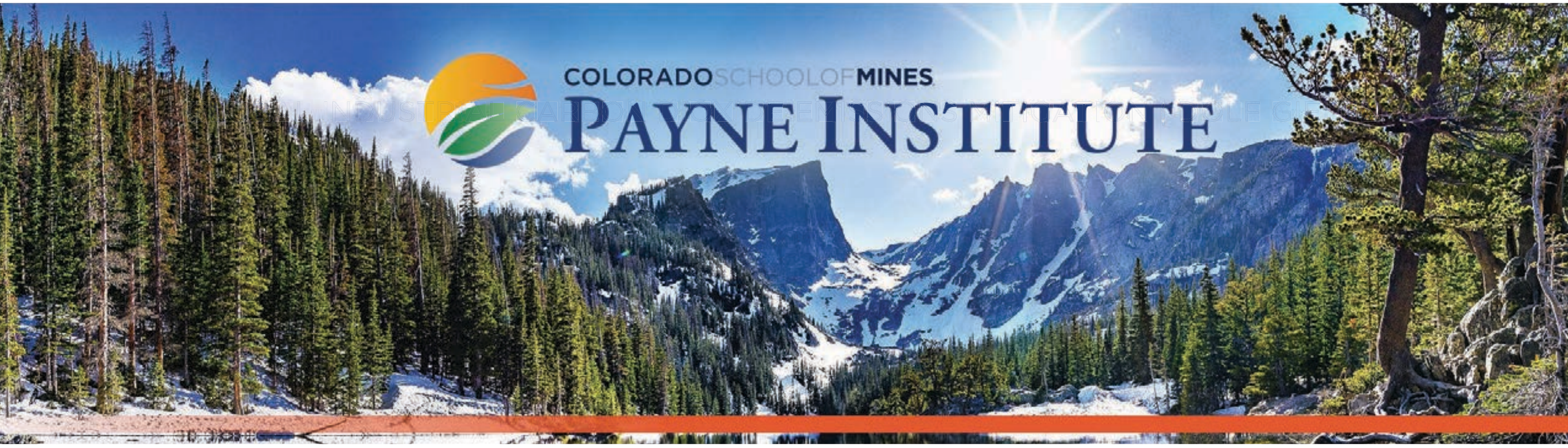


PAYNE INSTITUTE COMMENTARY SERIES: **WORKING PAPER**

GLOBAL INDUSTRIAL CARBON DIOXIDE EMISSIONS MITIGATION: INVESTIGATION OF THE ROLE OF RENEWABLE ENERGY AND OTHER TECHNOLOGIES UNTIL 2060

BY DOLF GIELEN AND DEGER SAYGIN
JUNE 2018

ABSTRACT

The Paris Climate Agreement objective of well-below 2 degrees global average temperature change requires the elimination of anthropogenic CO_2 emissions shortly after 2060. The industry sector is an important source of greenhouse gas emissions. In 2015, sector's direct carbon dioxide (CO_2) emissions represented around 30% of all energy sector CO_2 emissions. Three quarters of these emissions arise from the production of energy-intensive bulk materials like metals, chemical and petrochemical products and cement. Industry will require accelerated development and commercialization of new zero-carbon technology solutions to achieve this objective, but policy attention and progress to date has been limited. This study provides an overview of public and private sector initiatives that aim to find new technical solutions and strategies. All low-carbon energy technology options including renewable energy, electrification, carbon capture and storage (CCS), energy efficiency will play important roles moving forward. Special attention is paid to the role that renewable energy can play for decarbonisation, as well as the opportunity that lies in better management of material flows in the economy. The analysis concludes that renewables can account for 62% of final energy supply by 2060 (including renewable electricity). This opens the way for a 70% reduction in industrial emissions from baseline to 3.6 gigatonnes (Gt) per year in 2060 at a cost of 15-90 USD/t CO_2. Further breakthroughs are needed to eliminate the remaining emissions. Biomass carbon storage and use and new forms of concrete waste recycling are two examples of such potential breakthroughs that are discussed.

The United Nations Framework Convention on Climate Change Paris Climate Agreement calls for a limit to global temperature increase to well below 2 degrees Celsius (2°C) above preindustrial levels. A 67% chance of staying below 2°C limits global anthropogenic CO_2 emissions to 880 gigatonnes (Gt) for the period 2015-2100, leaving 90 Gt for industrial process emissions and 790 Gt for energy use CO_2 emissions. This emissions objective requires energy sector emissions below 10 Gt by 2050 and zero emissions shortly after 2060 (IRENA, 2017a).

Over the past few decades significant progress has been achieved in reducing industry sector's GHG emissions of substances that deplete the ozone layer, as outlined in the Montreal Protocol, as well as nitrous oxide (N_2O), sulphur hexafluoride (SF_6) and others (UN DESA, 2016). This demonstrates that industrial emissions reduction progress is possible under the right regulatory conditions.

The dominant remaining industrial GHG emission is CO_2, which can be divided into energy-related emissions from fossil fuel combustion to generate process heat in the form of hot water, steam and direct heat as well as process emissions such as from limestone calcination during the cement clinker making process. In addition, CO_2 is also emitted during the production of electricity and district heat for industrial use. Emissions also arise throughout the life cycle of industrial synthetic organic products, such as fugitive emissions during use of solvents, lubricants and other compounds and post-consumer plastic waste incineration (Patel et al., 2005). Industry sector represents one-third of the total final global energy use and about 40% of energy-related CO_2 emissions (IEA, 2009).

In 2015, industry's total CO_2 emissions have reached 15 Gt. Direct emissions account for around two-thirds of these emissions (9.5 Gt); the remaining one-third comes from indirect emissions in power and district heat generation (5.5 Gt). This also includes around 3.4 Gt per year (Gt/year) of industrial process emissions (Janssens-Maenhout et al., 2017; IEA, 2017a; IRENA, 2017a). It excludes emissions related to industrial product use (e.g. plastic waste incineration). This paper focuses on the assessment of options to reduce direct and indirect industrial emissions.

Industry sector will have a critical role in realising long-term decarbonisation goals (Fais, Sabio and Strachan, 2016; Wesseling et al., 2017). However, this issue has so far received limited attention in the policy debate. Also, policy plans reflected in the Nationally Determined Contributions (NDCs) attribute limited relevance to this sector. The World Bank NDC database shows only 31 measures for specific materials producing industry sectors out of 2,326 measures in total that countries have proposed (the Wold Bank, 2018). This is equivalent to only 1.3% of all measures and very low in comparison to the relevance of the sector. Carbon leakage because of relocation of industries to countries with more lenient policy frameworks has been often quoted as a major deterrent for an ambitious climate policy in industry though its potential. Opinions are divided, some conclude that its impact may be overstated (Gielen, 2000; Gielen and Yagita, 2002) while other analysis suggests CCS deployment would indeed result in decreased competitiveness (Onarheim, Mathiesen and Arasto, 2015). In general, a perceived lack of economically and technically viable and socially acceptable mitigation options for the industry plays an important role for the limited transition to date (Ahman, Nilsson and Johansson, 2017).

In fact, a range of technology options for emissions reduction in the industry sector exist:

- Earlier analysis has shown that industrial energy efficiency improvements could result in energy savings of up to 25% compared to today's level and reductions in CO_2 emissions on a similar magnitude of order (Gielen, Newman and Patel, 2008; Saygin et al., 2011). Improving energy efficiency is priority and it will be the core of making all new industrial installations low-carbon after 2020 (Kuramochi et al., 2018).
- Renewable energy accounts for 8 exajoules (EJ) or around 10% of the total current global industrial energy demand (excluding feedstock and electricity use) (Taibi, Gielen and Bazilian, 2012). Renewable energy is mainly used in the pulp and paper and food sectors, accounting for approximately 45% and 25% of their energy demand, respectively (Taibi, Gielen and Bazilian, 2012). Although renewable energy in industry has not yet received the same attention as in other energy sectors, it is technically and economically possible to substitute a quarter of the total global industrial fossil energy and feedstock use with biomass (Saygin et al., 2014).

Solar heating, geothermal and heat pumps could substitute 15% of fossil fuel use. Today only certain applications of renewable energy are cost effective such as low temperature process heat generation with solar water heaters or steam production from low-cost biomass residues. Breweries, dairy industry and textile processing industries are typical sectors where these technologies are applied. Important economic, technical and logistical barriers remain. Yet in the near future and with proper policy frameworks put in place, renewable energy technologies can provide practical and cost-effective alternatives for process heat generation and as a renewable carbon source for the production of chemical and plastics (Chen and Patel, 2011; IRENA, 2014; Saygin et al., 2014).

