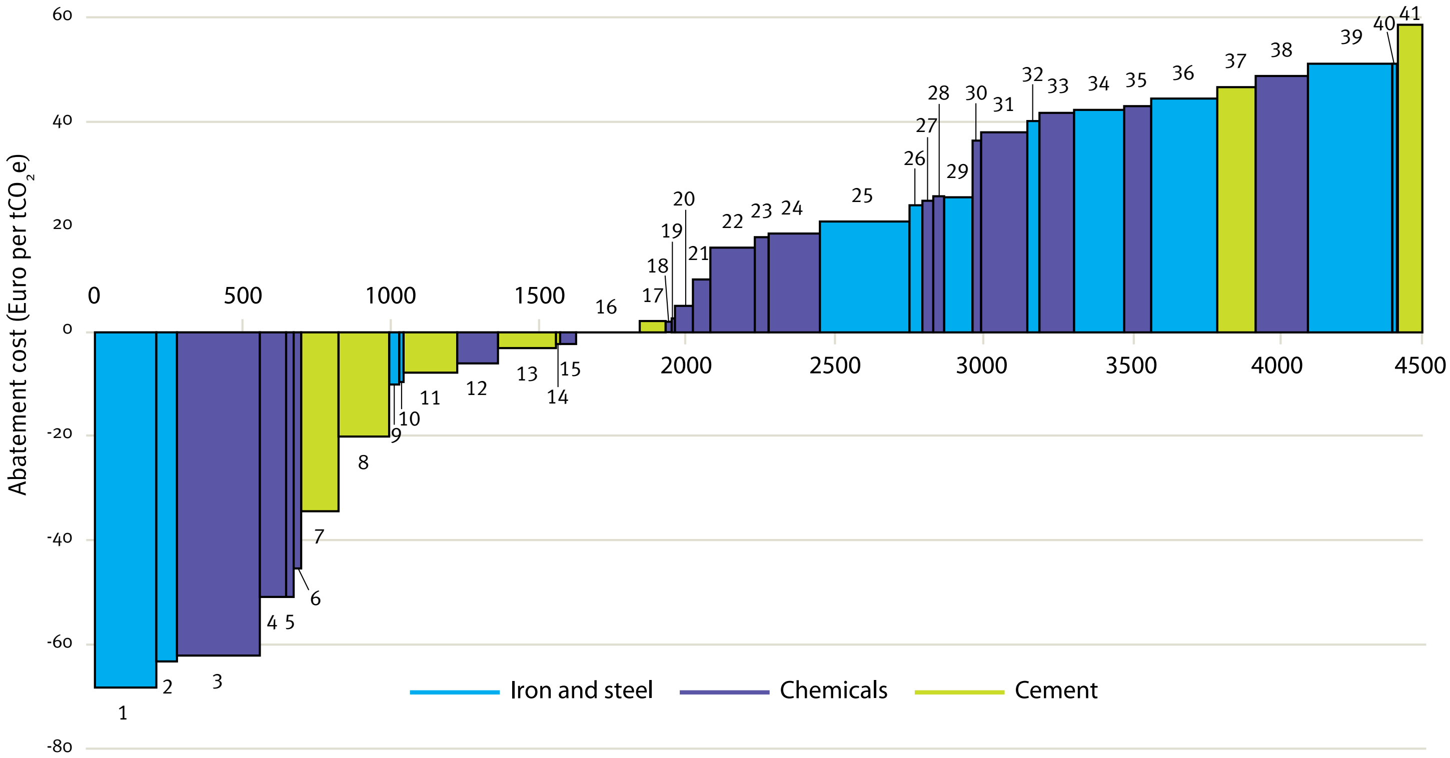
Where mitigation options have fallen in line with industry's own goals of minimising energy costs and ensuring competitiveness, industry has made progress in reducing CO_2 emissions and improving energy efficiency, though many apparently cost effective efficiency measures remain unrealised. However, these actions alone will not be sufficient. Owing to its diversity and issues of international competition, industry requires special attention from policy-makers. Broad policies, grouping industry with the power and buildings sectors, are unlikely to be effective. In summary:

