

Climate Change and Industry: Challenges and Opportunities

Maria Yetano Roche / Manfred Fishedick
Wuppertal Institute for Climate, Environment and Energy

Abstract The industry sector accounted for just over 30% of global GHG emissions in 2010 and scenarios envisage a continuing rise in demand for energy-intensive materials. This article sums up the most recent international analysis (IPCC, IEA, UNIDO, Global Energy Assessment) to give a broad view of the current prospects for reducing GHG emissions in industry. It does so from a global perspective, complementing where necessary where regional and sector-specific case studies. The article addresses the portfolio of options available, their technical and economic potentials, the experience in the use of policy instruments in industry, the synergies and tradeoffs that mitigation in the industry sector can have with other policy objectives, and the specific concerns of developing countries. Long-term decarbonisation pathways for the sector are also presented.

Key words Climate Change, GHG, Decarbonisation pathways

I. Introduction

The industry sector accounted for just over 30% of global GHG emissions in 2010 (Fishedick et al., 2014). When compared to the major energy-end use sectors (transport, buildings, AFOLU), industry is currently the largest emitter of greenhouse gas (GHG) emissions. The key energy intensive material-conversion sectors (cement, iron and steel, chemicals, pulp and paper and aluminium) dominate the energy use and emissions in industry. Most scenarios envisage a continuing rise in demand for materials, by between 45% to 60% by 2050, relative to 2010 production levels.

The transition from current patterns of industrial production to a future in which goods are produced sustainably requires new more integrated approaches. Two particular aspects of this change, from the standpoint of climate change mitigation, are:

On the one hand, there is the need to consider the industry sector as **inextricably linked** to the other sectors of the economy. From this perspective, opportunities for the reduction of GHG emissions can be found over the whole supply chain of industrial materials and goods, from the raw material to the provision of final services. As shown in Figure 1-1, energy and emissions efficiency are only part of the picture. Material efficiency in manufacturing (e. g., through reducing yield losses or re-using old materials without recycling) and in product design (e. g., designing for extended product life or for lower material use) are increasingly regarded as essential strategies for the industry sector. Moreover, industrial sector output can be reduced by using products more intensively in other sectors of the economy (e. g. in transport through car sharing, therefore reducing the number of cars per individual; or in buildings through higher building occupancy, potentially leading to lower cement demand). Finally, there is potential for reducing the demand for services without affecting wellbeing.

The other change in perspective relates to the need to see address the **multiple synergies** between policy goals. It has already been demonstrated that investing in industrial energy efficiency makes financial sense at the firm level, and many current policies aim to bring down the barriers between the investor and these financial gains. However, GHG mitigation in industry holds potential benefits to the wider economy that remain understudied and unexploited. The industry sector lies at the heart of the many governments' decisions regarding the maintenance of wealth and the creation of employment (see Box 1 for a closer look at the case of developing countries). It is in this context that sustainable industrial production can bring about productivity and competitiveness advantages, along with gains in public health and other policy realms.

Some of the above perspectives have been put forward by the most recent international analyses (e.g. IPCC, IEA, UNIDO, Global Energy Assessment). We sum these up to provide a broad view of the current prospects for reducing GHG emissions in industry. It does so from a global perspective, complementing where necessary where regional and sector-specific case studies. The article addresses, among other things: the portfolio of options available, their technical and economic potentials, the experience in the use of policy instruments in industry, the synergies and tradeoffs that mitigation in the industry sector can have with other policy objectives, and the specific concerns of developing countries. Long-term decarbonisation pathways for the sector are also presented. At the end, the most pressing gaps in knowledge are synthesized.

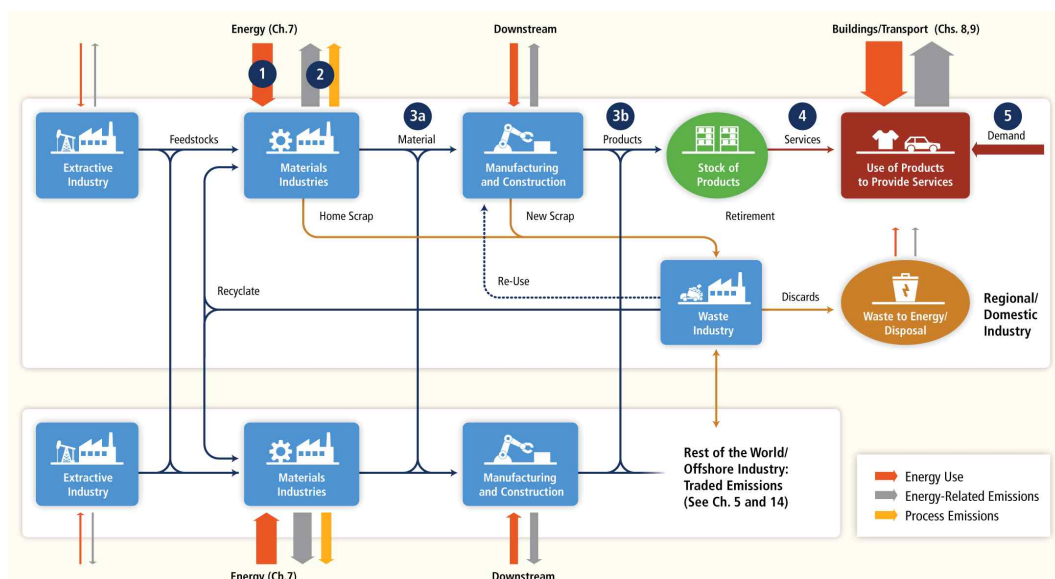


Figure 1–1. A schematic illustration of industrial activity over the supply chain (including traded emissions), according to latest Assessment Report of the IPCC. Options for climate change mitigation in the industry sector are indicated by the circled numbers: (1) Energy efficiency, including increased material recycling; (2) Emissions efficiency; (3a) Material efficiency in manufacturing; (3b) Material efficiency in product design; (4) Product-Service efficiency; (5) Service demand reduction. Source: Figure 10.2 in (Fischelick et al., 2014).

Box 1. Implications for developing countries

The industry sector lies at the heart of the many governments' decisions regarding the maintenance of wealth and the creation of employment. Manufacturing offers developing countries an opportunity to grow and improve the quality of life of their populations (UNIDO, 2013).

As discussed in Section 2, emerging economies now account for the majority of the production capacity for energy-intensive materials. The high shares of new energy-efficient capacity in India and China have however largely offset the upward effect of this change in the global centers of production (IEA, 2014). Moreover, small-scale industry sectors such as textile, food and beverage and SMEs are particularly important for developing countries (Saygin et al., 2011b). As developing countries reduce the income gap with developed countries, the shift seen in their economies in the last decades, from low-technology to medium- and high-technology manufacturing, will continue. Placing investments in new energy-efficient processes and plants at the right moments of a country's structural change will be one of the keys for managing global industrial emissions.

The strategy for promotion industrial energy efficiency in Least-developed countries (LDCs) will depend on the rate at which they follow the structural change trend of developing countries (Fischedick et al., 2014).

Notwithstanding structural considerations, there is also growing evidence of the financial case for energy efficiency investments in developing countries (e.g. as summarised in (UNIDO, 2011)), and of the role of co-benefits of mitigation in industry in a developing country context (see section 6). The effect of climate finance mechanisms, including future ones such as the Green Climate Fund, on the industrial sector is of importance in this context. The large volume of credits and projects in the CDM gives an indication of the potential, but the systems need to be improved to avoid strategic behaviour, as the case of industrial HFC-23 shows (Wara, 2008).

II. Global trends of the sector

Trends in industrial energy use and emissions are understood through the study of the changes in material consumption and production and in industrial energy intensity (amount of energy used to produce a unit of value added). The latter is in turn driven by both structural and technological factors. Industrial energy intensity decreased markedly from 1990 to 2000, especially in developing economies and due mainly to technological change. It has however remained fairly stable since (UNIDO, 2011). Moreover, this progress has been more than off set by growing industrial production worldwide (IEA, 2012). As a result, and despite the declining share of industry in global gross domestic product (GDP), total industrial energy consumption and GHG emissions have continued to rise. GHG emissions grew from 10.4 GtCO₂eq in 1990 to 13.0 GtCO₂eq and are now double the levels of 1970 (Fischedick et al., 2014), see Figure 2-1.

The increase is largely fuelled by rising materials demand in non-OECD countries, which now use 66% of industrial energy, up from 50% in 2000 (IEA, 2014). Developing countries are the also the largest producers of energy-intensive materials, and will continue to be so during the next decades (Banerjee et al., 2012; IEA, 2014) (see Box 1). At the same time structural changes in the industrial sector meant that the five most energy-intensive industry sectors – iron and steel, cement, chemicals and petrochemicals, pulp and paper, and aluminium – increased their share of total industrial energy use to 67% in 2011 from 57% in 1990 (IEA, 2014). These

sectors consume about three-quarters of all fossil fuels used in industry and are responsible for almost 80% of total industrial CO₂ emissions (IEA, 2012). Industry has a range of emission sources: direct energy-related emissions and indirect CO₂ emissions from the production of electricity and heat for industry each account for a 40% share of the total. The remaining 20% is composed of process-related emissions, mainly from cement production (Fischedick et al., 2014). In 2010 over half of global direct GHG emissions from industry originated in Asia, and a quarter in OECD countries (Fischedick et al., 2014).