- One strategy that has received some attention in recent years is the conversion of the existing thermal process to electricity-based alternatives coupled with renewable power generation. Renewable electricity can also be used to generate hydrogen that can be used to replace fossil fuels (IEA, 2017b). Electricity can also be used as a feedstock for chemicals and plastics production (McLellan et al., 2012; Schiffer and Manthiram, 2017).
- While renewables and energy efficiency could make significant contribution to industrial emission reductions, their joint potential is not enough to decarbonise the industry sector entirely. CO_2 capture and storage (CCS) can be deployed for manufacturing of iron, ammonia, cement clinker and ethylene oxide production (Mikunda et al., 2014). Especially for industries with high process emissions such as cement clinker production this option can play an important role. Up to one-third of all industrial CO_2 emissions could be mitigated by CCS (UNIDO, 2010). However, CCS technologies would reduce energy savings from improving energy efficiency since they require additional energy to run processes (Saygin et al., 2013).

- The transition to low-carbon technologies would also have implications on the metabolism of bulk materials life cycle. For instance, higher efficiency of materials use could reduce the demand for new materials production and interesting opportunities exist for product reuse and materials recycling (Worrell, Allwood and Gutowski, 2016; Scott et al., 2017). Thus, it is also a priority to understand the material flow related options better (UNEP, 2016; Krausmann et al., 2017a).

Against the significant potential offered by a range of low-carbon technologies, the progress in deep decarbonisation of the industry sector has been slow (Wesseling et al., 2017). The iron and steel, cement and chemical and petrochemical sectors pose important challenges (see Figure 1) (IRENA, 2017a;b). There is an urgency to find and deploy scalable and economically viable emission reduction technologies in these sectors given their significant contribution to global CO_2 emissions.

In view of these knowledge gaps and given the need for a better understanding of strategies to accelerate the uptake of low-carbon technologies in the industry sector, the objective of this working paper is to show the technology potential and what industry sector decarbonisation would imply on the material flows. The remainder of this paper is organized as follows: the next section briefly introduces the status of knowledge and the assessment methodology. In the subsequent section, results are presented regarding emission reduction potentials and their technological and economic aspects. Special attention is focused on the material flow perspective and its emissions reduction potential. In the last section, results are discussed, and the paper ends with general conclusions and recommendations for policy makers, companies and industry sector associations.

STATUS OF TECHNOLOGY AND ROADMAPS FOR INDUSTRY SECTOR DECARBONISATION AND THE VALUE ADDED OF THE PRESENT STUDY

It takes a decade or more for an energy technology to become commercially available. It is therefore important that efforts start now to realise the technology mix estimated for 2060. Considering the importance of the sectors selected for this analysis, recent years have seen an increasing number of roadmap and outlook studies carried out by sector industry associations that complement the efforts of the scientific community about the role low-carbon technologies can play in transition to a sustainable industry. An overview of these roadmaps for chemical and petrochemical, iron and steel and cement production sectors is presented in Table 1. Apart from global sectoral roadmaps several regional and country specific roadmaps exist, for example for Indian cement (IEA, 2013) or for the European pulp and paper (CEPI 2013; 2017) and aluminium (EEA, 2015) sectors. These industry roadmaps assess all types of low-carbon technologies that are relevant for the sectors. The level of assessment varies from high-level technology strategy discussions or individual technology assessments to long-term scenarios.

The results presented in this paper stem from IRENA's in-depth global energy modelling framework - REmap (IRENA, 2017a).[1] REmap is based on a unique

---

[1] Earlier results have been published as part of a joint study by IRENA and the International Energy Agency (IEA) for the G20 Presidency (IRENA and IEA, 2017; G20, 2017).

technology and project cost dataset. Technology status and outlook data were derived from a set of recent technology status and technology outlook reports. Technology costs and cost projections were derived from the costing database that has been developed by IRENA, the most comprehensive existing and publicly accessible database of renewable energy technology costs (IRENA, 2017c;d). Regarding the technology deployment potentials in the 2030 and 2050 timeframe, extensive consultations took place with country and sector experts and this information was combined with model analysis for power sector transformation.[2] It includes potentials and market information from 150 countries as well as the most recent national energy plans of 70 countries collected directly from governments. Two scenarios are developed in IRENA's global REmap modelling framework: (i) Reference Case which is a baseline that represents the energy demand based on the national energy plans of countries by considering policies in place or under consideration, and (ii) REmap Case which is the decarbonisation scenario of IRENA that aims to keep the CO_2 emissions from the global energy system within a carbon budget that is in line with the goals of the Paris Climate Agreement. Kempener et al. (2015), Saygin et al. (2015) and IRENA (2017e) provide additional insights into the methodology, strengths and limitations of REmap.

Table *2* provides the key assumptions used in this study for bulk materials production and the assessment of their energy use.

The value added of this study is:

- It sketches a pathway for decarbonisation that is consistent with the Paris Agreement;
- The analysis considers the latest technology and market information and considers country specific energy policy priorities and national energy plans of major economies;
- It is based on an energy systems perspective that accounts for global and economy wide scarcity of resources such as biomass. Electricity system constraints have been considered for renewable power;
- The analysis considers the potential benefits of combined energy and material systems optimisation, including intersectoral material flows.

RESULTS: ENERGY USE AND CO_2 EMISSIONS

This section discusses how industry's total energy demand and CO_2 emissions will evolve under the Reference Case and REmap Case between 2015 and 2060. Contribution of individual technologies and their costs are also separately presented.

Mitigation of Industrial CO_2 Emissions

Industry is the second-largest CO_2 emitting sector and within the sector, chemical and petrochemical and iron and steel are among the largest energy consumers representing more than 60% of the total final industrial energy demand (IEA, 2017d).[3] However, less energy-intensive sectors that represent the remaining 40%, such as pulp

---

[2] The analysis has been extended to 2060 mainly by using the activity levels estimated according to the IEA (IEA, 2017c).

[3] Data includes the non-energy use of fuels under the chemical and petrochemical sector and the energy use in blast furnaces and coke ovens as part of the iron and steel sector.

and paper, food and textile will also have an important role to play in reducing industrial CO_2 emissions.

Total industrial final energy and non-energy use (so including the use of fossil fuels as feedstock) is estimated to increase from around 153 exajoules (EJ) in 2015 to 238 EJ by 2060 (Figure 2). Reference Case includes autonomous improvements in energy efficiency as well as the uptake of renewable energy and other low-carbon technologies. In 2015, industrial energy use was about 128 EJ (including blast furnaces and coke ovens), equivalent to 83% of the total industrial consumption. The remainder (17%) was related to feedstock use for chemicals and polymers production. Feedstock's share is estimated to remain at a similar level until 2060. The share of coal decreases from 32% in 2015 to 20% by 2060. By comparison, the shares of biomass, gas and electricity would increase slightly in the same period. REmap Case projects a trajectory that consumes significantly less energy compared to the Reference Case. Sector's total final consumption would be 28% less at about 172 EJ by 2060 compared to the Reference Case. The fuel mix also changes significantly. Electricity's share would increase from 20% to 30%. When feedstock is excluded, the rise in electricity's share becomes more prominent: from 24% to 42%. Biomass share for process heat generation increases to 12% representing a more than doubling compared to today's level of 5%. Other renewables like solar thermal, geothermal and hydrogen would gain a share of about 8% compared to no or very limited use in 2015. The share of fossil fuels would decline from 55% in 2015 to 24% in 2060. The most significant reduction is projected for coal and its products that are predominantly used in the iron and steel and cement sectors (indicated with black shaded bars in the figure). Renewable's share (mainly from biomass, but also small quantities of renewable hydrogen for ammonia and methanol production) in non-energy use would increase to 33% by 2060 compared to around 4% today.

According to the Reference Case, industry's direct CO_2 emissions are estimated to increase from 9.5 Gt in 2015 to 11.7 Gt by 2060. In the REmap Case, emissions are reduced by more than 70% to 3.6 Gt (see Figure 3). Except for the chemical and petrochemical sector, in all other sectors the order of magnitude in the reduction of emissions is of a similar magnitude. Given the large share of fuels used as non-energy, the chemical and petrochemical sector has a somewhat lower reduction potential estimated at 53%.