- There needs to be a focussed effort to improve emissions measurements and benchmarking in order to understand the full extent of energy efficiency and emissions abatement opportunities.
- All newly built plants should be at BAT and existing plants to move to BAT as quickly as possible. BAT standards should also be regularly updated on an appropriate timescale in keeping with technological advancement. Capital stock turnover is the main limitation to penetration of advanced technologies.
- Barriers to the adoption of cross-cutting energy efficiency improvements should be identified and measures should be put in place to overcome them. These barriers are often 'social' such as organisational and managerial structures or lack of knowledge rather than financial. Energy efficiency improvements are often at low or even negative cost and could make significant CO_2 savings.
- The substitution of fuels and raw materials with biomass and waste should be incentivised through appropriate mechanisms such as a carbon price, subsidies or regulations.
- Current policy efforts should also focus on the early demonstration of CCS across a broad range of industrial processes. These processes need to be ready for demonstration and commercial deployment in the early 2020s in order to sufficiently reduce emissions from these sectors over the longer term.

As has been highlighted in this paper, these key areas are likely to provide the greatest gains and should be the focus of current efforts.

Appendix 1. Industrial abatement cost curve

Appendix 1 shows a global greenhouse cost curve for three industrial sectors in 2030. Derived from McKinsey data[47]. Please see the key below for the technology breakdown. NB = New Build. RF = Retrofit.



ID	Sector	Measure
1	Iron and steel	Co-generation (NB)
2	Iron and steel	Co-generation (RF)
3	Chemicals	Efficient motor systems (NB)
4	Chemicals	Fuel shift oil to gas (NB)
5	Chemicals	Efficient motor systems (RF)
6	Chemicals	Fuel shift oil to gas (RF)
7	Cement	Clinker substitution by other MIC (NB)
8	Cement	Clinker substitution by fly ash (NB)
9	Iron and steel	Coke substitution (NB)
10	Iron and steel	Coke substitution (RF)
11	Cement	Alternative fuels (waste) (NB)
12	Chemicals	CHP (NB*)
13	Cement	Clinker substitution by slag (NB)
14	Cement	Waste heat recovery (NB)
15	Chemicals	CHP (RF)
16	Chemicals	Process/catalyst intensification (level I) (NB)
17	Cement	Alternative fuels (bio) (NB)
18	Chemicals	Decomposition of N_2O from adipic and nitric acid production (NB)
19	Chemicals	Decomposition of N_2O from adipic and nitric acid production (NB)
20	Chemicals	Decomposition of N_2O from adipic and nitric acid production (RF)
21	Chemicals	Decomposition of N_2O from adipic and nitric acid production (NB)
22	Chemicals	Fuel shift coal to biomass (NB)
23	Chemicals	Fuel shift coal to biomass (RF)
24	Chemicals	Process/catalyst intensification (level II) (NB)
25	Iron and steel	Energy efficiency I (NB)
26	Iron and steel	Direct casting (NB)
27	Chemicals	Ethylene cracking improvements (RF)
28	Chemicals	Ethylene cracking improvements (NB)
29	Iron and steel	Smelt reduction (NB)
30	Chemicals	CCS ammonia (RF)
31	Chemicals	Process/catalyst intensification (level III) (RF)
32	Iron and steel	Smelt reduction (RF)
33	Chemicals	CCS combustion (NB)
34	Iron and steel	Energy efficiency II (NB)
35	Chemicals	CCS ammonia (RF)
36	Iron and steel	CCS (NB)
37	Cement	CCS new build (NB)
38	Chemicals	CCS combustion (RT)
39	Iron and steel	CCS (RF)
40	Iron and steel	BF/BOF to EAF-DRI shift (NB)
41	Cement	CCS retrofit (RF)