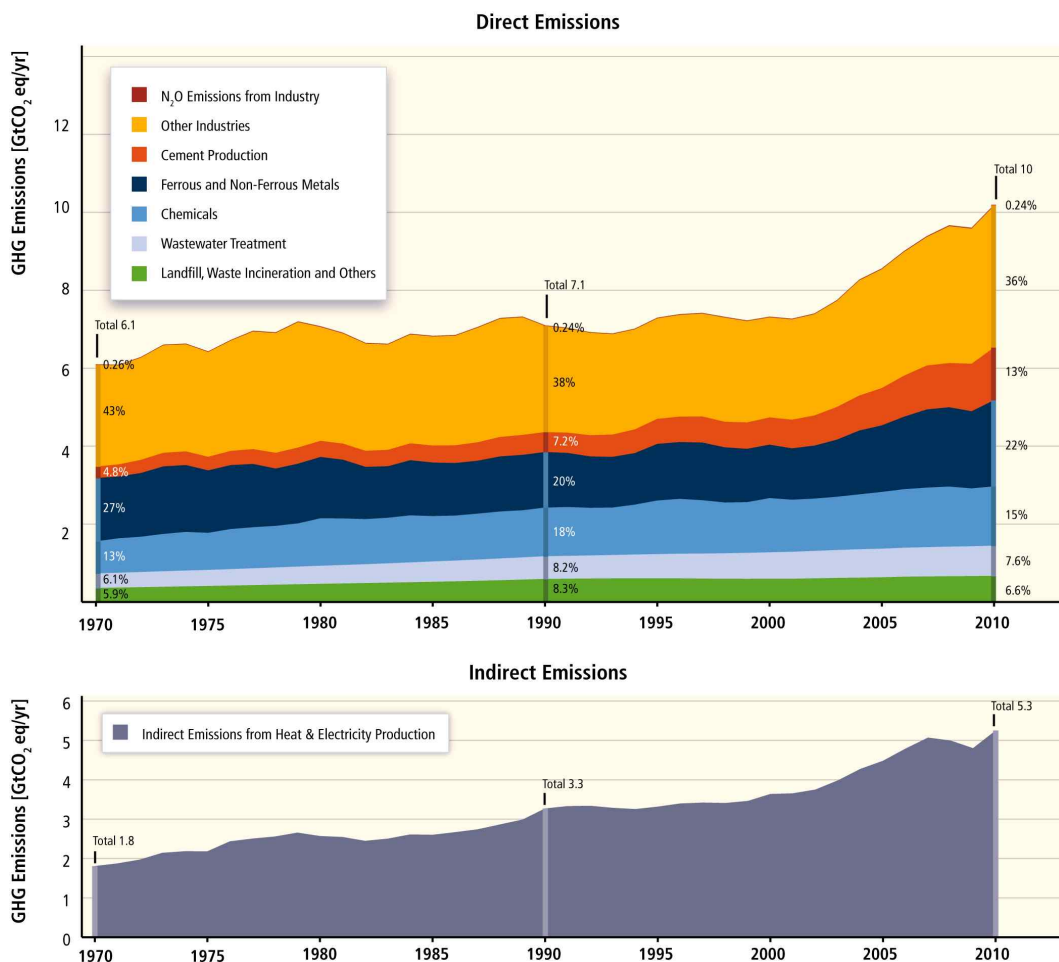


Figure 2-1. Total global industry direct and indirect GHG emissions by source, 1970 – 2010 (Source: Figure 10.4 in (Fischedick et al., 2014)). Note: the categories "wastewater treatment and landfill" and "waste Incineration and others", while shown in this figure, are not included in the scope of this paper.

It is important to note that the trade of products leads to significant differences between ‘territorial’ and ‘consumption-based’ measures of industrial emissions (as indicated in Figure 1-1 by the area named "Rest of the world"). Thus, in China, the share of embodied emissions in exports (mainly electronics, metal products, textiles, and chemical products) to total annual emissions accounted for 27% of total emissions, or a value greater than the total emissions from any country other than the U.S. (Minx et al., 2011). Western Europe tends to top the list of largest net importers of emissions (Skelton et al., 2011).

Box 2. Cross-sectoral GHG mitigation effects

Some strategies for GHG mitigation require a system-wide view, as emissions reductions in one end-use sector (e.g. transport, buildings, AFOLU) may come at the expense of increased emissions in industry. Examples of this involve material substitution in vehicles and the demand for new materials for new buildings. GHG emissions from vehicle use can be reduced if cars are built with lightweight materials such as high-strength steel and aluminum. However, for primary aluminum, the increase in GHG emissions from material production may be larger than the GHG savings from vehicle weight reduction (Geyer, 2008). Emissions reductions for aluminum-intensive vehicles would require the creation of a closed-loop recycling system of the resulting end-of-life scrap; a practice that does not currently occur (Kim et al., 2011). An example of a vehicle technology aimed at reducing GHG emissions with positive effect in industrial emission is the replacement of the conventional air conditioning refrigerant, HFC-134a, with an alternative refrigerant with lower global warming potential such as CO₂ (refrigerant 744) (Lutsey and Sperling, 2008).

Emissions embodied in construction materials are in general not considered when a building is designed and constructed, as focus often lies on improving the energy efficiency of its operation and maintenance (Yeo and Gabbai, 2011). Embodied carbon can however be particularly relevant for low energy buildings because of the increased levels of insulation, the heavier mass of materials used and the additional technologies (Monahan and Powell, 2011). Sartori and Hestnes (2007) found out that between 2% and 38% of a traditional building lifetime energy demand is associated with all the material used in the construction, rehabilitation and maintenance phases. This range may increase to 9-46% for a low-energy building.

III. Options and potential for climate change mitigation

In the following sections, we review estimates of potential for reduction of GHG emissions from industry. We do this by following loosely the options outlined in Figure 1-1. The options

related to reducing the energy and carbon intensity of production processes are dealt with under a broad "technology-related" category. Other options include material efficiency, collaboration among industries, and demand-side options. Finally, we make a synthesis of the overall potential (be it technical or economic) in the industrial sector as a whole and in specific sub-sectors, drawing from quantitative analysis where possible.

1. Technology-related options

Despite significant improvements in energy and process efficiency in the energy-intensive sectors in the last decades, substantial potential to further technology-based improvements still exists. New-build facilities in emerging economies can employ the most energy-efficient technologies, whereas a range of options exist for retrofitting. Moreover, in the less energy intensive industries, there are still many energy efficiency options both for process and system-wide technologies and measures (Fischedick et al., 2014). The following sections look at key best-practice and best-available technologies¹⁾ which can be applied in a cross-cutting or sector-specific manner, as well as the most promising break-through innovations.

1) Cross-cutting options

In industry, energy efficiency opportunities are found across all sectors, with savings potentials of over 10% in steam and process heating systems and of over 20% in motor systems (e.g., pumps, fans, air compressors) (Banerjee et al., 2012; McKane and Hasanbeigi, 2011). Electronic control systems and the use of ICT can cost-effectively help to optimize the performance of motors, compressors, steam combustion, heating, etc. in both large industrial plants and SMEs (Masanet, 2010). Improved insulation in industrial plants is an example of a saving potential that is often overlooked: it has been estimated that installing or improving industrial energy insulation would cost-effectively reduce the energy consumption of EU27 industry by 3% (EIIF and Ecofys, 2013).

1) BAT and BPT can be defined as: "BAT (Best Available Technology): the most energy-efficient way of producing goods and services that is commercially viable and in use; BPT (Best Practice Technology): the top performing technologies and practices for industrial energy efficiency among those in use by most plants within an industry" (UNIDO, 2011).

Other cross-cutting opportunities include process integration, heat pumps and cogeneration (Banerjee et al., 2012). Brown et al (2013) estimate that industrial cogeneration could meet 18% of U.S. electricity requirements by 2035, compared with its current 9% market share.

Including non-energy uses, industry consumes 84% of global coal and peat (Bruckner et al., 2014). The switch to less emission-intensive fuels and feedstocks is already underway in most sectors and regions due to structural or cost optimization reasons, however most forecasts present a need to further accelerate fuel switching in order to achieve emission targets in industry. Similarly, indirect emissions from electricity use in industry are also forecast to decrease as the grid decarbonises, but greater electrification of industrial processes is needed to reduce carbon intensity to the necessarily levels.

Direct use of biomass, waste and other renewable energy sources accounted for 6% of the final energy use in 2009 (IEA, 2012). This is mainly due to the use of black liquor in pulp and paper sectors and the use of bagasse in sugar factories and other uses in traditional industries. It is however feasible to increase the share of renewables in industry for process heating (e.g. solar thermal for low-grade steam, biomass-based thermal energy), cooling, and power (Banerjee et al., 2012). Some key opportunities for renewable energy are dealt with in the individual sector-specific sections below.

Significant improvements in recycling technologies and practices are possible in all sectors (Gutowski et al., 2013). Recycling leads to an energy saving when producing new material and is already applied –sometimes to very high degrees– in industry, particularly in steel, aluminium and paper. Although often seen as a material efficiency strategy, strictly, recycling does not reduce demand for material, as it shifts demand to the secondary material market. It is important to remember that recycled metal uses can be limited by the limited grade of secondary metals: the quality of recycled metals is often dependent on the addition of pure primary materials. Additionally, recycling depends on the availability of secondary materials: the rate of stock replacement and of demand affect decisions on investing in recycled materials. This is particularly the case for new materials because there is no stock in products where the secondary material can be taken from.

Most forecasts envisage that a large part of emission reduction in energy-intensive industry will occur by carbon dioxide capture (up to 30 % in 2050, see Box 4). Innovative materials such as lightweight steel, high-strength aluminium, novel chemical and construction materials

may help in achieving emissions reductions in the industry or other sectors (see Box 2). Finally, in terms of non-energy emissions reductions, opportunities exist for hydrofluorocarbons used as refrigerants to be replaced by alternatives (e. g., ammonia) and for emissions to be reduced by leak repair, refrigerant recovery and recycling (Fischedick et al., 2014).

Box 3. Estimating improvement potentials with benchmarking

Benchmarking is primarily a tool that helps plant managers to assess their improvement potential. However, it can be used as a policy tool, for estimating the improvement potential for the whole sector compared to BPT (Banerjee et al., 2012; Fischedick et al., 2014; Saygin et al., 2011b). Benchmarking methods vary: some systems choose a representative sample of plants, or propose the average energy use of the most-efficient region as the international benchmark. However, increased data disclosure by companies (including by associations such as the Cement Sustainability Initiative, the World Steel Association and the International Aluminum Association) is translating in a way of carrying out benchmarking for a significant share of the total production volume. By compiling actual energy use data measured at companies globally, Saygin et al (2011b) estimate a global energy saving potential at 17.3 ± 4.6 EJ/yr (see Table 1 below). Uncertainty around these values is nevertheless significant as there is a paucity of high-quality data, especially for complex sectors like chemicals.

Table 1. Energy saving potentials in the manufacturing industries by application of the methodology in (Saygin et al., 2011b)

Sector	Improvement Potential (%) ¹	Total final energy use (EJ/yr) ¹	Total worldwide energy savings potential (EJ/yr)
Iron and steel	9-30	7.7-18.2	6.1
Cement and lime	22-26	3.7-7.8	3.1
Chemical and petrochemical	7-19	7.7-9.7	2.3
Pulp and paper	28-25	5.2-1.6	1.9
Non-ferrous metals	19-29	1.6-2.4	1.0
Food and beverages	40 ²	3.0-3.4	2.1

1 First value of each ranges indicates the value estimated for Industrialised countries, whereas the second value corresponds to developing countries.

2 Value only available for industrialized countries.

Source: adapted from (Saygin et al., 2011b).