Emissions Reduction Strategies

Decarbonisation of the industry sector requires the acceleration of a combination of various technologies. Under the REmap Case, in the period 2015-2060, 40% of industrial emissions reductions is estimated to come from energy efficiency, 25% from renewable energy, 25% from CCS and 10% from materials flows management including recycling/reuse, new materials and products, among others. This reduces industrial CO_2 emissions from a baseline of 11.7 Gt/yr to 3.6 Gt/yr by 2060 (see Figure 4).

The industry sector can benefit from the cost savings that come from improvements in energy efficiency. As a result, energy efficiency is a priority (IEA, 2009; Saygin et al., 2011; IEA, 2007). In the industry sector, energy efficiency would improve on average by up to 1%/yr in the REmap Case over the 2015-2060 period compared to 0.3-0.5%/yr in the Reference Case. The annual improvements exceed 1% until 2030 with the introduction of best available technologies and continue between 0.6-1%/yr between 2030 and 2060 as innovative and novel processes are employed. By that time key processes operate near their thermodynamic minimum energy use.

CCS is a key technology under the REmap Case for the industry sector. However, its uncertain prospects and potential will depend on a number of factors, including location, geology, water resources and others. In fact, using CCS in industry is more challenging than in the power sector, because industry plants are more diverse, smaller and more scattered than power plants (Leeson et al., 2017).

The CCS process itself must be tailored for the specific industry processes. Costs for most CCS technologies throughout the industry sector were found to range from USD 20-120 per ton of CO_2 avoided, with large variations in cost projections. Technology development and deployment needs to be accelerated if the technology is to play a role in the sector (Leeson et al., 2017; Kuramochi et al., 2012).

Renewables can play a key role in the industry sector. According to Table 3, renewable energy's share in the total energy demand to generate process heat can grow from 10% in 2015 to 45% in 2060. This renewable energy would be supplied in the form of biofuels, solar thermal and geothermal. Accounting for the demand of electricity and district heat and their portions supplied by renewables, the share of renewables in total final energy consumption of the industry would jump to 62%. This is largely because of the significant share of renewables in electricity generation that approaches 90% by 2060. When non-energy use is also included, the share of renewables is estimated at 55% in 2060 because only about one third of all non-energy use can be supplied by renewables.

In absolute terms, renewable energy would contribute around 98 EJ to industry's total demand for energy and feedstock. Roughly half of this would be from renewable power, a third from biomass as fuel and feedstock and 8% from solar thermal. Renewable hydrogen, direct geothermal applications and renewable district heat compromise the remaining 8% (see Figure 5).

Biomass, due to its versatility, has the highest potential among the different renewable energy options in the industry sector. Biomass can be used as a feedstock to replace fossil fuels, it can be used to produce low, medium and high temperature heat, and it can be used as a fuel for localised electricity production. Current direct renewable energy use in industry (8 EJ) is predominantly in the form of biofuels and waste. This is mainly due to by-products and waste use, such as bagasse and rice husk in sugar production, and other traditional industries; biogas from sewage and farms for food processing; and black liquor in the pulp and paper sector. The versatility of biomass also results in competitive uses within and between the industry sector, and other sectors of the economy. In the REmap Case, its use as a fuel can increase by nearly three times to around 21 EJ by 2060, which equals around 12% of industrial energy and non-energy use. Additionally, 11 EJ/yr would be used as feedstock, predominantly for bioplastics production (9.6 EJ to produce about 150 Mt of bio-based plastics), representing another 6% of industrial energy and non-energy use. Another 0.6 EJ biomass would be used as feedstock for ammonia and methanol besides 1.2 EJ of renewable hydrogen. Realising cost-effective and sustainable biomass potential depends on a number of factors, including local feedstock availability as well as biomass logistics (IRENA, 2014; Saygin et al., 2014).

With low- and medium-temperature heat accounting for nearly half of all process heat demand, solar thermal systems possess large potential, equivalent to around 5% of total energy and non-energy use. Under REmap, solar water heater use for industrial applications would grow to about 8.3 EJ in 2060. This could represent up to 2,000 GW installed capacity equivalent to more than 2,800 million m^2 solar thermal area (around five times global installed SWH capacity today). Reaching this level represents a significant effort since the current installed industrial SWH capacity is less than 100 MW. High initial capital costs, a low number of operating hours and land requirements at site constitute the main barriers, but cost reductions can be achieved with an increase in solar thermal deployment. Only with higher rates of deployment, and subsequent learning, will the technology become cost-competitive. A large opportunity exists at the small and medium sized enterprises outside of the energy-intensive sectors since the temperature of the process heat is generally lower in such plants and the amount of energy that is needed is smaller (IRENA, 2014).

The largest contribution to enabling renewables for industrial applications will come from renewable power. Electricity demand is expected to continue to grow in the manufacturing industry, partly due to an electrification of production processes and production growth in electricity-intensive industries, such as the non-ferrous metals sector. As the renewables share in power generation grows, this increases the renewables share in industry. Relocation of such industries close to renewable power plants is one option that would increase the renewable energy share in the electricity sector. Already many electricity-intensive industries such as aluminium smelters are linked with generation assets that offer cheap electricity from hydro or geothermal power and this is likely to increase in the coming years.

Several large manufacturing companies are integrating renewable energy power generation into their existing manufacturing plants either through solar PV panels on the production facilities, wind turbines on site, or other sources of renewable energy. Process technology R&D should also focus on electricity-based alternatives, ensuring that the electricity sector is decarbonised (IRENA, 2014). An interesting trend is direct corporate sourcing of renewable power. For instance, one of the largest aluminium producers of Europe is now planning to buy most of its electricity demand from a wind farm in Sweden (FT, 2017).

In an energy system that would rely more than half of its energy supply from renewables, industry sector will play a central role. Its role in the energy transition will need to be defined broader than what today's manufacturing industry supplies to the economy. This becomes more obvious as the share of renewable energy in both the industry and power sectors increases and as the sectors will increasingly couple across different applications. As such, industry would bear the responsibility of developing smart systems to connect energy production and consumption, such as smart grids, virtual power plants and other forms of digitisation and faster, more intelligent and more efficient production systems. With widespread electrification of industrial processes and the increased use of renewables-based hydrogen use will also provide means of demand response to integrate higher shares of renewables in the power system (Energie Agentur NRW, 2016; UNIDO, 2017). An example would be aluminium smelters who can ramp production and electricity demand up and down with minor modifications, an option that is currently being implemented in Germany.

Monitoring the Progress Needed for Decarbonising the Industry Sector

Table 4 provides a summary of the deployment needs for specific industrial low-carbon technologies. Most of the listed renewable energy technologies lack significant installed capacity today. The same is the case for CCS. This implies that an accelerated energy transition is needed in the coming decades. Energy efficiency improvement rates need to increase by two to three times compared to the Reference Case. Table 4 illustrates the remarkable scale of change that is required, given there are nearly 10,000 industrial plants for bulk materials production.

Also, significant amount of biomass needs to be mobilised for the industry. Only for iron and steel, chemical and petrochemical and cement production, around 1,000 Mt per year biomass needs to be supplied in 2060 (see next sections).

The challenges are also indicated by the mitigation costs of each technology. For the entire industry, the emission reduction potential estimated could come at an average cost between USD 15 and USD 90 per tonne CO_2 by 2060. The costs of individual technologies differ from each other depending on maturity and technology uncertainty. Mitigation costs range widely from -80 to 300 USD/t CO_2. Most renewable energy technologies have average costs above USD 100 per tonne CO_2. Material and energy efficiency improvement alternatives come at modest cost or even cost savings. Depending on the application, CCS costs are in between energy efficiency and renewable energy technologies or even exceed these costs.

To enable the transition, various industry groups, inter-governmental organisations, academia and other relevant stakeholders are establishing initiatives on a wide range of topics with focus on various sectors. An overview of such initiatives is provided in Table 5.

Promising real-life examples to development and deployment of new low-carbon technologies are emerging. It takes a decade or more for an energy technology to become available commercially. It is therefore important that efforts start today to realise the technology mix estimated for 2060.

Two pilot-plants in Europe will come in operation over the coming years to produce renewable electricity and hydrogen-based steel (HYBRIT, 2018; Salzgitter AG, 2018). Charcoal continues to be widely used in Brazil's small-scale blast furnaces. More advanced forms of biomass use for steel industry, however, are only at research stage. One consortium in Australia focuses on sustainable forms of charcoal and another in Germany explores hydrothermal carbonisation to cook biomass into a biocoal-slurry (CSIRO, 2018; SunCoal, 2018). A new Direct Reduced Iron (DRI) production plant integrated with CCS has started operation in Abu Dhabi in 2017.