Appendix 2. Cost of CCS from different industries

	Option	Annualised cost (USD/t CO_2 captured)	Source	Notes
Power plant	Post combustion	30–90	50	Capture, transportation and storage
Iron and steel	DRI	25–50	2	Capture, transportation and storage
	CCS and smelting reduction	25–50	2	Capture, transportation and storage
	Oxygen blown blast furnace	40–60	2	Capture, transportation and storage; includes productivity effects
Cement	Post combustion	60	51	Capture and compression, excl. transport and storage
	Oxyfuel	34	51	Capture and compression, excl. transport and storage
	Carbonate looping	7.1–31	52	Capture and compression, excl. transport and storage
Ammonia	Post combustion	4–47	46	Capture cost only
Hydrogen	CCS	15	46	Capture cost only
Coal to liquid		less than 25	46	Capture cost only
Refineries	CCS	34–61	2	Capture cost only

Abbreviations and acronyms

BAT – Best Available Technology

BF – Blast Furnace

BOF – Basic Oxygen Furnace

BPT – Best Practice Technology

CCA – Climate Change Agreements

CCL – Climate Change Levy

CCS – Carbon Capture and Storage

CDM – Clean Development Mechanism

CHP – Combined Heat and Power

CSI – Cement Sustainability Initiative

DRI – Direct Reduced Iron

EAF – Electric Arc Furnace

ETS – Emissions Trading Scheme

GHG – Greenhouse Gas

IEA – International Energy Agency

IGCC – Integrated Gasification Combined Cycle

IPCC – Intergovernmental Panel on Climate Change

MACC – Marginal Abatement Cost Curve

TRT – Top-gas Recycling Turbine

ULCOS – Ultra Low CO_2 Steel

References

1. Based on an IEA study of 19 countries – Austria, Australia, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Italy, Japan, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, the United Kingdom and the United States.

2. International Energy Agency, 2010. Energy technology perspectives 2010: scenarios and strategies to 2050, Paris: IEA.

3. International Energy Agency, 2008. World Energy Balances 2008 Edition, Paris, IEA.

4. Jiang, K. et al., 2009. Low-Carbon Economy Scenario Studies up to 2050, Energy Research Institute, NDRC.

5. Allwood, J.M., Cullen, J.M. and Milford, R.L., 2010. Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050. Environmental Science and Technology, 44(6), pp.1888–1894.

6. International Energy Agency, 2008. Energy technology perspectives 2008: scenarios and strategies to 2050., Paris: IEA.

7. Worrell, E. et al., 2008. Industrial energy efficiency and climate change mitigation. Energy Efficiency, 2(2), pp.109–123.

8. International Energy Agency, 2010. Energy technology perspectives 2010: scenarios and strategies to 2050, Paris: IEA.

9. International Energy Agency, 2007. Tracking industrial energy efficiency and CO_2 emissions, Paris: IEA.

10. Worldsteel Association, Energy Fact Sheet. Available at: www.worldsteel.org/publications/fact-sheets.html

11. China's cement and cement clinker exports see increase. Available at: www.worldcement.com/sectors/cement/articles/Chinas_cement_and_cement_clinker_exports_see_increase.aspx [Accessed 8 August 2011].

12. US Geological Survey – Cement Statistics. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/cement/ [Accessed 4 August 2011].

13. Based on comments from experts on Chinese industry.

14. Saygin, D. Et al., 2009. Chemical and Petrochemical Sector: Potential of best practise technology and other measures for improving energy efficiency, Paris: IEA.

15. Towards a future policy on industrial emissions. European Commission on Environment. Available at: http://ec.europa.eu/environment/air/pollutants/stationary/ippc/index.htm [Accessed 8 August 2011].

16. Global steel can recycling rate reaches highest level. Press release by Recycling International on 16 March 2011. Available at: www.recyclinginternational.com

17. International Energy Agency, 2009. Energy technology transitions for industry: strategies for the next industrial revolution, Paris: IEA.