2) Sector-specific options

(1) Iron and steel

Energy intensity is relatively stable in the steel sector, but its energy use grew by 6.2% annually from 2000 to 2011 (IEA, 2014). The demand for material is projected to increase from 210 kg of crude steel in 2010, to between 270 kg/capita and 319 kg/capita by 2050 (IEA, 2012). The IEA (2014) estimates that about 21% of energy use could be saved if current BATs were applied in all new and refurbished plants, while (Kermeli et al., 2014) puts the figure at 31% of the projected levels of consumption in 2050. Increasing the use of the more efficient electric arc furnaces (EAF) is constrained by the costs of electricity and the availability of scrap (Fischedick et al., 2014; Milford et al., 2013). Indeed, due to insufficient scrap availability, China has recently increased its share of blast furnace/basic oxygen furnace (BOF) technologies (IEA, 2014). The phasing out of open-hearth furnaces and limiting coal-based direct reduced iron (DRI) production are also required to meet targets.

Additional options in this sector include improved heat and energy recovery from process gases, better process coupling, improved fuel delivery through pulverized coal injection, fuel switching and feedstock substitution (use of biomass, waste, electrolysis, gas-based DRI, charcoal, ferro-coke) and use of coke dry quenching and top pressure recovery turbines (Fischedick et al., 2014; Hasanbeigi et al., 2013c; IEA, 2014; Worrell, E et al., 2010; Xu et al., 2011).

Emerging technologies include CCS, hydrogen reduction, capture and recovery of blast furnace gases and smelting reduction (Hasanbeigi et al., 2013a; IEA, 2014). The European-based Ultra-Low Carbon Dioxide Steelmaking (ULCOS) consortium has faced technical and financial problems, and is now replaced by the Low Impact Steel making project, which aims to demonstrate a commercial-scale blast furnace with CCS (IEA, 2014; Tsupari et al., 2013).

(2) Cement

Cement accounts for most of the energy use in the processing of non-metallic minerals (lime, glass, soda, ceramics, brick, etc), with clinker production being the most energy intensive step. Despite the recent improvements observed in the energy and emission intensity of cement plants (IEA, 2012), many options still exist to improve the thermal and electric efficiency of cement production as well as for fuel and feedstock switching. The IEA (2014) estimates that the

overall technical potential for current energy use reduction is 18%. Oda et al. (2012) found that the least efficient regions consumed 75% more energy than the best in 2005.

Cost-effective options in cement manufacturing are in switching to best practice clinker-to-cement ratio (i.e. reducing the clinker content in cement). Energy savings can also be obtained by using clinker substitutes, although the potential and costs are dependent on regional availability and the price of substitutes (Fischedick et al., 2014). The use of alternative fuels (e.g. waste, biomass, scrap tires and waste oils) is an important area of study, and it is estimated 12% to 15% of the power consumed in a cement plant can be generated through waste heat recovery (IEA, 2014). Hasanbeigi et al. (2013b, 2010) estimate that about 20% of the fuel used by Thailand's cement industry in 2005 could have been reduced (80% of which cost-effectively) and that savings equivalent to 6 and 1.5 times the total electricity and fuel use in the Indian cement industry in 2010, respectively, could be realized almost cost-effectively for the period 2010 –2030.

Fitting cement kilns for CCS is technically feasible but it has yet to be piloted, and it is estimated that it could increase the costs of cement considerably (Croezen and Korteland, 2010; IEAGHG, 2008; Naranjo et al., 2011). Other innovations, including emerging alternative cement products, are awaiting commercialization (Hasanbeigi et al., 2012).

(3) Chemicals and fertilisers²⁾

The chemical industry is very heterogeneous, with a large number of inputs, processes and products. This poses considerable challenges in terms of data availability and analysis. However, a small number of intermediate products dominate the energy use in this sector: for example, ammonia (for fertilizer production), chlorine and ethylenes. Ethylene is produced via steam-cracking, which is the most energy consuming processing the chemical industry (Ren et al., 2006). Upgrading all steam cracking plants to BPT could reduce energy intensity by 23% with a further 12% saving possible with BAT (Fischedick et al., 2014; Saygin et al., 2011a). In the sector as a whole, the IEA (2014) estimates that application of BPT could save 24% of current energy use, while Broeren et al. (2014) find that 25% of emission reductions are possible with BPT. Between 2010 and 2030, 60% of new capacity for production of chemical

2) The way the scope of this sector is defined has important implications on its emission balances and mitigation aspects: refining or the processing of fossil fuels for use as energy vectors may or may not be considered within the chemicals sector.

products is projected to be built in non-OECD regions (Broeren et al., 2014).

The chemicals sector is a great consumer of fossil fuels as feedstocks. Carbon emissions from this use are projected to increase due to greater use of coal in ammonia and methanol production (Daioglou et al., 2014). Promoting the switch to natural gas or biomass as a feedstock could reduce carbon emissions but at a higher cost and land-use requirements (Ren and Patel, 2009)

Other options in the portfolio for emission reductions are switching to low-carbon fuels, increasing recycling and saving on process heat. Emerging technologies such as CCS/CCU in ammonia/urea production and polymer synthesis, or catalytic cracking can provide further energy efficiency benefits. Abatement of non-CO₂ gases is particularly important in this sector: the use of secondary catalysts, thermal destruction of N₂O emissions from nitric and adipic acid production and the improvement of plant operation conditions for nitric and adipic acid production are key options, as are the reduction of HFC-23 emissions from HFC-22 production (EPA, 2013).

(4) Pulp and paper

Demand for paper and cardboard continues to grow at rates of over 3% per year (Banerjee et al., 2012). A broad range of energy efficiency technologies are available for this sector (Kramer et al., 2009; Laurijssen et al., 2012). This is particularly the case in countries that operate small-scale mills (e.g. China, India), although these countries are rapidly installing larger modern paper mills using imported recovered paper (Banerjee et al., 2012). Indeed, increased feedstock substitution (i.e. using recovered paper) is one of the main areas of potential for decreasing energy and carbon intensity in this sector. The share of recovered paper used in paper manufacturing is increasing steadily, and paper recycling in Europe and North America approached 70% in 2011 (CEPI, 2012). Overall, the IEA (2014) estimates that the technical potential for energy use reduction in paper and pulp production is 26%.

The European paper industry reports that over 50% of its energy supply is from biomass, and CHP accounted for 95% share of its power use in 2011, according to the Confederation of European Paper Industries (CEPI, 2012). This means that biomass and CHP hold further potential globally. Regarding innovative breakthroughs, in 2013 CEPI announced promising lab-scale results of the application of deep eutectic solvents (DES) allowing production of pulp

at low temperatures and atmospheric pressure, which could potentially reduce CO₂ emissions by 20% from current levels by 2050 (CEPI, 2013). CCS for the European pulp and paper industry has been studied by Jönsson and Berntsson (2012), showing that there is a challenging geographic miss-match between the location of the emission clusters and the location of probable CCS infrastructure.

(5) Non-ferrous metals (Aluminium)

The per capita consumption of finished aluminium is expected to either double or triple between 2010 and 2050, due to higher penetration of aluminium as a material in a wide range of sectors, especially transport (see Box 2) and construction (IEA, 2012). The ongoing decline in energy intensity of the sector has been brought about by the build up of new energy-efficient capacity in emerging economy. For example, China is now among the world's most energy-efficient primary aluminium producers, thanks to high shares of new capacity (Sinden et al., 2011). However, most of the reduction potential still lies in China, where most lower-quality bauxite sources are currently used (IEA, 2014). Energy intensity reductions is however not sufficient to offset the demand-driven increase in emissions. Reducing carbon intensity in this highly electricity-dependent sector is key: although as many as half of aluminium plants are supplied by hydroelectric sources, indirect emissions emissions-mainly electricity-related emissions from smelters- account for over 80 % of total GHG emissions in the sector (Fischedick et al., 2014). Moreover, there is still scope for energy efficiency improvements by applying current BATs. Overall, the IEA estimates that the technical potential to reduce energy use is 11% compared to current levels (IEA, 2014).

Production from recycled aluminium requires 3% to 8% of the energy to produce primary aluminium (IEA, 2014), so a large share of emissions reduction could come from an increased use of aluminium scrap. Most aluminium recycling currently arises at pre-consumer stage (i.e. is internally recycled during production and in construction) (Cullen and Allwood, 2013). Recycling rates can be increased through increased use of post-consumer scrap and new technologies for separating the different alloys (Liu et al., 2012) and by increasing the availability of end-of-life aluminium through demand management strategies.

Aluminium production innovations which continue to be at an R&D stage include multipolar electrolysis, inert anodes and carbothermic reactions, while CCS for aluminium is currently

starting to be explored.

(6) Other sectors

Substantial technology-related mitigation potential exists in other less energy-intensive manufacturing processes such as textile and wood processing, particularly where they take place in Small- and Medium-Sized Enterprises. SMEs are typically the cornerstone of industrial activity in many developing countries (see Box 1), and can represent a large share of the economy in emerging economies (Banerjee et al., 2012). Many of the options relate to cross-cutting technologies such as CHP, improved heat exchange and boilers, which are described above. Here we select the examples of food and beverage processing in order to provide specific insights. In food processing, literature suggests that reductions between 5% and 35% of total CO₂ emissions can be realized cost-effectively in the meat and slaughtering sector, by fuel switching and investing in increased heat exchanger networks or heat pumps meat and slaughtering (Fritzson and Berntsson, 2006). Thermal and mechanical vapour recompression in drying of wet corn milling would allow for energy savings of 15 to 20% (Galitsky et al., 2003). Xu and Flapper (2011) suggest that there is also a large global potential for energy savings in dairy processing plants. Improvements in refrigeration (e.g. better insulation, reduced ventilation) could bring improvements throughout the industry (Cullen et al., 2011).

Box 4. CCS for industry

Most forecasts envisage that a large part of emission reduction in industry will occur with CCS (up to 30% in 2050, see Section 4). However, while there are at least seven gas processing plants in operation equipped with CCS, and another seven under construction for gas processing and power generation, worldwide there is only one large-scale industrial CCS facility currently in operation, and another in execution (both for fertilizer production) (Global CCS Institute, 2011). CCS in gas processing and parts of chemical industry (ammonia production) are seen as possible early opportunities as the CO₂ in flue gas is already highly concentrated, resulting in lower costs and higher process energy efficiency (Kuramochi et al., 2012a). Emission-intensive industrial sectors like cement or iron and steel (see section 3.1) have less pure CO₂ concentrations in flue gas, although these are nonetheless higher than from power plants (Cheng et al., 2010). One of the attractions of CCS is that it does not require significant changes to production processes, where other mitigation options might require a considerable changes or retro-fitting (Croezen and Korteland, 2010). As regards industrial use of captured CO₂, the

potential is thought to be rather small and the storage time of CO₂ in industrial products often short (Mazzotti et al., 2005).