Alternative fuels, biomass and waste are increasingly used in the global cement sector. But novel forms of biomass utilization, such as through gasification where syngas is combusted at the precalciner is limited to few plants in Europe only (Seboka, Getahun and Haile-Meskel, 2009). New types of carbon-free cement such as Calera and Novacem are only at R&D or pilot-plant stages although their deployment has started (Novacem, 2008; Calera, 2018).

The bio-economy with the chemical and petrochemical sector at its core is growing in several country and regions. Europe is one of the largest producers worldwide. A total of 13 million tonnes of bio-based products have been produced worldwide (4 Mt of non-food starch products excluded its use for ethanol and paper production, 7.3 Mt cellulosic fibres and other cellulosic products, 1 Mt alkyd resins, and 0.4 Mt other bio-based plastics). The total production volume of bio-based chemicals in the region has reached 20 million tonnes (including animal and vegetable fertilisers, fats and oils) (Piotrowski, Carus and Carrez, 2018). The total production of bio-succinic acid, which is one of the twelve most promising bio-based building blocks according to the US Department of State has reached 50,000 tonnes in 2016 (Nova-Institut, 2018). The production of bio-based ethylene is already commercial for several years in Brazil and India. Likewise, several bio-based methanol production plants are in operation in the Canada, Netherlands and Sweden by utilising various feedstocks such as glycerine, black liquor or treated wood. Renewable hydrogen is at R&D stage with the exception of a single plant in Iceland that uses renewable power-based electrolysis technology (IRENA, 2014; IRENA-IEA/ETSAP, 2012a,b).

More solar-based process heaters are being installed across the world. Since 2009, on average 16 new plants came in operation every year (AEE-INTEC, 2018). Progress in demonstration CCS plants that are key to prove the technology’s feasibility is slow and the costs remain high. According to the latest statistics, the current installed capture capacity shows a significant shortfall from its long-term potential (Global CCS Institute, 2017). A demonstration of CCS for cement is planned in Norway to start operation after 2019 (Ministry of Petroleum and Energy Norway, n. d.).

Companies in 75 countries actively sourced 465 terawatt hours (TWh) of renewable energy in 2017, an amount close to the overall electricity demand of France. Over 1,200 large companies analysed are voluntarily and actively procuring or investing in self-generation of renewable electricity for their operations. More than 200 have been identified that source at least half of their power from renewables. Electricity self-generation is the most common sourcing model, followed by unbundled energy attribute certificates (EACs) and power purchase agreements (PPAs). Drivers are companies seeking to reduce electricity bills, hedge against future price spikes and address sustainability concerns (IRENA, 2018).

Given the sector’s nature to maintain profits, majority of these initiatives are private sector driven by companies and businesses for technologies that enable this. Energy efficiency and renewable power are at the core of today’s initiatives. There are only few global scale academia-industry partnerships. The focus is predominantly on developed countries with participation from those that have seen a facet of industrialisation within the past two decades. Enabling transition will require the development of more sectoral approaches and major initiatives at the sector level like ULCOS for iron and steel.

RESULTS: EMISSIONS REDUCTION POTENTIALS BY INDUSTRY SECTORS

This section presents the technology options for the major CO_2 emitting industrial sectors and the implications on material flows.

Cement Industry

The cement sector is the largest individual CO_2-emitting industry sector. Making cement clinker, the main cement ingredient, which produces large amounts of CO_2. As a result, this industry sector was responsible for 8% of all global CO_2 emissions in 2015 (2.5 Gt/yr), with the majority (1.6 Gt/yr) of this total being process emissions. The high CO_2 concentrations in the flue gases make that in this industry CCS could play a role. Under the REmap Case, 12% of emissions reductions in the entire industry sector is estimated to come from using CCS in the cement industry, representing 65% of all emission reductions in the cement sector. Additional emissions reductions – 10% of the total from the sector – would come from new and less-emission intensive cement types like geopolymer cement and substitutes for clinker like pozzolanic material and other materials such as finely ground lime stone and silica fume. Biomass and waste fuels can be injected into cement kilns and replace most fossil fuels which would contribute another 9% of the total emission reductions. Finally, energy efficiency improvements would make up the remainder 26% where cement kilns would use nearly the minimum required energy just above the theoretical limit (IRENA and IEA, 2017).

In 2015, around 4.2 billion tonnes of cement was produced (Figure 6). Around 4.7 billion tonnes of limestone were required to produce clinker. Clinker-to-cement ratio in 2015 was 74%, thereby requiring about 1.1 Gt clinker substitutes for cement production such as gypsum, blast furnace slag and fly ash. A total of 400 Mt of fuels were used, including a 95% fossil fuel share. The sector generated about 200 Mt of waste in 2015 (Kajaste and Hurme, 2017). The bulk of cement is used for production of concrete that is used for buildings and infrastructure works. Post-consumer concrete waste is typically landfilled or used as a filling material elsewhere. The product stock in use grew by 5% or 3.5 Gt cement-equivalents in 2015.

Under the REmap Case, limestone use remains at the same level despite a 20% growth in total cement production because of the increased use of clinker substitutes. Total fuel input is equally split between renewables (biofuels and waste) and fossil fuels. Compared to the Reference Case, the major differences are related to fuel and raw material inputs: about 0.5 Gt more clinker substitutes. Total fossil fuel input is more than halved at 0.14 Gt because of the reduced clinker production volume, increased use of alternative fuels, as well as higher energy efficiency of the clinker kilns.

Iron and Steel Industry

Production of iron and steel ranks as the second largest source of industrial emissions and emits about half as much CO_2 as the cement industry. These emissions are from the use of coal and coke as chemical reducing agents for iron production in traditional blast furnaces. Since the 18th century, coal and coke have been used as chemical reducing agents in blast furnaces to make iron. There are several alternatives to the blast furnace process like hydrogen-based direct reduced iron (DRI) or even electrolysis processes similar to the technologies being employed in aluminium making (IRENA and IEA, 2017). The direct reduced iron (DRI) production process is commercially available and the installed capacity worldwide today uses a mix of natural gas and other fossil fuels to produce 6% of the total global iron production. Smelting reduction is another route. There are several configurations and technologies available for the smelting reduction process. Some are already commercial, others are still in research stage. The main principle of this process is it eliminates the need for coke ovens and it relies on gasified coal to reduce iron ore. CO_2 emissions from smelting reduction process can also be captured easier as the CO_2 concentration in the flue gas is higher. In the REmap Case, coal-based blast furnace use is estimated to decline by 90% between 2015 and 2060. This requires half of all iron production to come from smelt reduction coupled with CCS and a quarter from direct reduced iron (partly fuelled with renewable hydrogen). In addition, half of all steel production would be from scrap. Biomass, in the form of charcoal or other solid biofuels accounts for up to one-third of the energy needs of the remaining blast furnace capacity in use. Also, electricity can be injected into blast furnaces or smelt reduction furnaces and this replaces coal and coke on an energy equivalent basis.

Also, steel can be produced from its recycled products in an electric arc furnace which eliminates the need for iron production. However, the extent this technology can be deployed depends on the availability of steel scrap. The amount of steel in use continues to grow and steel metal is lost during use and processing as rust. Therefore, scrap recycling can only account for part of the total steel production. Scrap purification and scrap sorting is essential to ensure that quality criteria for new steel are met. Cascading approaches in recycling can help in this context to limit build-up of trace elements.

Under the REmap Case, emissions from the industry is estimated to decline by about 80% to 0.4 Gt in 2060, compared to the Reference Case. About 40% of this reduction would be achieved with CCS, of which a large share can be attributed to the switch to smelt reduction process for iron production. Around 15% would come from renewables (largely biomass) and 45% from energy and material efficiency measures.

In 2015, a total of 1.5 Gt finished steel products were manufactured (Figure 7). Blast furnace - basic oxygen furnace route represented nearly three-quarters of the total production. The remainder came from the electric arc furnace route (EAF, 27%) that used primarily scrap. This category includes iron and steel produced through the DRI – EAF route that accounted for around 4% of total steel production. In 2015, nearly 400 Mt of post-consumer scrap was generated. This is equivalent to a quarter of the total finished steel products manufacturing volume and around 1.3% of the total steel stock. Combined with the processing scrap and home run scrap (within steel mills), total scrap input for steel production has totalled more than 600 Mt.