18. Hasanbeigi, A. et al., 2010. Analysis of energy-efficiency opportunities for the cement industry in Shandong Province, China: A case study of 16 cement plants. Energy, 35(8), pp.3461–3473.

19. ECRA/CSI, 2009. Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead.

20. Worrell, E., Price, L. and Galitsky, C., 2004. Emerging Energy-Efficient Technologies in Industry: Case Studies of Selected Technologies, Lawrence Berkeley Lab., CA (United States).

21. Einstein, D., Worrell, E. and Khrushch, M., 2001. Steam systems in industry: Energy use and energy efficiency improvement potentials. Lawrence Berkeley Lab., CA (United States).

22. de Keulenaer, H. et al., 2004. Energy efficient motor driven systems: Can save Europe 200 Billion kWh of electricity consumption and 100 Million tonne of greenhouse gas emissions a year.

23. Breeze, P., 2005. Power generation technologies. Elsevier, Oxford.

24. What is CHP? Combined Heat and Power Association. Available at: www.chpa.co.uk/what-is-chp_15.html [Accessed 4 January 2011].

25. CHPA website. Available at: www.chpa.co.uk [Accessed 20 June 2011].

26. Speirs, J. et al., 2010. Building a roadmap for heat: 2050 scenarios and heat delivery in the UK, Combined Heat and Power Association.

27. Bonsall, R., 2010. Industrial CHP – The first 20 years.

28. Howarth, R.W., Santoro, R. and Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change, 106(4), pp.679–690.

29. Wang, J., Ryan, D. and Anthony, E.J., 2011. Reducing the greenhouse gas footprint of shale gas. Energy Policy, 39(12), pp.8196–8199.

30. European parliament and the council of the European Union, Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste.

31. Chandelle, J.-M., 2007. Waste co-processing in cement plants – new developments in Europe.

32. ULCOS research website. Available at: www.ulcos.org/en/research/isarna.php [Accessed 10 June 2011].

33. Allwood, J.M., Cullun, J.M., et al., 2010. Conserving our metal energy: Avoiding melting steel and aluminium scrap to save energy and carbon.

34. Worldsteel Association. Advanced Applications Fact Sheet. Available at: www.worldsteel.org/publications/fact-sheets.html

35. Worldsteel Association. 3R's Fact Sheet. Available at: www.worldsteel.org/publications/fact-sheets.html

36. Wind Energy Potential. Available at: http://archive.awea.org/faq/wwt_potential.html [Accessed 12 December 2011].

37. Shen, L., Worrell, E. and Patel, M., 2010. Present and future development in plastics from biomass. Biofuels, Bioproducts and Biorefining, 4(1), pp.25–40.

38. Carbon8 website. Available at: www.c8s.co.uk/technology.php [Accessed 13 June 2011].

39. International Energy Agency, 2007. Tracking industrial energy efficiency and CO_2 emissions, Paris: IEA.

40. IEA-IETS, 2006. Industrial Energy-related Technologies and Systems – Annual Report. www.iea-iets.org

41. McKinsey and Company, 2008. Carbon Capture and Storage: Assessing the Economics. McKinsey and Company, London.

42. ECRA, 2007. Carbon Capture Technology – Options and Potentials for the Cement Industry, European Cement Research Academy.

43. Metz, B., 2005. IPCC special report on carbon dioxide capture and storage, Cambridge University Press.

44. CEMEX website on Carbon Capture and Storage. Available at: www.cemex.com/SustainableDevelopment/CarbonCapture.aspx [Accessed 27 July 2011].

45. IEA-WBCSD., 2009. CSI Forum 2009: Cement Sector Technology Roadmap.

46. UNIDO, 2010. Carbon Capture and Storage in Industrial Applications. IEA/UNIDO. And: The United States CCS Financing Overview. Available at http://sequestration.mit.edu/tools/projects/us_ccs_background.html. Accessed on 1 February 2012.