CCS in industry – as in the power sector – faces a set of barriers which are subject to much research. A global survey of industry stakeholders revealed that, among the barriers of implementing CCS, ‘uncertainty in payback’ was perceived to be the greatest risk across all sub-sectors and regions. The ‘risk of stakeholder acceptance’ was rated second highest, followed by risks of productivity losses (Napp, 2014).

3) Material–efficiency

It is increasingly acknowledged that measures beyond energy and carbon efficiency technologies are needed if GHG emission reductions in the industry sector are to meet the needed levels (Allwood et al., 2013, 2012, 2010; Fischedick et al., 2014; Gutowski et al., 2013; Milford et al., 2013). Reducing yield losses in materials production, reusing old material, designing for extended product life and light-weight design and de-materialization are some of the options available. They can be implemented through process innovations and new approaches to design. These strategies require not only technical but also policy changes (see Section 7) that can impact manufacturer and consumer behaviour by raising awareness and changing preferences (see demand-side options section below). Their potential is currently difficult to quantify, and there is comparatively less experience in the implementation of these strategies. System approaches are needed to advance understanding of how these measures can contribute to emissions reductions in the industry sector and how they impact other sectors (see Box 2). To illustrate the potential, some selected examples are given below.

(1) Reducing yield-losses:

A quarter of all steel, and a half of all aluminium produced each year does not make it into final products and is scrapped (and then internally recycled) in the process of manufacturing. The technical potential for reducing the production of scrap in production by process innovations (e.g. in blanking and stamping sheet metal) and new approaches to design has been investigated quantitatively via case studies (Milford et al., 2013, 2011): it is estimated that total energy use could be reduced by 17% and 6% and total CO₂ emissions by 16% and 7% for the steel and aluminium industries respectively.

(2) Reusing material and remanufacturing:

Mass flow and stakeholder analysis studies (Cooper, 2014; Cooper and Allwood, 2012) have suggested that up to 30% of old structural steel and aluminium components could be reused components at end of their product life. End-of-life materials can be "cascaded" to lower-quality uses, refurbished for higher quality ones, or remanufactured in the case for goods that have significant residual value at its end of life (e.g. toner cartridges). For steel, areas for reuse include the replacement of building components and the reforming of ship plates. For aluminium, the main areas of reuse are in buildings and car wheels. Potential barriers include incompatibility between products and corrosion, while drivers include financial savings and a currently growing supply of material. However not all options are energy efficient: that is the case, for example, of the remanufacturing of energy-using products or of products that are transported over long distances (Gutowski et al., 2011).

(3) Lightweight design

Many products could be one-third lighter without loss of performance. Case studies show that around 30% of global metal use could be saved by lightweight design: exploiting lightweight design opportunities for these five products which cumulatively account for 30% of global steel product output could reduce global steel requirements by 5%, and similar opportunities could reduce global aluminium requirements by 7%. However, many of these light-weighting face economic and consumer preference barriers (Carruth et al., 2011).

(4) Increasing life span of components or whole products

Approximately 40% of annual demand for steel worldwide is used to replace products that are discarded because of failure. However, many of the steel components within products are still usable when the product is discarded. In particular, the potential lifespan of the steel-rich structure is typically much greater than its actual lifespan (Cooper et al., 2014). Design strategies could be exploited to facilitate the replacement of components (instead of that whole products), and to make the repair and upgrade of products more attractive. In the buildings sector, refurbishment and new build have similar costs, but currently buildings are replaced long before the end of their lifespan due to changing user needs or planning permissions.

Box 5. Collaboration among industries and cross-sectoral cooperation

Collaboration between two or more companies that lie in geographic proximity, such as in eco-industrial parks or industrial clusters, can help to achieve the economies-of-scale needed for implementing mitigation options, and to overcome technological and infrastructure barriers. Companies that collaborate can benefit from exchange of by-products (e.g. waste heat) and infrastructure sharing, as well as joint purchase of energy efficient technologies. Few assessments exist on the exact impacts of such collaborations on improved material and energy use.

Kalundborg, a small industrial zone on the Danish coast near Copenhagen is seen as the archetype of the spontaneous evolution of industrial symbiosis (Jacobsen, 2006). The web of material and energy exchanges among companies (and with the local community) has developed over the last sixty years. Many national programmes now promote industrial symbiosis actively through the set up of eco-industrial parks, such as the Chinese National Eco-industrial Park Demonstration Program launched in 2000 (Shi et al., 2010). Information is often all that is needed to bring down the transaction costs: the UK's National Industrial Symbiosis Programme (NISP) is free for businesses and brokers resource exchanges between companies. The programme is regarded as successful by industry, whose rapid results in a cost-effective manner (International Synergies Ltd, 2009). The obstacles encountered in practice relate to a lack of technological solutions and of capacity building (Zhu et al., 2014).

Cross-sectoral cooperation, such as CCS clusters that serve the power generation and manufacturing industries jointly, offers further opportunities. In particular, urban symbiosis is seen as a win-win strategy in many countries, particularly in China where cities suffer the impacts from the local pollution of surrounding manufacturing areas (Dong et al., 2014, 2013; Geng et al., 2010). Within the Eco-town programme in Japan (van Berkel et al., 2009), an example of a single urban-industry symbiotic relationship in the city of Kawasaki showed that using municipal solid wastes to make cement lead to a reduction of more than 15% in industrial CO₂ emissions, with further potential for improvement (Hashimoto et al., 2010).

Economic clusters of SMEs are of particular importance in developing economies, and the potential for exploiting mitigation opportunities through collaboration remains underexploited. (Fischedick et al., 2014). Two particular areas in which intra-industry and cross-sectoral cooperation can enhance energy and material use is that of waste and recycling (Chen et al., 2012), and of water reuse and wastewater treatment. Industry is a large water user: global water demand for manufacturing is projected to increase by four-fold from 2000 to 2050, which is higher than for other sectors (OECD, 2012). A number of measures are available to help industrial parks improve water resource management (Geng et al., 2007).

2. Demand-related options

The level of demand for material goods and manufactured products has a significant effect on the activity of the industry sector and resulting GHG emissions (Fischedick et al., 2014). Products that replace other products at the end of their lifespans, as well as new products -introduced to satisfy new needs, or as a result of technological advances- both come into the equation. The demand for products is ultimately driven by the human demand for the services that such products deliver. Demand for services is thus in part responsible for the resulting GHG emissions of the sector.

As introduced in section 2 above, demand is growing globally. The IEA (2012) states that per capita consumption of crude steel amounted to 201 kg in 2010, and is expected to increase to between 270 kg/capita and 319 kg/capita by 2050. Regarding cement, the global average per capita consumption was about 450 kg in 2009. By 2050, the demand will average between 470 kg/capita and 590 kg/capita. This may seem a relatively small increase but regional differences are important: non-OECD countries (excluding China) are expected to rise from an average of 218 kg/capita in 2009 to between 480 kg/capita and 570 kg/capita in 2050. The demand for household, sanitary wrapping and packaging paper is expected to more than double by 2050, while the demand for newsprint and printing paper will increase at a much slower pace (IEA, 2012).

As introduced in section 3.1 above, technical options exist to deliver current levels of products and services with less material, but many of them -in particular many material-efficiency options- are dependent on changing the preferences of consumers (be them individual consumers or sectors, such as the public sector). Policies that incentivize technology-related options in industry (e.g. carbon pricing, voluntary agreements etc) are not always suited for changing consumer preferences towards products. Demand-related options therefore include a range of policy tools aimed at driving cultural and lifestyle shifts in consumer preferences, habits of individuals, and social norms. Such policies can either target the:

Reduction of product demand without reducing the service provided, through using products for longer or more intensively. More intense use can entail either more precise use of consumables (e.g. using the right amount of detergent, reducing food waste – see (Bajžlj et al., 2014)), or less idle time of durable products(e.g. car-sharing initiatives). Delivering the same level of service with

fewer products can also include dematerialisation (e.g. use of e-readers instead of paper),

Management of demand for services so that it can be satisfied with less emission-intensive products (e.g. in transport, promoting mode switching to satisfy mobility needs with less cars), or

Reduction of the demand for services (e.g. travelling shorter distances for leisure), without reducing overall wellbeing.

There are no quantitative estimates of mitigation potential for these options. Case studies and examples from the as yet scarce literature on demand-related options as they relate to specific industry sectors are reviewed by Fischedick et al. (2014).

There are still relatively few policies directly targeted towards reducing the amount of materials needed to make a product and the amount of products needed to satisfy demand for a service. Sustainable consumption and production (SCP) policies are moreover only recently being assessed from the perspective of climate change mitigation. Policy packages directly reducing the products needed per unit of service, or the material input per unit of product include the European Action Plan on Sustainable Consumption and Production and Sustainable Industry (EC, 2008). This plan takes a two-pronged approach: supporting the supply of sustainable products and services and stimulating the demand for these. It includes both voluntary and regulatory instruments, such as the Eco-design, Eco-label and Energy Label Directives, as well as the Green Public Procurement policies. However these packages include few specific policies and, most importantly, do not set quantitative targets nor explicitly address the reduction of demand for products and services.

The concept of "demand management" brings up complex and controversial issues, in particular with regards to developing countries where product and service demand will most grow due to rising incomes and levels of wellbeing. For this reason SCP policies call for different strategies in developing and developed countries. Initiatives that question the use of wealth indicators such as GDP are also gaining terrain (for example, the EU's "Beyond GDP Initiative"). There are moreover initiatives that arise from the bottom-up (e.g. social innovation), on which policy could tap in order to trigger wider changes.

We acknowledge that this is only a brief approximation to the issue of demand-related options. There are a host of other influencing factors and fields of knowledge, such as the

symbolic uses of products, attitudes towards new (and vintage) products, etc. The social sciences are currently producing far more knowledge on this issue than what can be covered here.

IV. Long term decarbonisation pathways

The sections above have described key emission-reducing options, noting where possible their quantitative potential and profitability. This section sums up the quantitative mitigation potentials of different sector scenarios, reviewing recent assessments and focusing on the more long-term pathways that aim for deeper cuts in GHG emissions.

The IEA (2014, 2012) estimates that the implementation of BATs globally could by 2050 reduce industrial overall energy consumption by 20% from current levels. For this to occur at least-cost, all new facilities and retrofitted equipment need to reach BAT level, otherwise later upgrades will be very costly. On the other hand, industry-specific studies suggest that broad application of BAT could reduce energy intensity by about 25%, while innovation could delivering further reductions of 20% (Fischedick et al., 2014) (see Box 3 for further sector-specific estimates). These studies suggest that low cost options (in the ranges of 0-50 USD/tCO₂eq, and even below 0) exist, but to achieve near-zero emission intensity levels in the industry sector would require a significant change of end-use mix or innovative options like CCS, which are associated with higher costs (50-150 USD/tCO₂) (Fischedick et al., 2014). However, important regional variations exist with regards to the estimates of mitigation potential.