In 2060, there are several notable changes in the material flows of the iron and steel sector. Hot metal output from blast furnaces is halved at the expense of DRI and the newly introduced smelting reduction process. Moreover, the production of steel from electric arc furnaces doubles between 2015 and 2060. Despite the increasing share of steel production from scrap, demand for iron ore slightly grows. With less blast furnaces production, slag output is halved. This has consequences for the cement sector that uses blast furnace slag as clinker substitute. Post-consumer scrap will account for nearly 70% of all scrap supply, compared to a 60% share in 2015. Post-consumer scrap generation equals 0.8% of the total steel stock. Currently, the level of post-consumer scrap generation ranges between 1% and 1.5% (IEA, 2007).

Sinter and pellet needs under the REmap Case are about half those in the Reference Case where there is no capacity for smelt reduction. Steel recycling increases by less than 5%. In the REmap Case, 150 Mt less fossil fuel is used (mainly coal and its products), which is compensated by 80 Mt more biomass.

Chemical and Petrochemical Industry

Chemical and petrochemical industry emissions are similar in size to those from the iron and steel industry. The production of ammonia, methanol and the building blocks of the organic chemical sector, namely ethylene, propylene, butadiene and aromatics, resulted in total CO_2 emissions of approximately 1.3 Gt in 2015 (including about 0.3 Gt of CO_2 emissions from feedstock use in ammonia production). Another 1 Gt of CO_2 is stored in the form of carbon in plastics. This CO_2 is released when plastics are incinerated at the end of their lifetime. The emissions from waste incineration have reached about 0.4 Gt per year. Incineration emissions lag storage because of net plastic accumulation in the economy. These emissions can be reduced by recycling of plastics waste or more efficient incineration techniques with higher energy recovery.

However, today less than 10% of all waste generated is mechanically recycled, a quarter of all waste is incinerated, and the remainder is landfilled. In addition, biomass can be used as a source of renewable carbon instead of fossil fuels to mitigate the emissions from carbon stored in chemicals. During the production of bio-based plastics, fossil fuel use for process heat production can also be replaced with biofuels. In the Reference Case, chemical and petrochemical sector's energy, process and waste emissions is estimated to increase from 1.7 Gt in 2015 to 2.6 Gt in 2060. Under the REmap Case, these emissions could be reduced by 0.9 Gt to 1.5 Gt per year in 2060. 30% of these emission reductions are related to process energy savings caused by a reduced demand for fossil fuel-based chemicals. Under the REmap Case, up to 60% of all plastic waste would be recycled in 2060, thereby saving virgin polymer production. In addition, a quarter of all chemical feedstocks would be biomass-based compared to around 1% today. Energy efficiency improvements account for a quarter of all savings. The remainder 45% is split between renewables (28%) and CCS (17%). Important potentials exist for replacing fossil fuel feedstock with biomass feedstock; production of bioethylene, for example, is already a commercial technology. In addition, recycling and bio-based chemicals also reduce around 1 Gt of fossil CO_2 emissions because of reduced plastics waste incineration. The economics of bio-based chemicals, however, pose a challenge at today's oil prices and a proper accounting scheme for storing biomass carbon in materials is needed (IRENA/IEA-ETSAP, 2012a;b; Saygin et al., 2014).

According to Figure 8, a total of 453 Mt synthetic organic materials and chemicals were produced in 2015. Plastics compromise the largest share with a total production of 322 Mt per year. In total 305 Mt of hydrocarbon and 30 Mt biomass feedstock was used. In the same year, 178 Mt of post-consumer waste was generated and 77 Mt material was lost resulting in net addition of 224 Mt per year to the total stock of 3.7 Gt chemicals and plastics in use. Of the total plastics waste volume, only 34 Mt was recycled (around 19% of all waste generated). A large share is still landfilled and about a quarter is incinerated for energy recovery (Geyer, Jambeck and Law, 2017). Estimates suggest that of a large waste share is lost into the environment. For instance, of all 78 Mt plastic packaging material nearly one-third leaks in this way (EMAF, 2016).

Under the REmap Case, the global organic chemical sector will see important changes. In 2060, total output of chemicals and plastics nearly doubles by 2060 compared to the 2015 level. A large share of about one-third of all plastics used will be sourced from recycled plastics waste. About 36% of all new plastics (or a quarter of all plastics used) would be from bio-based plastics which would require about 585 Mt of primary biomass only for the chemical sector. To put this challenge in perspective, in 2015 chemical sector used around 30 Mt of primary biomass for chemicals production only and the global wood pellet production was at a similar level of around 26 Mt (IEA Bioenergy, 2017). Given the high shares of plastics recycling and production of bio-based plastics, hydrocarbon use as feedstock and energy remain at around today's levels.

Compared to the Reference Case, there are some notable differences in material flows of the REmap Case. The total production of plastics and other chemicals from virgin sources is about 150 Mt per year higher than in the Reference Case in 2060. Therefore, less feedstock input is required. Hence about 260 Mt less hydrocarbon feedstock and 110 Mt less hydrocarbon energy is required but 360 Mt more biomass is used. Recycling reduces the incineration volume by about 130 Mt.

BREAKTHROUGH OPTIONS TO CLOSE THE EMISSIONS GAP

The analysis has discussed options that can bring emissions down to 3.5 Gt per year in 2060. But the objective is zero emissions by 2060. This means an additional effort will be needed based on new technologies that are currently not considered. A number of these breakthrough options are discussed here.

Biomass is unique as the only source of renewable carbon. Biomass carbon is routinely stored in products such as construction wood on a massive scale. This carbon storage is not taken into account in today's CO_2 accounting. A shift towards more wood use in construction can result in larger amounts of carbon storage. When oil and gas is used as feedstock for petrochemical products, this carbon is considered to be stored. If the same petrochemical products would be manufactured from biomass, this would imply the same storage but from biomass that has captured the CO_2 from air. So, it would result in net CO_2 storage. The 500 Mt CO_2 that can be used for petrochemicals in 2060 would imply a net storage of 1-1.5 Gt CO_2 equivalent. This requires an adjustment in the current emissions accounting scheme and accelerated development of biochemical manufacturing. Also, CO_2 from biomass conversion in industrial processes can be captured and stored underground. This offers the prospect of processes with net negative CO_2 emissions. There are some ethanol plants in operation where CO_2 is captured and sold commercially.

Concrete consists of rock, sand and cement. If concrete is heated in a microwave, it is possible to separate it back into the components and recycle the cement material into cement making (Lippiatt and Bourgeois, 2012). This opens up the perspective of significant volumes of clinker substitutes. However, the technology will need massive upscaling, technical and economic feasibility on a commercial scale are unclear as of yet. Carbonation refers to the natural reaction of cement with CO_2. It is the reverse of the reaction that takes place when cement clinker is produced. This process can be accelerated if concrete demolition waste is ground. As there are no statistics it is not clear how significant this process is today and to what extent it can be accelerated, and what the cost would be (PCA, not dated).

The deployment of negative emission technologies can offset the emissions remaining in sectors where mitigation is challenging such as energy-intensive industries and international aviation and navigation. Most of these technologies are at early stages of deployment and therefore are costly, there are large uncertainties about the extent they can be deployed and their impacts. Currently most focus is on afforestation strategies and biomass coupled with CCS (BECCS) (IRENA, 2017b), however, in realising zero energy CO_2 emissions after 2060, research needs to be accelerated and new pathways should be explored (Kuramochi, et al., 2018; Obersteiner, et al., 2018).

This discussion is not comprehensive, it is likely that many more new solutions can be identified once the industry really start to focus on the zero-emission objective. It is critical that an enabling policy framework is created that facilitates the necessary technology development and technology deployment.

DISCUSSION OF FINDINGS AND RECOMMENDATIONS

Gaining better understanding of the technology options for the industry sector is very important as its direct emissions represent 30% of all energy sector's CO_2 emissions. The analysis shows that sector's emissions could be eliminated after 2060, however, the sector is currently not on this pathway. By 2060, more than half of all energy and feedstock use of the industry could be sourced from renewables. Renewable power accounts for half and biomass accounts for one-third of total renewable energy deployed.

Achieving higher renewable energy share in industry is key to realising reductions in the sector's fossil fuel demand and related CO_2 emissions. Supplying more than 60% of industry's total final energy demand from renewables can only be realised if specific policies are developed to create a business environment conducive to private sector investments.

Cost effective and more efficient solar thermal, geothermal and heat pump technologies constitute an important area that governments can support through R&D grants, the creation of knowledge networks and information provision (IRENA, 2017a;b). This will require policies to be complemented with a broad array of industry, academia and government initiatives that facilitate the development and deployment of all types of low-carbon technologies.