47. McKinsey and Company, 2009. Pathways to a low-carbon economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve. McKinsey and Company: London.

48. Lejeune, O. and Hanschmidt, K., 2009. Carbon Markets – EU ETS Research Note. Bloomberg New Energy Finance, UK.

About the authors

Dr Tamaryn Brown is a Research Associate at the Grantham Institute for Climate Change at Imperial College London investigating technologies and policies for mitigating climate change. Tamaryn recently completed her PhD entitled 'Chemical-looping combustion* with Solid Fuels' at the Department of Chemical Engineering at Cambridge University. Her research interests include technologies for reducing CO_2 emissions from heavy industries, energy efficiency and carbon capture and storage.

*Chemical-looping combustion is a capture process for Carbon Capture and Storage.

Ajay Gambhir is a Research Fellow working on mitigation technology and policy at the Grantham Institute for Climate Change, Imperial College London. He previously worked as a climate change economist and policy analyst in the UK Government and UK Committee on Climate Change. He has Masters degrees in Chemical Engineering and Economics.

Dr Nick Florin is an Imperial Junior Research Fellow working on CO_2 capture technology development, and he is an Energy Engineering Group and Grantham Institute Researcher. He has provided advice to the UK Department for Energy and Climate Change (DECC) and the Environment Agency (EA) on CCS technology and policy issues and was invited to be on an International Panel of Experts to review CCS research and development project proposals.

Dr Paul Fennell heads the Energy Engineering group at Imperial Chemical Engineering and has published widely on the subject of calcium-looping technology and in the wider field of chemical engineering. He sits on the Institution of Chemical Engineers Energy Conversion subject panel, the International Energy Authority High-Temperature Solid Looping Cycles Network Executive, and has written reports for the UK Department for Energy and Climate Change (DECC) on future technologies for Carbon Capture and Storage (CCS) and carbon capture readiness. He is also a deputy director of Imperial's Centre for Carbon Capture and Storage. He has published more than 25 papers since 2005.

49. Hodges, R. and Hawkes, A., 2010. Analysing the opportunities for abatement in major emitting industrial sectors. Prepared for the Committee on Climate Change by AEA Consultancy, UK.

50. Florin, N. and Fennell, P.S., 2010. Carbon capture technology: future fossil fuel use and mitigating climate change, Grantham Institute for Climate Change, Briefing Paper number 3.

51. Barker, D.J. et al., 2009. CO_2 Capture in the Cement Industry. Energy Procedia, 1(1), pp.87–94.

52. Dean, C.C. et al., 2011. The calcium looping cycle for CO_2 capture from power generation, cement manufacture and hydrogen production. Chemical Engineering Research and Design, 89(6), pp.836–855.

53. Cement Sustainability Initiative, 2009. Cement Industry Energy and CO_2 performance: 'Getting the Numbers Right.'

54. International Aluminium Institute, 2009. The Aluminium Industry's Sustainable Development Report. IAI. www.world-aluminium.org

55. Worldsteel Association. Breakthrough technologies Fact Sheet. Available at: www.worldsteel.org/publications/fact-sheets.html

56. Bureau of Energy Efficiency, Government of India, 2011. Perform, Achieve and Trade (PAT) Consultation Document.

57. Department of Energy and Climate Change, 2009. Introduction to Climate Change Agreements. CCA-A02. DECC: London.

58. Ekins, P. and Etheridge, B., 2006. The environmental and economic impacts of the UK climate change agreements. Energy Policy, 34(15), pp.2071-2086.

59. Andersen, M.S., 2004. Vikings and virtues: a decade of CO_2 taxation. Climate Policy, 4, pp.13-24.

60. Martin, R., de Preux, L.B. and Wagner, U., 2009. The Impacts of the Climate Change Levy on Business: Evidence from Microdata.