Integrated models analyzing all end use sectors and their interdependencies point towards possible reductions in industrial final energy compared to baseline and depending on the ambition of GHG mitigation of 22 to 38% (see Figure 4.1 below, from (Clarke et al., 2014; Fischedick et al., 2014)). The same studies see the potential for switching to low carbon fuels, including electricity, heat, hydrogen and bioenergy ranges from 44 to 57% of final energy.

Most of these scenarios are aggressive, not only requiring immediate deployment of BAT across a large number of production processes, but also quick commercialization of new innovations. In particular, CCS (see Figure 4.2 and Box 4) is considered the most important new technology option for reducing direct emissions in the sector. The IEA (2014, 2012) estimates that more than 30% of industrial emission reductions in its so called 2DS scenario

(i.e. the scenario which has the highest probability of staying within the 2°C targets) would be brought about by CCS, and that without CCS, emissions in 2050 would not be reduced.

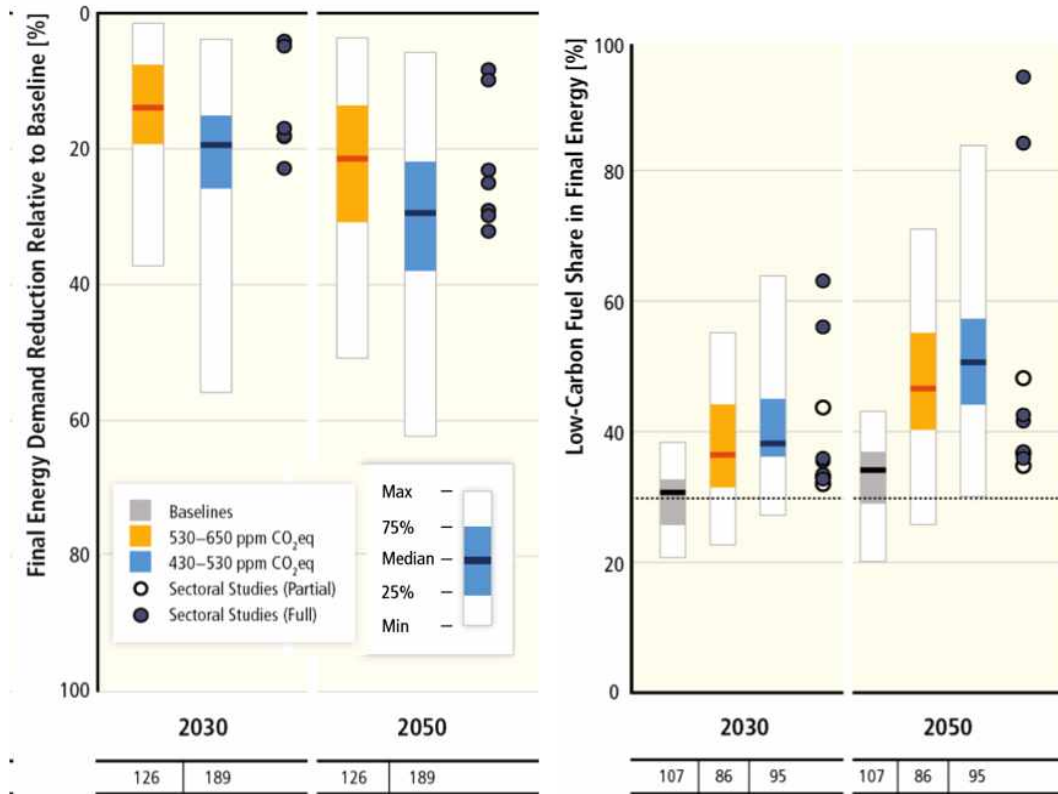


Figure 4-1. Left panel: Final energy demand reduction relative to baseline in the industry sector by 2030 and 2050 in mitigation scenarios reaching 430-530 ppm and 530-650 ppm CO₂eq in 2100 compared to sectoral studies. Right panel: Development of final energy low-carbon fuel shares in the industry sector by 2030 and 2050 in baseline and mitigation scenarios reaching 430-530 ppm and 530-650 ppm CO₂eq in 2100 compared to sectoral studies. Low-carbon fuels include electricity, heat, hydrogen, and bioenergy. Source: Figures 6.37 and 6.38 in (Clarke et al., 2014).

The 2DS scenario and similar scenario investigations suggest that trends in industrial CO₂ emissions must be reversed very soon if the increase of global average temperature is to be limited to 2°C compared to pre-industrial level. To meet the IEA's 2DS targets, emissions must be reduced by 17% by 2025, which is the same rate at which emissions grew from 2007 to 2011. The high risk of not achieving these targets calls for the implementation of cost-efficient

measures beyond energy efficiency and CCS. Most recent assessments and modeling exercises (e.g. IPCC's AR5, IEA's ETP 2014) acknowledge that on a short- and mid-term perspective a further contribution could come from material efficiency and demand reduction. On the long-run decarbonisation of end-use carriers (e.g. renewable energy based electricity or synthetic gases and fuels) is a promising option.

However, to date integrated assessment scenarios cannot accurately project the effect of changes in material efficiency and demand reduction, although the IEA does make a first exploration of the effects of demand in its high and low demand scenarios (see Figure 4.2, left panel), while some of the more detailed industry models contain some elements of material demand in the analysis. The rudimentary representation of materials and demand aspects in long-term scenarios limits the evaluation of the relative importance of these options (Fischedick et al., 2014), and leads to a bias in the emphasis of policymakers who prefer to rely on quantitative targets.

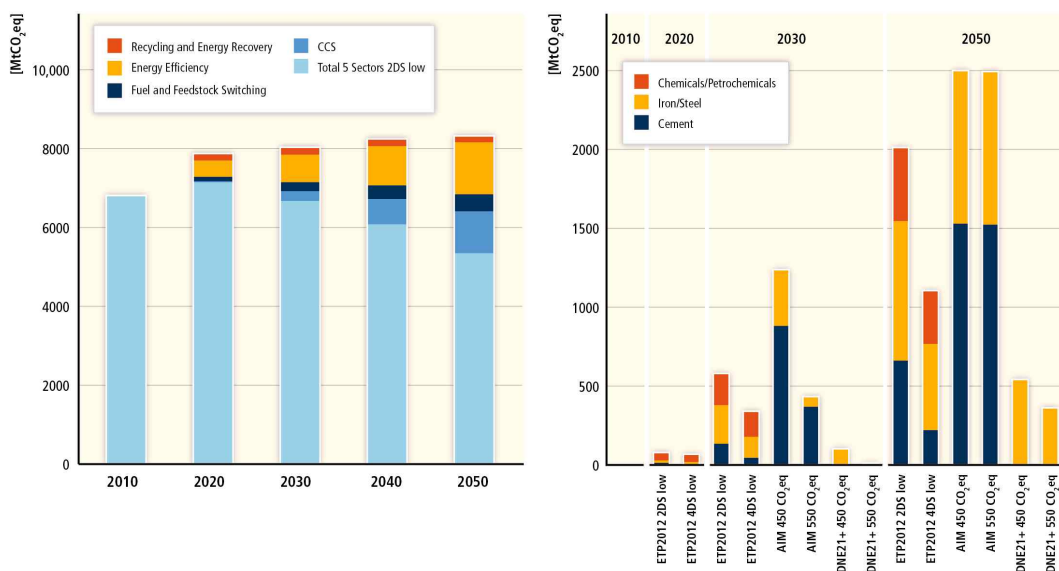


Figure 4-2. Mitigation of direct CO₂eq annual emissions in five major industrial sectors: iron/steel, cement, chemicals/petrochemicals, pulp/paper, and aluminium. The left panel shows results from IEA scenarios (IEA, 2012), broken down by mitigation option. The tops of the bars show the IEA 4DS low demand scenario, the light blue bars show the 2DS low demand scenario. The bar layers show the mitigation options that contribute to the emission difference from the 4DS to the 2DS low demand scenario. The right panel shows mitigation by CCS of direct industrial emissions in IEA, AIM Enduse and DNE21+ models. Scenarios are shown for those subsectors where CCS was reported. Source: Figure 10.14 in (Fischedick et al., 2014).

Box 6. A regional study: NRW's mitigation scenarios for industry sector, a participatory approach

North Rhine-Westphalia (NRW) is home to one of the most important industrial regions in Europe, and is the first German state to have adopted its own Climate Protection Law (CPL), which binds the state to reducing its GHG emissions by at least 25% by 2020 and by at least 80% by 2050 compared to 1990 levels. NRW emits about a third of German greenhouse gas (GHG) emissions (305 MtCO₂eq in 2012) or about 7% of the EU's GHG emissions, and its total emissions are equivalent to those of Spain. The state is therefore key for meeting national and European climate targets. The CPL mandated the development of a Climate Protection Plan (CPP) which will break down the state-wide reduction targets into sectors and time frames and which envisaged strong stakeholder participation. Stakeholders representing the industrial sector were involved in the modelling of the regional industrial energy and emissions scenarios and in the identification of sectoral potentials of climate protection via participatory scenario development (Schneider et al., 2015). Six stakeholder consultation workshops with about 40 stakeholders of 16 stakeholder groups representing main energy-intensive industries, industrial associations, trade unions, chambers of commerce, environment-/conservation and consumer organisations, associations of municipalities, academia and others.

In the realm of energy and climate change mitigation, stakeholder-based scenario building is being increasingly used for inputting relevant data and for improving interpretations of model outputs, as well as for translating the results of the analysis into strategies (Mathy et al., 2015; Schmid and Knopf, 2012). NRW's is a rare example of the use of participatory modelling as a basis for implementing mandatory long-term climate mitigation goals.

V. The challenges, the opportunities

Barriers and opportunities to mitigation of GHG emissions are actor-specific and can be addressed by various levels of governance: from the broader governance framework (planning, targets), through specific policies and instruments (see section 6).

A relatively longstanding research activity into energy efficiency in industry has revealed that, while there may not be many insurmountable technical barriers for a large decrease in emissions, and although many of the options are cost-effective, there are a range of information, motivation and financial barriers that hinder energy efficient upgrades (the so-called "energy efficiency gap"), as well as various unintended consequences of mitigation such as rebound effects (Fischel et al., 2014). In a firm, efficiency is often one feature of a broader

investment decision with multiple objectives (IEA, 2013). Currently, more and more databases are helping firms and policy makers to identify the costs and benefits of efficiency with a particular focus on the impacts on competitiveness (e.g. (IEEP, 2013)). Lack of information on the energy and no-energy savings that can be achieved are addressed by Energy management systems (EnMS), audits and benchmarking, although in most countries such programmes are either semi-voluntary or completely voluntary. Material efficiency also faces significant implementation barriers as the share of the costs of materials in products is relative low compared to the cost of labour and energy. This, together with a lack of research on the potential, inhibits this opportunity. Demand-reduction options, as reviewed in section 3.2, face even greater obstacles, as pricing does not reflect the externalities of the use of material products, and national accounting systems reward increases in spending for products.