Also, industrial commodity flows and management of materials life cycle offers specific opportunities for industrial decarbonisation. The analysis shows that the efforts to deploy low-carbon technologies need to be complemented with strategies and options to improve material efficiency and creating a circular economy. However not all options are within the boundaries of the industry sectors. An important effort will be required in the waste management sector, especially related to steel products and plastics. This is essential to increase recovery rates of materials from products that have reached their end-of-lives, ensure cost effective and efficient logistics, develop cost-effective recycling technologies and develop the global infrastructure to circulate these materials. The analysis points to structural changes that will have impacts throughout the product life cycle. The material flows across sectors will be impacted by emission reduction efforts elsewhere in the economy, such as the reduced availability of blast furnace slag and fly ash for cement production which will require new material solutions to be developed.

Additional effort will be needed to reduce emissions based on new technologies that are currently not widely considered including for example biomass energy use in combination with CCS, biomass carbon use and proper accounting of such storage in synthetic organic materials, wood materials use for construction and the accounting of its carbon storage effects, recycling of concrete for cement powder recovery, carbonation of concrete for CO_2 capture from the air and negative emission technologies. However, the volumes required for a meaningful impact are very significant, therefore efforts need to be ramped up quickly for significant impact in the coming decades, given long investment cycles. Solutions will also be required to overcome institutional barriers in these sectors, such as addressing carbon leakage in industry. Global sectoral agreements can play an important role moving forward.

REFERENCES

AEE-INTEC (2018). Database for applications of solar heat integration in industrial processes. AEE-INTEC, Gleisdorf. http://ship-plants.info/.

Aeschelmann et al. (2015). Bio-based Building Blocks and Polymers in the World. Nova Institute, Hürth. http://www.bio-based.eu/market_study/media/files/15-05-13_Bio-based_Polymers_and_Building_Blocks_in_the_World-nova_Booklet.pdf.

AFS (2016). Global Production 2015. Modern Casting, December 2016, pp. 25-29. http://www.afsinc.org/content.cfm?ItemNumber=7814.

Ahman, M., Nilsson, L.J. and Johansson, B. (2017). Global climate policy and deep decarbonization of energy-intensive industries. Climate Policy 17, pp. 634-649.

Alvarado, M. (2016). The changing face of the global methanol industry. IHS Chemical Bulletin 3, pp. 10-11. http://www.methanol.org/wp-content/uploads/2016/07/IHS-ChemicalBulletin-Issue3-Alvarado-Jun16.pdf.

Argus Media (2015). Global methanol. Argus Media, London. http://www.argusmedia.com.br/Home/Petrochemicals/2015-Methanol Annual/~/media/BFCDF8E8A1D44543940F7BC82AC5327A.ashx.

Calera (2018). Beneficial Reuse of CO2 – the Process. Calera, Moss Landing, CA. http://www.calera.com/beneficial-reuse-of-co2/process.html.

CEFIC (2013). European chemistry for growth – Unlocking a competitive, low carbon and energy efficient future, The European Chemical Industry Council, Brussels. http://www.cefic.org/Documents/RESOURCES/Reports-and-Brochure/Energy-Roadmap-The%20Report-European-chemistry-for-growth.pdf.

CEMBUREAU (2013). The role of cement in the 2050 low carbon economy. The European Cement Association, Brussels. https://cembureau.eu/media/1500/cembureau_2050roadmap_lowcarboneconomy_2013-09-01.pdf.

CEPI (2013). Unfold the future - The Two Project Team. Confederation of European Paper Industries, Brussels. http://www.cepi.org/system/files/public/documents/publications/innovation/2013/finaltwoteamprojectreport_website.pdf.

CEPI (2017). Investing in Europe for Industry Transformation. 2050 Roadmap to a low-carbon economy. CEPI,Brussels. http://www.cepi.org/system/files/public/documents/publications/innovation/2017/roadmap_2050_v07_printable_version.pdf.

Chen, G.Q. and Patel, M.K. (2011). Plastics derived from biological sources: present and future: a technical and environmental review. Chemicals Review 112 (4), pp. 2082-2099.

Corsten (2009). Global CO2 abatement potential in the iron and steel industry up to 2030, M.Sc. thesis, August 2009. NWS-S-2009-25. Utrecht University, Utrecht.
CSIRO (2018). Environmentally-friendly steelmaking. CSIRO, Canberra.
https://www.csiro.au/en/Research/MRF/Areas/Community-and-environment/Responsible-resource-development/Green-steelmaking.

DECHEMA (2017). Low carbon energy and feedstock for the European chemical industry, Gesellschaft für Chemische Technik und Biotechnologie e.V., Frankfurt am Main.
https://dechema.de/dechema_media/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry-p-20002750.pdf.

Dunham, W. (2018). World's oceans clogged by millions of tons of plastic trash. Scientific American, February 12. https://www.scientificamerican.com/article/world-s-oceans-clogged-by-millions-of-tons-of-plastic-trash/.

EEA (2015). Common goals, shared action – The European Aluminium Industry's Sustainability Roadmap Towards 2025. European Aluminium Association, Brussels.
https://www.european-aluminium.eu/media/1034/sustainability-roadmap.pdf.

EMAF (2016). The New Plastics Economy: Rethinking the future of plastics. Ellen MacArthur Foundation, Cowes.
https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics.

Energie Agentur NRW (2016). Lastmanagement in Nordrhein-Westfalen: Potenziale, Hemmnisse, Handlungsoptionen. Energie Agentur NRW, Aachen.
https://broschueren.nordrheinwestfalendirekt.de/herunterladen/der/datei/eigenpublikation-lastenmanagement-in-nrw-web-final-pdf/von/lastmanagement-in-nordrhein-westfalen-potenziale-hemmnisse-handlungsoptionen/vom/energieagentur/2279.

EuBP (2018). Bioplastics. Facts and Figures. European Bioplastics, Berlin.
http://docs.european-bioplastics.org/publications/EUBP_Facts_and_figures.pdf.

Eurofer (2013). A steel roadmap for a low carbon Europe 2050. The European Steel Association, Brussels.
http://eurofer.org/News%26Events/PublicationsLinksList/2013-Roadmap.pdf.

Fais, B., Sabio, N. and Strachan, N. (2016). The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and renewable targets. Applied Energy 162, pp. 699-712.

FT (2017). Norsk Hydro in 'biggest' deal to secure wind farm energy. Financial Times, November 7.

Geyer, R., Jambeck, J.R. and Law, K.L. (2017). Production, use and fate of all plastics ever made. Science Advances 3, pp. 1-5.

Gielen, D.J. (2000). On Carbon Leakage and Technological Change. Energy and Environment 11, pp. 49-63.

Gielen, D.J., Newman, J. and Patel, M.K. (2008). Reducing Industrial Energy Use and CO_2 Emissions: The Role of Materials Science. MRS Bulletin 33, pp. 471-477.

Gielen, D.J. and Yagita, H. (2002). The long term impact of GHG reduction policies on global trade: A case study for the petrochemical industry. European Journal of Operational Research 139, pp. 665-681.

Global CCS Institute (2017). Large-scale CCS facilities. Global CCS Institute, Docklands. https://www.globalccsinstitute.com/projects/large-scale-ccs-projects.

GVR (2016). Oleochemicals Market Size to Reach $30.15 Billion by 2024. Grand View Research, San Francisco, CA. https://www.grandviewresearch.com/press-release/global-oleochemicals-industry.

G20 (2017). Climate and Energy Action Plan for Growth. https://www.g20.org/Content/DE/_Anlagen/G7_G20/2017-g20-climate-and-energy-en.pdf.

Horner, S.G. (2014). Global ferrous metallics balance: longer range outlook and issues. OECD Steel Committee Raw Materials Workshop, 11 December, Cape Town. http://www.oecd.org/sti/ind/Session%201%20-%20IIMA%20%20-%20OECD-SA%20Dec%202014.pdf.

HYBRIT (2018). HYBRIT Fossil-free steel. LKAB, SSAB and Vattenfall, Lulea, Stockholm and Solna. http://www.hybritdevelopment.com.

IC (2017). Weltproduktion von Textilfasern. Industrievereinigung Chemiefaser e.V, Frankfurt am Main. https://www.ivc-ev.de/live/index.php?page_id=43.

IEA (2007). Tracking Industrial Energy Efficiency and CO_2 Emissions. IEA/OECD, Paris. https://www.iea.org/publications/freepublications/publication/tracking_emissions.pdf

IEA (2009). Energy technology transitions for industry: Strategies for the Next Industrial Revolution. IEA/OECD, Paris. https://www.iea.org/publications/freepublications/publication/industry2009.pdf

IEA (2013). Low-carbon technology for the Indian cement industry. IEA/OECD, Paris. http://www.iea.org/publications/freepublications/publication/low-carbon-for-the-indian-cement-industry.html.