61. CCC, The Fourth Carbon Budget: Reducing emissions through the 2020s. 2010. Committee on Climate Change: London.

62. CCC, Meeting Carbon Budgets – 3rd Progress Report to Parliament. 2011. Committee on Climate Change: London.

63. Barriers to Energy Efficiency in Industry in Asia – Review and Policy Guidance, 2006. UNEP.

64. Improving Energy Efficiency in Industry in Asia – A Policy Review, 2006. UNEP.

65. Price, L., Wang, X. and Yun, J., 2010. The challenge of reducing energy consumption of the Top-1000 largest industrial enterprises in China. Energy Policy, 38(11), pp.6485–6498.

66. Review of low carbon development in China: 2010 Report. Climate Policy Initiative, Tsinghua University, China.

67. International Energy Agency, 2010. World Energy Outlook 2010. Paris: IEA.

68. Department of Energy and Climate Change, 2011. Renewable Heat Incentive Impact Assessment.

69. Ellerman, A.D., Convery, F.J. and de Perthius, C., 2010. Pricing Carbon: The European Union Emissions Trading Scheme. Cambridge University Press, Cambridge, UK.

70. Environment Agency, 2011. Report on 2010 EU ETS emissions data. Environmental Agency Horizon House, Bristol, Report No. GEHO1111BVEC-E-E.

About the Grantham Institute

The Grantham Institute is committed to driving research on climate change, and translating it into real world impact. Established in February 2007 with a £12.8 million donation over ten years from the Grantham Foundation for the Protection of the Environment, the Institute's researchers are developing both the fundamental scientific understanding of climate change, and the mitigation and adaptation responses to it. The research, policy and outreach work that the Institute carries out is based on, and backed up by, the world-leading research by academic staff at Imperial.

www.imperial.ac.uk/climatechange

About Imperial College London

Consistently rated amongst the world's best universities, Imperial College London is a science-based institution with a reputation for excellence in teaching and research that attracts 13,000 students and 6,000 staff of the highest international quality.

Innovative research at the College explores the interface between science, medicine, engineering and business, delivering practical solutions that improve quality of life and the environment – underpinned by a dynamic enterprise culture. Since its foundation in 1907, Imperial's contributions to society have included the discovery of penicillin, the development of holography and the foundations of fibre optics.

This commitment to the application of research for the benefit of all continues today, with current focuses including interdisciplinary collaborations to improve health in the UK and globally, tackle climate change and develop clean and sustainable sources of energy.

www.imperial.ac.uk

71. Martin, R., Muuls, M. and Wagner, U., 2011. Climate Change, Investment and Carbon Markets and Prices – Evidence from Manager Interviews. Climate Strategies.

72. Intergovernmental Panel on Climate Change, 2007. Climate Change 2007: Working Group III: Mitigation of Climate Change.

73. Kuik, O. and Hofkes, M., 2010. Border adjustment for European emissions trading: Competitiveness and carbon leakage. Energy Policy, 38(4), pp.1741–1748.

74. Carbon Trust, 2010. Tackling carbon leakage – Sector-specific solutions for a world of unequal prices (CTC767).

75. HM Treasury, 2011. Autumn Statement 2011. Stationery Office Ltd.

76. Reinaud, J., 2008. Issues behind Competitiveness and Leakage: Focus on Heavy Industry. IEA Information Paper. Paris: IEA.

77. Steel industry goes to European Court on EU Emissions Trading Scheme. Press release: www.eurofer.org on 25 July 2011.

78. UNFCCC, 2010. Decision 7/CMP.6: Carbon dioxide capture and storage in geological formations as clean development mechanism project activities.

79. Jamasb, T., Nuttall, W.J. and Pollitt, M., 2008. The case for a new energy research, development and promotion policy for the UK. Energy Policy, 36(12), pp.4610–4614.

80. Vermeeren, R. 2008. Experience with Energy Management Standards in the Netherlands Long Term Agreements. SenterNovem presentation in Beijing, China on 11 April 2008.

Notes

Notes