While mitigation measures often face barriers at the company or sector level, they also represent opportunities. A typical example of a co-benefit from GHG mitigation in the industry sector is an increase in productivity via reduced use of energy or raw materials inputs and resultant production cost reduction. A study of the impact of energy saving technologies and innovation investments on the productivity of Chinese iron and steel enterprises found that productive efficiency growth can be attributed among other factors to the adoption and amelioration of energy saving measures and the investments in improved techniques associated with energy saving (Zhang and Wang, 2008). Zhang et al (2014) analysed investment required to add energy efficiency end-of-pipe pollutant control options to reduce air pollutants emission in Chinese iron and steel industry. The results show that energy efficiency measures are more cost-effective to reduce air pollutant emissions than end-of-pipe controls, especially for SO₂ emission reduction. They also find that some end-of-pipe technologies not only cost more but also consume more energy.

Investments can also lead to reduced costs of environmental compliance and waste disposal, decreased liability, new business opportunities, or improved work conditions. They also present opportunities to improve innovation in industrial processes and stimulate investment in more efficient production techniques (Bourgouin, 2014; Fischedick et al., 2014). It is important to note that co-benefits need to be assessed in the light of the costs of implementation of the mitigation options (e.g. training requirements, losses during technology installation) (Worrell et al., 2003), which may be larger for SMEs or isolated enterprises (Zhang and Wang, 2008).

The implementation of industrial GHG mitigation options can also lead to positive and negative effects at the macro-level, i.e. on the whole economy and society. The quantification of the benefits and costs that a mitigation technology or practice produces at this level is only recently becoming mainstream. Moreover different stakeholders may have different perspectives of what the corresponding losses and gains are. A recent study by the IEA (OECD, 2014) estimates that large-scale energy efficiency programmes would result in GDP growth rate of between 0.25 to 1.1% per year, create employment and bring about significant energy cost savings. Health and well-being impacts could quadruple the economic savings. Identifying mitigation technology options that results in emissions reduction and energy efficiency improvements as well as minimizing negative outcomes on socio-economic issues is therefore becoming crucial, including with regards to the climate mitigation-adaptation nexus (see Box 6).

At the economy-wide level, mitigation policies in industry and services can have a positive effect on other policy objectives such as local pollution and therefore health. Quantification of these benefits is often done on a case-by-case basis. For example, Mestl et al. (2005) find that the environmental health benefits of using electrical arc furnaces for steel production in the city of Tiyan (China) could potentially lead to higher benefits than other options, despite being the most costly option. If existing barriers to deployment of industrial application of CCS (see Box 4) can be overcome, it could bring about local pollution benefits as it would lead to very low emissions rates, even in the absence of local pollutant regulations (Kuramochi et al., 2012b).

Box 6. Industry and Climate Change

While this article focuses on the way in which industry can reduce its effect on the climate, the question of what are the impacts of climate change on primary is of interest. While the effects of climate change on energy production, agriculture and services sectors such as health, insurance and tourism are relatively well understood, in the case of mining and manufacturing there is only a small number of studies (IPCC, 2014). Kjellstrom et al (2009) make a theoretical assessment of the potential impact of climate change on labour productivity under an assumption of no adaption. Depending on the scenario considered, they estimate that productivity losses could reach maximums of between 15 and 27% in the long-term, particularly in humid countries. Other countries may also experience benefits (up to 6%). Hsiang (2010) finds a statistically significant effect of thermal stress on non-agricultural output of Caribbean countries in the last decades.

There is a strong need for more knowledge on which are the most climate-sensitive production processes and what locations, types of facilities and machinery have the greatest potential vulnerability. Impacts could damage global supply-chains (Khazai et al., 2013), infrastructure and industrial capital assets, and could reduce availability of renewable natural resources, including water. Rising demand for products used to adapt to climate impacts (e.g. materials for flood protection) could, perversely, create pressures to increase industrial emissions (Bourgouin, 2014).

VI. Policy aspects

There is no single policy that can address the full range of mitigation measures available for industry and overcome associated barriers (Fischedick et al., 2014), and current practice acknowledges the importance of policy mixes and of national contexts. Policies can target various barriers, such as lack of awareness, lack of economic incentives, and lack of commercially available technologies, or try to harness different opportunities, such as firm-level co-benefits or health benefits. There is a relatively solid basis of knowledge on the policies that are currently working in the fields of energy and carbon efficiency as part of voluntary agreements, carbon pricing and regulations (e.g. see (Abeelen et al., 2013; IIP, 2014)), but practically no experience in the field of material efficiency, and little attention to the link between demand-related policies and industry (see section 3.2).

Although we cannot delve into the details of the factors driving policy effectiveness in industry, a birds'-eye view of the instruments available to policy makers in the field of energy and emissions efficiency is given in Figure 6-1 below (some examples of ex post evaluations on these types of policies can be found in (Fischedick et al., 2014)). We may compare this traditional view of the policy portfolio with the instruments that could potentially incorporate material efficiency and demand-related mitigation options into policy mixes (e.g. rewarding lightweight design, enforcing waste prevention targets, raising consumer awareness on the need to reduce emissions embodied in material products (Allwood et al., 2012)).

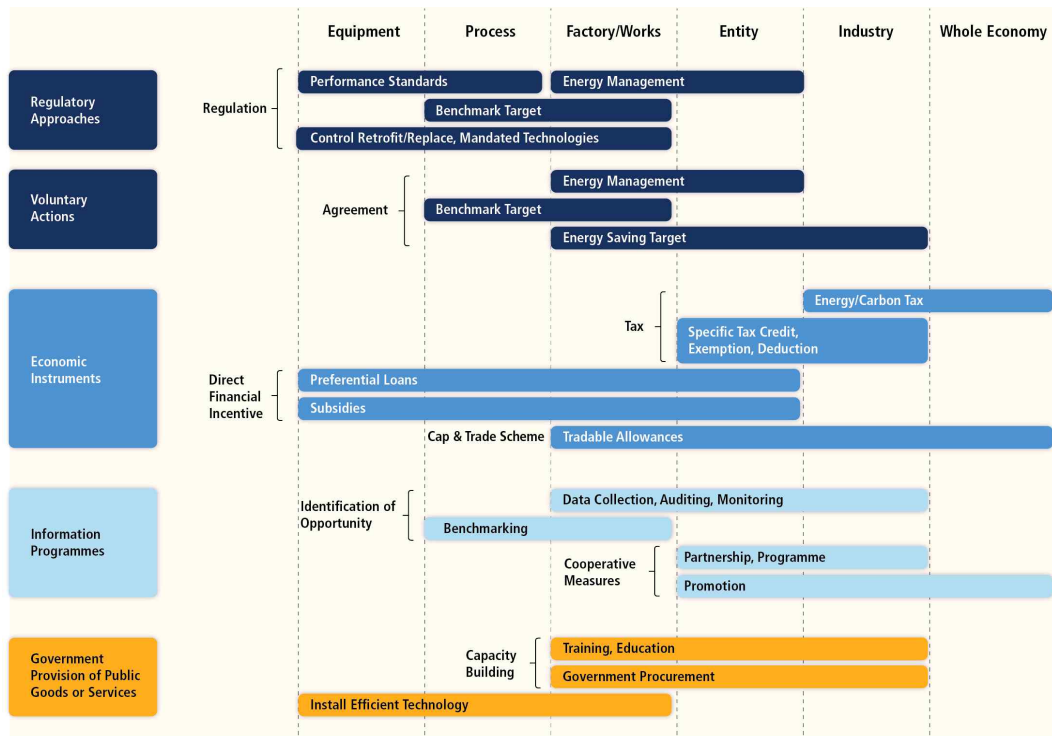


Figure 6–1. Policies available to address energy and carbon efficiency-related options in industry (Source: Figure 10.15 in (Fischelick et al., 2014), based on (Tanaka, 2011))

VII. Conclusions, knowledge gaps and issues for future research

Industry is one of the largest GHG emitting sectors and has particular qualities such as its exposure to trade and its inherent link to all other economic sectors that depend on material commodities (e.g. cement in construction) and products (e.g. vehicles in transport). Industry is not only the concern of industrialized countries: as we move towards the Sustainable Development Goals, manufacturing plays an important role in stimulating economic development and decreasing poverty worldwide (UNIDO, 2014).

By drawing from international analysis, we have seen that despite the ongoing decline in energy intensity, there is still significant potential for improvements in energy and process efficiency in the most-energy intensive material conversion and manufacturing sectors as well as in cross-cutting industrial technologies such as motor systems and co-generation. Other main

technology-related energy and emissions efficiency options for industry include feedstock substitution, electrification, and use of renewable energy sources. Analyses of these options are however still limited for most countries and sectors because of the lack of publicly available data.

Substantial promise for a reduction in emissions lies in a more efficient use of materials and products, as well as through policies aimed at reducing demand for material goods. However estimates of potentials and costs for implementing material efficiency and demand-related reduction strategies are not available. Material flows are often not appropriately accounted for in modeling exercises, which further inhibits the quantitative analysis of these options. We acknowledge that this article has only provided a broad view and that even at this general level we have left aside many issues that would deserve mention. One example is the role that the waste industry has in creating incentives and disincentives for material efficiency.

Various barriers inhibit adoption of mitigation options (even those which are profitable or have low direct costs). Even energy efficiency investments, which are the target of most industry-oriented mitigation policies in most countries, still face high capital cost barriers. Several innovative technologies are awaiting commercialization, but the chief example – CCS – has as yet not been sufficiently demonstrated at a large scale in an industrial context. There are moreover several obstacles to taking a system view: the many interactions among industries, and between industry and other economic sectors have significant implications for GHG mitigation. We have described possibilities for collaboration among industries, and for looking at the whole supply chain in search for opportunities (e.g. upstream for opportunities for substitution of materials, or downstream for enhancing material efficiency through changes in consumer preferences). Lastly, more research is needed on the quantification of synergies between firms' goals and policy goals, as well as on the evaluation of possible co-benefits of mitigation in industry, which can help to tackle different policy problems jointly and therefore enhance the political acceptability of mitigation measures.