IEA (2017a). CO_2 emissions from fuel combustion 2017. IEA/OECD, Paris. http://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustion2017Overview.pdf.

IEA (2017b). Renewable energy for industry. From green energy to green materials and fuels. IEA/OECD, Paris. https://www.iea.org/publications/insights/insightpublications/Renewable_Energy_for_Industry.pdf.

IEA (2017c). Energy Technology Perspectives 2017 – Catalysing Energy Technology Transformations. IEA/OECD, Paris. http://www.iea.org/etp/.
IEA (2017d). World Energy Balances 2017 edition. IEA/OECD, Paris.

IEA Bioenergy (2017). Global Wood Pellet Industry and Trade Study 2017. IEA Bioenergy: Task 40. http://task40.ieabioenergy.com/wp-content/uploads/2013/09/IEA-Wood-Pellet-Study_final-2017-06.pdf.

IEA/ICCA/DECHEMA (2013). Energy and GHG reductions in the chemical industry via catalytic processes. IEA/OECD, ICCA and DECHEMA, Paris, Brussels and Frankfurt am Main. https://www.americanchemistry.com/Catalysis-Roadmap/.

IHS Markit (2013). Global solvents – Opportunities for greener solvents. IHS Markit, London. https://ihsmarkit.com/products/chemical-special-reports-global-solvents.html.

Industry Experts (2016). Carbon Black – A global market overview. Industry Experts, Chino, CA. http://industry-experts.com/verticals/files/articles/cp024-carbon-black-a-global-market-overview.pdf.

IPTS/EC (2013a). Best available techniques reference document for the production of cement, lime and magnesium oxide. EUR 26129 EN. Institute for Prospective Technological Studies, European Commission, Seville. http://eippcb.jrc.ec.europa.eu/reference/.

IPTS/EC (2013). Best available techniques reference document for iron and steel production. EUR 25521 EN. Institute for Prospective Technological Studies, European Commission, Seville. http://eippcb.jrc.ec.europa.eu/reference/.

IRENA (2014). Renewable energy in manufacturing. IRENA, Abu Dhabi, http://irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap-2030-Renewable-Energy-in-Manufacturing.pdf

IRENA (2016). REmap: Roadmap for a Renewable Energy Future, 2016 edition. IRENA, Abu Dhabi. http://www.irena.org/documentdownloads/publications/irena_remap_2016_edition_report.pdf.

IRENA (2017a). [Executive Summary/Chapter [3/4]] of Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System. IRENA and IEA, Abu Dhabi.www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf.

IRENA (2017b). Accelerating the energy transition through innovation: Working paper based on global REmap analysis. IRENA, Abu Dhabi. http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Jun/IRENA_Energy_Transition_Innovation_2017.ashx

IRENA (2017c). IRENA IEA-ETSAP technology briefs. http://www.irena.org/publications/2013/Jan/IRENA-IEA-ETSAP-Technology-Briefs.

IRENA (2017d). Costs of renewables database. IRENA, Abu Dhabi. http://irena.org/costs.

IRENA (2017e). Methodology background document: Development of a decarbonisation pathway for the global energy system to 2050. A country-by-country analysis for the G20 based on IRENA's REmap and Renewable Energy Benefits programmes. IRENA, Abu Dhabi. http://www.irena.org/-/media/Files/IRENA/REmap/Methodology/IRENA_REmap_Decarbonisation_Pathway_Methodology_2017.pdf.

IRENA (2018) Corporate Sourcing of Renewables: Market and Industry Trends. IRENA, Abu Dhabi. http://irena.org/-/media/Files/IRENA/Agency/Publication/2018/May/IRENA_Corporate_sourcing_2018.pdf.

IRENA and IEA (2017). Perspectives for Energy Transition – Investment needs for a low-carbon energy system. IRENA and IEA/OECD, Abu Dhabi and Paris. https://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf.

IRENA/IEA-ETSAP (2012a). Production of bio-ethylene. Technology Brief. IRENA, Abu Dhabi. https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20I13%20Production_of_Bio-ethylene.pdf.

IRENA/IEA-ETSAP (2012b). Production of bio-methanol. Technology Brief. IRENA, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA-ETSAP-Tech-Brief-I08-Production_of_Bio-methanol.ashx.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E. *et al.* (2017). Fossil CO_2 & GHG emissions of all world countries, European Commission Joint Research Centre, Brussels.

Kajaste, R. and Hurme, M. (2017). Cement industry greenhouse gas emissions – management options and abatement cost Journal of Cleaner Production 112, pp. 4041-4052.

Kempener, R., Assoumou, E., Chiodi, A., Ciorba, U., Gaeta, M. *et al.* (2015). A Global Renewable Energy Roadmap: Comparing Energy Systems Models with IRENA's REmap 2030 Project. Lecture Notes in Energy 30, pp. 43-67.

Kok, E. (2017). Global Chlorine Market. Recovery now? 32nd Annual World Petrochemical Conference. 22 March. https://cdn.ihs.com/www/Events/WPC2017/Presentations/IHSM-Kok-Globalchlorine-March22.pdf.

Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., Jackson, T. (2017a). Material flow accounting: Measuring global material use for sustainable development. Annual Review of Environment and Resources 42, pp. 647-675.

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H. *et al.* (2017b). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. PNAS 114, pp. 1880-1885.

Kuramochi, T., Ramirez, A., Turkenburg, W., Faaij, A. (2012). Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes. Progress in Energy and Combustion Science 38, pp. 87-112.

Kuramochi, T., Höhne, N., Schaeffer, M., Cantzler, J., Hare, B. *et al.* (2018). Ten key short-term sectoral benchmark to limit warming to 1.5°C. Climate Policy 18, pp. 287-305.

Lechtenböhmer, S., Nilsson, L.J., Ahman, M., Schneider, C. (2016). Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. Energy 115, pp. 1623-1631.

Leeson, D., Mac Dowell, N., Shaha, N., Petita, C., Fennella P.S. (2017). A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. International Journal of Greenhouse Gas Control 61, pp. 71–84.

Link, J. (2008). IRMA - Flowsheet Model Examples of Application. 1-2 October 2008, Proceedings of the 4th ULCOS seminar, Essen.

Lippiatt, N. and Bourgeois, L. (2012). Investigation of microwave-assisted concrete recycling using single-particle testing. Minerals Engineering 31, pp. 71-81.

McLellan, B.C., Corder, G.D., Giurco, D.P., Ishihara, K.N. (2012). Renewable energy in the minerals industry: a review of global potential. Journal of Cleaner Production 32, pp. 32-44.

Mikunda, T., Kober, T., de Coninck, H., Bazilian, M., Rösler, H. *et al.* (2014). Designing policy for deployment of CCS in industry. Climate Policy 15, pp. 665-676.

Ministry of Petroleum and Energy Norway (not dated). Feasibility study for full-scale CCS in Norway.

Nexant (2013). Ammonia and urea. Strategic business analysis. Nexant, London. http://thinking.nexant.com/sites/default/files/report/field_attachment_prospectus/201311/SBA2012-13_Ammonia_Urea_Prospectus_R3_0.pdf.

Nova Institute (2018). Succinic acid: New bio-based building block with a huge market and environmental potential? Nova Institute, Hürth. http://news.bio-based.eu/media/2018/02/18-02-28-PR-Succinic-acid-Report.pdf.

Novacem (2008). Novacem-carbon negative cement to transform the construction industry. Innovation and Investment Opportunities in Carbon Capture and Storage. Imperial College, London. http://www3.imperial.ac.uk/pls/portallive/docs/1/50161701.PDF.

NSA (not dated). Types of iron and steel slag. Nippon Slag Association, Tokyo. http://www.slg.jp/e/slag/kind.html.

Obersteiner, M., Bednar, J., Wagner, F., Gasser, T., Ciais, P. *et al.* (2018). How to spend a dwindling greenhouse gas budget. Nature Climate Change 8, pp. 7-10.

OGJ (2015). International Survey of Ethylene from Steam Crackers – 2015. Oil and Gas Journal, July 6, 2015.

Onarheim, K., Mathiesen, A. and Arasto, A. (2015). Barriers and opportunities for application of CCS in Nordic industry-A sectorial approach. International Journal of Greenhouse Gas Control 36, pp. 93-105.

Palm, E., Nilsson, L.J. and Ahman, M. (2016). Electricity-based plastics and their potential demand for electricity and carbon dioxide. Journal of Cleaner Production 129, pp. 548-555.