References

- Abeelen, C., Harmsen, R., Worrell, E., 2013. Implementation of energy efficiency projects by Dutch industry. *Energy Policy* 63, 408–418. doi:10.1016/j.enpol.2013.09.048

- Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2013. Material efficiency: providing material services with less material production. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 371.
- Allwood, J.M., Cullen, J.M., Carruth, M.A., Cooper, D.R., McBrien, M., Milford, R.L., Moynihan, M., Patel, A.C.H., 2012. *Sustainable Materials: with both eyes open*. UIT Cambridge Ltd, Cambridge, England.
- Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050. *Environ. Sci. Technol.* 44, 1888–1894. doi:doi: 10.1021/es902909k
- Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E., Gilligan, C.A., 2014. Importance of food-demand management for climate mitigation. *Nature Clim. Change* 4, 924–929. doi:10.1038/nclimate2353
- Banerjee, R., Cong, Y., Gielen, D., Jannuzzi, G., Maréchal, F., McKane, A.T., Rosen, M.A., van Es, D., Worrell, E., 2012. Chapter 8 - Energy End Use: Industry, in: *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 513–574.
- Bourgouin, F., 2014. *Climate Change: Implications for Extractive and Primary Industries. Key Findings from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)*. European Climate Foundation (ECF), Business for Social Responsibility (BSR), University of Cambridge's Judge Business School (CJBS) and Institute for Sustainability Leadership (CISL), Cambridge, UK.
- Broeren, M.L.M., Saygin, D., Patel, M.K., 2014. Forecasting global developments in the basic chemical industry for environmental policy analysis. *Energy Policy* 64, 273–287.
- Brown, M.A., Cox, M., Baer, P., 2013. Reviving manufacturing with a federal cogeneration policy. *Energy Policy* 52, 264–276. doi:10.1016/j.enpol.2012.08.070
- Bruckner, T., Bashmakov, I.A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H.B., Riahi, K., Strachan, N., Wiser, R., Zhang, X., 2014. Energy Systems, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow,

- T. Zwickel and J.C. Minx (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Carruth, M.A., Allwood, J.M., Moynihan, M.C., 2011. The technical potential for reducing metal requirements through lightweight product design. *Resources, Conservation and Recycling* 57, 48 – 60. doi:10.1016/j.resconrec.2011.09.018
- CEPI, 2013. Unfold the Future: The Two Team Project [WWW Document]. URL <http://www.unfoldthefuture.eu/>
- CEPI, 2012. Key Statistics 2011–European Pulp and Paper Industry. Confederation of European Paper Industries, Brussels, Belgium, Brussels, Belgium.
- Cheng, H.-H., Shen, J.-F., Tan, C.-S., 2010. CO₂ capture from hot stove gas in steel making process. *International Journal of Greenhouse Gas Control* 4, 525–531. doi:16/j.ijggc.2009.12.006
- Chen, X., Fujita, T., Ohnishi, S., Fujii, M., Geng, Y., 2012. The Impact of Scale, Recycling Boundary, and Type of Waste on Symbiosis and Recycling. *Journal of Industrial Ecology* 16, 129–141. doi:10.1111/j.1530-9290.2011.00422.x
- Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P.R., Tavoni, M., van der Zwaan, B., van Vuuren, D.P., 2014. Assessing Transformation Pathways, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Cooper, D., 2014. Reuse of steel and aluminium without melting (Thesis). University of Cambridge.
- Cooper, D.R., Allwood, J.M., 2012. Reusing steel and aluminum components at end of product life. *Environ. Sci. Technol.* 46, 10334–10340. doi:10.1021/es301093a
- Cooper, D.R., Skelton, A.C.H., Moynihan, M.C., Allwood, J.M., 2014. Component level strategies for exploiting the lifespan of steel in products. *Resources, Conservation and Recycling* 84, 24–34. doi:10.1016/j.resconrec.2013.11.014
- Croezen, H., Korteland, M., 2010. Technological developments in Europe: A long-term view of CO₂ efficient manufacturing in the European region (No. 10.7207.47), CE Delft Report. CE Delft, Delft.
- Cullen, J.M., Allwood, J.M., 2013. Mapping the Global Flow of Aluminum: From Liquid Aluminum to

- End-Use Goods. *Environ. Sci. Technol.* 47, 3057–3064. doi:10.1021/es304256s
- Cullen, J.M., Allwood, J.M., Borgstein, E.H., 2011. Reducing Energy Demand: What Are the Practical Limits? *Environ. Sci. Technol.* 45, 1711–1718. doi:10.1021/es102641n
- Daigoglou, V., Faaij, A.P.C., Saygin, D., Patel, M.K., Wicke, B., Vuuren, D.P. van, 2014. Energy demand and emissions of the non-energy sector. *Energy Environ. Sci.* 7, 482–498. doi:10.1039/C3EE42667J
- Dong, L., Fujita, T., Zhang, H., Dai, M., Fujii, M., Ohnishi, S., Geng, Y., Liu, Z., 2013. Promoting low-carbon city through industrial symbiosis: A case in China by applying HPIMO model. *Energ. Policy* 61, 864–873. doi:10.1016/j.enpol.2013.06.084
- Dong, L., Gu, F., Fujita, T., Hayashi, Y., Gao, J., 2014. Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China. *Energy Policy* 65, 388–397. doi:10.1016/j.enpol.2013.10.019
- EC, 2008. Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan. {SEC(2008) 2110} {SEC(2008) 2111}.
- EIIF, Ecofys, 2013. Climate protection with rapid payback: Energy and CO₂ savings potential of industrial insulation in EU27. European Industrial Insulation Foundation and Ecofys.
- EPA, 2013. Global Mitigation of Non-CO₂Greenhouse Gases: 2010-2030 (No. EPA-430-R-13-011). United States Environmental Protection Agency, Washington, D.C., USA.
- Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J.M., Ceron, J.-P., Geng, Y., Kheshgi, H.S., Lanza, A., Perczyk, D., Price, L., Santalla, E., Sheinbaum, C., Tanaka, K., 2014. Industry, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Fritzson, A., Berntsson, T., 2006. Energy efficiency in the slaughter and meat processing industry—opportunities for improvements in future energy markets. *Journal of Food Engineering* 77, 792–802. doi:10.1016/j.jfoodeng.2005.08.005
- Galitsky, C., Worrell, E., Ruth, M., 2003. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. US Environmental Protection Agency.
- Geng, Y., Côté, R., Tsuyoshi, F., 2007. A quantitative water resource planning and management model for an industrial park level. *Regional Environmental Change* 7, 123–135.

doi:10.1007/s10113-007-0026-4

- Geng, Y., Fujita, T., Chen, X., 2010. Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. *Journal of Cleaner Production* 18, 993–1000. doi:10.1016/j.jclepro.2010.03.003
- Geyer, R., 2008. Parametric assessment of climate change impacts of automotive material substitution. *Environmental Science and Technology* 42, 6973–6979.
- Global CCS Institute, 2011. The global status of CCS. Global CCS Institute, Canberra.
- Gutowski, T.G., Sahni, S., Allwood, J.M., Ashby, M.F., Worrell, E., 2013. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. *Phil. Trans. R. Soc. A* 371, 20120003. doi:10.1098/rsta.2012.0003
- Gutowski, T.G., Sahni, S., Boustani, A., Graves, S.C., 2011. Remanufacturing and Energy Savings. *Environ. Sci. Technol.* 45, 4540–4547. doi:10.1021/es102598b
- Hasanbeigi, A., Arens, M., Price, L., 2013a. Emerging Energy-Efficiency and Greenhouse Gas Mitigation Technologies for the Iron and Steel Industry (No. LBNL-6106E). Lawrence Berkeley National Laboratory, Berkeley, CA.
- Hasanbeigi, A., Menke, C., Price, L., 2010. The CO₂ abatement cost curve for the Thailand cement industry. *Journal of Cleaner Production* 18, 1509–1518. doi:10.1016/j.jclepro.2010.06.005
- Hasanbeigi, A., Morrow, W., Masanet, E., Sathaye, J., Xu, T., 2013b. Energy efficiency improvement and CO₂ emission reduction opportunities in the cement industry in China. *Energy Policy* 57, 287–297. doi:10.1016/j.enpol.2013.01.053
- Hasanbeigi, A., Morrow, W., Sathaye, J., Masanet, E., Xu, T., 2013c. A bottom-up model to estimate the energy efficiency improvement and CO₂ emission reduction potentials in the Chinese iron and steel industry. *Energy* 50, 315–325. doi:10.1016/j.energy.2012.10.062
- Hasanbeigi, A., Price, L., Lin, E., 2012. Emerging energy-efficiency and CO₂ emission-reduction technologies for cement and concrete production: A technical review. *Renewable and Sustainable Energy Reviews* 16, 6220–6238. doi:10.1016/j.rser.2012.07.019
- Hashimoto, S., Fujita, T., Geng, Y., Nagasawa, E., 2010. Realizing CO₂ emission reduction through industrial symbiosis: A cement production case study for Kawasaki. *Resources Conservation and Recycling* 54, 704–710. doi:10.1016/j.resconrec.2009.11.013
- Hsiang, S.M., 2010. Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences* 107, 15367–15372. doi:10.1073/pnas.1009510107
- IEA, 2014. Energy Technology Perspectives 2014: Harnessing Electricity's potential. Organisation for

- Economic Co-operation and Development, Paris.
- IEA, 2013. Energy Efficiency. Organisation for Economic Co-operation and Development, Paris.
- IEA, 2012. Energy Technology Perspectives 2012: Pathways to a clean energy system. International Energy Agency (IEA), Paris, France.
- IEAGHG, 2008. CO₂Capture in the Cement Industry (Technical Study No. 2008/3). International Energy Agency Greenhouse Gas R&D Programme, Cheltenham.
- IEEP, 2013. Review of Cost and Benefits of Energy Savings. Institute for European Environmental Policy.
- IIP, 2014. Institute for Industrial Productivity [WWW Document]. URL <http://www.iipnetwork.org> (accessed 10.17.14).
- International Synergies Ltd, 2009. National Industrial Symbiosis Programme - The Pathway to a low carbon sustainable economy. by Peter Lay-bourn and Maggie Morrissey.
- IPCC, 2014. Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jacobsen, N.B., 2006. Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. *Journal of Industrial Ecology* 10, 239–255. doi:10.1162/108819806775545411
- Jönsson, J., Berntsson, T., 2012. Analysing the potential for implementation of CCS within the European pulp and paper industry. *Energy, Integration and Energy System Engineering, European Symposium on Computer-Aided Process Engineering* 2011 44, 641–648. doi:10.1016/j.energy.2012.05.028
- Kermeli, K., Graus, W.H.J., Worrell, E., 2014. Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector. *Energy Efficiency* 1–25. doi:10.1007/s12053-014-9267-5
- Khazai, B., Merz, M., Schulz, C., Borst, D., 2013. An integrated indicator framework for spatial assessment of industrial and social vulnerability to indirect disaster losses. *Nat Hazards* 67, 145–167. doi:10.1007/s11069-013-0551-z
- Kim, H.-J., Keoleian, G.A., Skerlos, S.J., 2011. Economic Assessment of Greenhouse Gas Emissions Reduction by Vehicle Lightweighting Using Aluminum and High-Strength Steel. *Journal of Industrial Ecology* 15, 64–80.
- Kjellstrom, T., Kovats, R.S., Lloyd, S.J., Holt, T., Tol, R.S.J., 2009. The direct impact of climate change

- on regional labor productivity. *Arch Environ Occup Health* 64, 217–227.
doi:10.1080/19338240903352776
- Kramer, K.J., Masanet, E., Xu, T., Worrell, E., 2009. Energy Efficiency Improvement and Cost Saving Opportunities for the Pulp and Paper Industry: An ENERGY STAR Guide for Energy and Plant Managers (No. LBNL-2268E). Lawrence Berkeley National Laboratory, Berkeley, CA.
- Kuramochi, T., Ramírez, A., Turkenburg, W., Faaij, A., 2012a. Comparative assessment of CO₂ capture technologies for carbon-intensive industrial processes. *Progress in Energy and Combustion Science* 38, 87–112. doi:10.1016/j.pecs.2011.05.001
- Kuramochi, T., Ramírez, A., Turkenburg, W., Faaij, A., 2012b. Effect of CO₂ capture on the emissions of air pollutants from industrial processes. *International Journal of Greenhouse Gas Control* 10, 310–328. doi:10.1016/j.ijggc.2012.05.022
- Laurijssen, J., Faaij, A., Worrell, E., 2012. Benchmarking energy use in the paper industry: a benchmarking study on process unit level. *Energy Efficiency* 6, 49–63.
doi:10.1007/s12053-012-9163-9
- Liu, G., Bangs, C.E., Müller, D.B., 2012. Stock dynamics and emission pathways of the global aluminium cycle. *Nature Climate Change*. doi:10.1038/nclimate1698
- Lutsey, N.P., Sperling, D., 2008. America's Bottom-Up Climate Change Mitigation Policy.
- Masanet, E., 2010. Energy Benefits of Electronic Controls at Small and Medium Sized U.S. Manufacturers. *Journal of Industrial Ecology* 14, 696–702.
doi:10.1111/j.1530-9290.2010.00286.x
- Mathy, S., Fink, M., Bibas, R., 2015. Rethinking the role of scenarios: Participatory scripting of low-carbon scenarios for France. *Energy Policy* 77, 176–190. doi:10.1016/j.enpol.2014.11.002
- Mazzotti, M., Abanades, J., Allam, R., Lackner, K., Meunier, F., Rubin, E., Sanchez, J., Yogo, K., Zevenhoven, R., 2005. Mineral carbonation and industrial uses of carbon dioxide, in: IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press, Cambridge, UK and New York, USA.
- McKane, A., Hasanbeigi, A., 2011. Motor systems energy efficiency supply curves: A methodology for assessing the energy efficiency potential of industrial motor systems. *Energy Policy* 39, 6595–6607. doi:10.1016/j.enpol.2011.08.004
- Mestl, H.E.S., Aunan, K., Fang, J., Seip, H.M., Skjelvik, J.M., Vennemo, H., 2005. Cleaner production as climate investment—integrated assessment in Taiyuan City, China. *Journal of Cleaner Production* 13, 57–70. doi:10.1016/j.jclepro.2003.08.005
- Milford, R.L., Allwood, J.M., Cullen, J.M., 2011. Assessing the potential of yield improvements,

- through process scrap reduction, for energy and CO₂ abatement in the steel and aluminium sectors. *Resources, Conservation and Recycling* 55, 1185 – 1195.
doi:10.1016/j.resconrec.2011.05.021
- Milford, R.L., Pauliuk, S., Allwood, J.M., Müller, D.B., 2013. The Roles of Energy and Material Efficiency in Meeting Steel Industry CO₂ Targets. *Environ. Sci. Technol.* 47, 3455–3462.
doi:10.1021/es3031424
- Minx, J.C., Baiocchi, G., Peters, G.P., Weber, C.L., Guan, D., Hubacek, K., 2011. A "Carbonizing Dragon": China's Fast Growing CO₂ Emissions Revisited. *Environ. Sci. Technol.* 45, 9144–9153. doi:10.1021/es201497m
- Monahan, J., Powell, J.C., 2011. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings* 43, 179–188. doi:10.1016/j.enbuild.2010.09.005
- Napp, T., 2014. Attitudes and Barriers to Deployment of CCS from Industrial Sources in the UK, Grantham Report GR6: February 2014. Grantham Institute - Imperial College London.
- Naranjo, M., Brownlow, D.T., Garza, A., 2011. CO₂ capture and sequestration in the cement industry. *Energy Procedia* 4, 2716–2723. doi:10.1016/j.egypro.2011.02.173
- Oda, J., Akimoto, K., Tomoda, T., Nagashima, M., Wada, K., Sano, F., 2012. International comparisons of energy efficiency in power, steel, and cement industries. *Energy Policy* 44, 118–129.
doi:10.1016/j.enpol.2012.01.024
- OECD, 2014. Capturing the Multiple Benefits of Energy Efficiency. Organisation for Economic Co-operation and Development, Paris.
- OECD, 2012. OECD Environmental Outlook to 2050. Organisation for Economic Co-operation and Development, Paris.
- Ren, T., Patel, M., Blok, K., 2006. Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes. *Energy* 31, 425–451.
doi:10.1016/j.energy.2005.04.001
- Ren, T., Patel, M.K., 2009. Basic petrochemicals from natural gas, coal and biomass: Energy use and CO₂ emissions. *Resources, Conservation and Recycling* 53, 513–528.
doi:10.1016/j.resconrec.2009.04.005
- Sartori, I., Hestnes, A.G., 2007. Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings* 39, 249–257. doi:10.1016/j.enbuild.2006.07.001
- Saygin, D., Patel, M.K., Worrell, E., Tam, C., Gielen, D.J., 2011a. Potential of best practice technology to improve energy efficiency in the global chemical and petrochemical sector. *Energy* 36,

- 5779–5790. doi:10.1016/j.energy.2011.05.019
- Saygin, D., Worrell, E., Patel, M.K., Gielen, D.J., 2011b. Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries. *Energy* 36, 6661–6673. doi:10.1016/j.energy.2011.08.025
- Schmid, E., Knopf, B., 2012. Ambitious mitigation scenarios for Germany: A participatory approach. *Energy Policy, Renewable Energy in China* 51, 662–672. doi:10.1016/j.enpol.2012.09.007
- Schneider, C., Höller, S., Lechtenböhmer, S., Yetano Roche, M., 2015. Re-industrialisation and low-carbon economy – can they go together? Results from stakeholder-based scenarios for energy-intensive industries. forthcoming.
- Shi, H., Chertow, M., Song, Y., 2010. Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China. *Journal of Cleaner Production* 18, 191–199. doi:10.1016/j.jclepro.2009.10.002
- Sinden, G.E., Peters, G.P., Minx, J., Weber, C.L., 2011. International flows of embodied CO₂ with an application to aluminium and the EU ETS. *Climate Policy* 11, 1226–1245. doi:10.1080/14693062.2011.602549
- Skelton, A., Guan, D., Peters, G.P., Crawford-Brown, D., 2011. Mapping Flows of Embodied Emissions in the Global Production System. *Environ. Sci. Technol.* 45, 10516–10523. doi:10.1021/es202313e
- Tanaka, K., 2011. Review of policies and measures for energy efficiency in industry sector. *Energy Policy* 39, 6532–6550. doi:10.1016/j.enpol.2011.07.058
- Tsupari, E., Kärki, J., Arasto, A., Pisilä, E., 2013. Post-combustion capture of CO₂ at an integrated steel mill – Part II: Economic feasibility. *International Journal of Greenhouse Gas Control* 16, 278–286. doi:10.1016/j.ijggc.2012.08.017
- UNIDO, 2014. Industry 4 inclusive and sustainable development.
- UNIDO, 2013. Industrial Development Report 2013. Sustaining Employment Growth: The Role of Manufacturing and Structural Change, United Nations Industrial Development Organisation. ed. United Nations Pubns.
- UNIDO, 2011. Industrial Development Report 2011 Industrial Energy Efficiency for Sustainable Wealth Creation: Capturing Environmental, Economic and Social Dividends, United Nations Industrial Development Organisation. ed. United Nations Pubns.
- Van Berkel, R., Fujita, T., Hashimoto, S., Geng, Y., 2009. Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. *Journal of Environmental Management* 90, 1544–1556. doi:10.1016/j.jenvman.2008.11.010

- Wara, M.W., 2008. Measuring the Clean Development Mechanism's Performance and Potential (SSRN Scholarly Paper No. ID 1086242). Social Science Research Network, Rochester, NY.
- Worrell, E., Blinde, P., Neelis, M., Blomen, E., Masanet, E., 2010. Energy efficiency improvement and cost saving opportunities for the U.S. iron and steel industry (No. LBNL-4779E). Ernest Orlando Lawrence Berkeley National Laboratory.
- Worrell, E., Laitner, J.A., Ruth, M., Finman, H., 2003. Productivity benefits of industrial energy efficiency measures. *Energy* 28, 1081–1098.
- Xu, T., Flapper, J., 2011. Reduce energy use and greenhouse gas emissions from global dairy processing facilities. *Energy Policy* 39, 234–247. doi:10.1016/j.enpol.2010.09.037
- Xu, T., Sathaye, J., Galitsky, C., 2011. Development of Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Iron and Steel Sector (No. LBNL-4314E). Lawrence Berkeley National Laboratory.
- Yeo, D., Gabbai, R.D., 2011. Sustainable design of reinforced concrete structures through embodied energy optimization. *Energy and Buildings* 43, 2028–2033. doi:10.1016/j.enbuild.2011.04.014
- Zhang, J., Wang, G., 2008. Energy saving technologies and productive efficiency in the Chinese iron and steel sector. *Energy* 33, 525–537. doi:10.1016/j.energy.2007.11.002
- Zhang, S., Worrell, E., Graus, W., 2014. Integrated assessment of co-benefits between energy efficiency improvement and emission mitigation in Chinese iron and steel industry. Presented at the Eceee Industrial Summer Study.
- Zhu, Q., Geng, Y., Sarkis, J., Lai, K.-H., 2014. Barriers to Promoting Eco-Industrial Parks Development in China. *Journal of Industrial Ecology* n/a–n/a. doi:10.1111/jiec.12176