Patel, M., Neelis, M.P., Gielen, D.J., Olivier, J., Simmons, T. *et al.* (2005). Carbon dioxide emissions from non-energy use of fossil fuels: Summary of key issues and conclusions from country studies: Resources, Conservation and Recycling 45, pp. 195-209.

PCA (not dated). CO2 and the concrete industry: Cement and concrete as a carbon dioxide sink. http://www.cement.org/for-concrete-books-learning/concrete-technology/concrete-design-production/concrete-as-a-carbon-sink

Piotrowski, S., Carus, M. and Carrez, D. (2018). European Bioeconomy in Figures, 2008-2015. Nova-Institute for Ecology and Innovation, Hürth. http://biconsortium.eu/sites/biconsortium.eu/files/documents/Bioeconomy_data_2015_20150218.pdf.

Plastics Europe (2016). Plastics – the Facts 2016. An analysis of European plastics, production, demand and waste data. Plastics Europe, Brussels. http://www.plasticseurope.org/application/files/4315/1310/4805/plastic-the-fact-2016.pdf.

RSB (2018). Statistical Summary of World Rubber Situation. Rubber Statistical Bulletin, January-March 2018 edition. http://www.rubberstudy.com/documents/WebSiteData_Feb2018.pdf.

Rohde, L., Nunez, W.P., Ceratti, J.A.P. (2003). Electric arc furnace steel slag. Base material for low-volume roads. Transportation Research Record 1819, pp. 201-207.

Salzgitter AG (2018). SALCOS Low Carbon Steelmaking. Salzgitter AG, Salzgitter. https://salcos.salzgitter-ag.com/en/

Saygin, D. Worrell, E., Patel, M.K., Gielen, D.J. (2011). Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries. Energy 36, pp. 6661-6673.

Saygin, D., van den Broek, M., Ramirez, A., Patel, M.K., Worrell, E. (2013). Modelling the future CO2 abatement potentials of energy efficiency and CCS: The case of the Dutch industry. International Journal of Greenhouse Gas Control 18, pp. 23-37.

Saygin, D., Gielen, D.J., Draeck, M., Worrell, E and Patel, M.K. (2014). Assessment of the technical and economic potentials of biomass use for the production of steam, chemicals and polymers. Renewable and Sustainable Energy Reviews 40, pp. 1153-1167.

Saygin, D., Kempener, R., Wagner, N. Ayuso, M., Gielen, D. (2015). The implications for renewable energy innovation of doubling the share of renewable energy options and their policy implications. Energies 8, pp. 5828-65.

Schiffer, Z.J. and Manthiram, K. (2017). Electrification and decarbonization of the chemical industry. Joule 1, pp. 10-14.

Scott, K., Roelich, K., Owen, A., Barrett, J. (2017). Extending European energy efficiency standards to include material use: an analysis. Climate Policy 38, pp. 1-15.

Seboka, Y., Getahun, M.A. and Haile-Meskel, Y. (2009). Biomass energy for cement production: opportunities in Ethiopia. United Nations Development Programme, UNEP, UNEP RISO Centre, New York. http://www.undp.org/content/dam/aplaws/publication/en/publications/environment-energy/www-ee-library/climate-change/biomass-energy-for-cement-production-opportunities-in-ethiopia/Biomass_energy_for_cement_production_opportunities_barriers.pdf.

Silkstrom, P. (2013). ULCORED Direct Reduction Concept for ULCOS. A brief introduction. 11 November 2013. https://ieaghg.org/docs/General_Docs/Iron%20and%20Steel%202%20Secured%20presentations/2_1430%20Peter%20Sikstrom.pdf.

SunCoal (2018). High-value carbons from biomass. SunCoal, Ludwigsfelde. https://www.csiro.au/en/Research/MRF/Areas/Community-and-environment/Responsible-resource-development/Green-steelmaking.

Taibi, E., Gielen, D. and Bazilian, M. (2012). The potential for renewable energy in industrial applications. Renewable and Sustainable Energy Reviews 16, pp. 735–744.

The World Bank (2018). Intended Nationally Determined Contributions database. Washington, DC.
http://spappssecext.worldbank.org/sites/indc/Pages/mitigation.aspx

UN DESA (2016). Montreal Protocol. United Nations Department of Economic and Social Affairs, New York City, NY.
https://sustainabledevelopment.un.org/index.php?page=view&type=30022&nr=135&menu=3170.

UNEP (2016). Global material flows and resource productivity. Assessment report for the UNEP International Resource Panel. United Nations Environmental Programme, Paris. http://wedocs.unep.org/handle/20.500.11822/21557.

UNIDO (2010). Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report. Working Paper, November 2010. United Nations Industrial Development Organization, Vienna. https://www.unido.org/sites/default/files/2010-12/synthesis_final_0.pdf.

UNIDO (2017). Accelerating clean energy through Industry 4.0: manufacturing the next revolution. United Nations Industrial Development Organisation, Vienna.
https://www.unido.org/fileadmin/user_media_upgrade/Resources/Publications/REPORT_Accelerating_clean_energy_through_Industry_4.0.Final.pdf.

USGS (2017). Nitrogen (fixed) – Ammonia. United States Geological Survey, Reston, VA. https://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/mcs-2017-nitro.pdf

WBCSD and IEA (2009). Cement Technology Roadmap 2009 – Carbon emissions reductions up to 2050. World Business Council for Sustainable Development and IEA/OECD, Geneva and Paris.
https://www.iea.org/publications/freepublications/publication/Cement.pdf.

WCC (2017). World Chlorine Council. http://www.worldchlorine.org/.

Weiss, M., Neelis, M.L., Zuidberg, M.C., Patel, M.K. (2008). Applying bottom-up analysis to identify the system boundaries of non-energy use data in international energy statistics. Energy 33, pp. 1609-1622.

Wesseling, J.H., Lecthenböhmer, S., Ahman, M., Nilsson, L.J., Worrell, E. *et al.* (2017). The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. Renewable and Sustainable Energy Reviews 79, pp. 1303-1313.

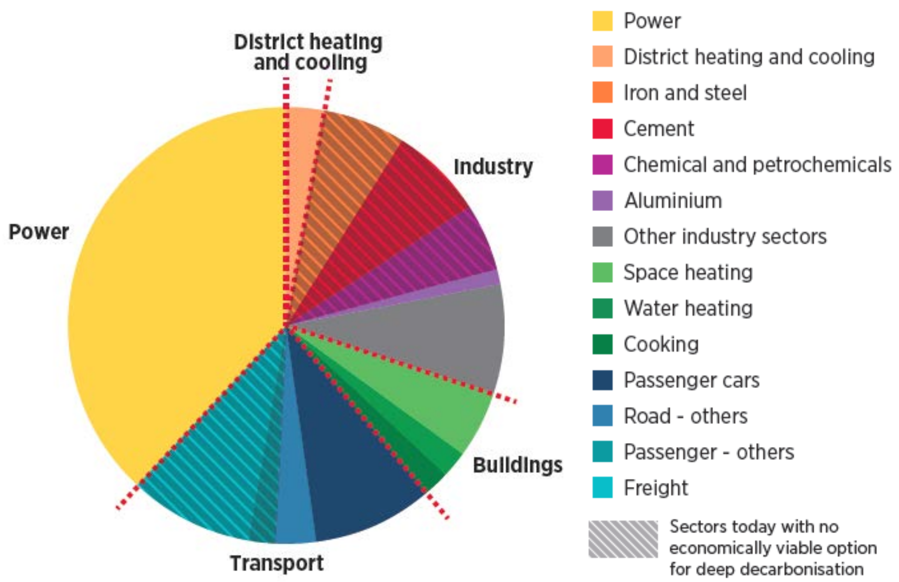
WSA (2016). World Steel in Figures 2016. World Steel Association, London. https://www.worldsteel.org/en/dam/jcr:4f060d8b-3602-4ffe-9e87-7e93e0659449/Word+Steel+in+-Figures+2016.pdf.

Worrell, E., Allwood, J. and Gutowski, T. (2016). The role of material efficiency in environmental stewardship. Annual Review of Environment and Resources 41, pp. 575-598.

Zoller, U. and Sosis, P. (2008). Handbook of Detergents, Part F. Taylor & Francis Group, Boca Raton. https://www.taylorfrancis.com/books/9781420014655.

FIGURES

Figure 1: Global CO_2 emissions by sector, 2015



Source: (IRENA, 2017a; IRENA, 2017b)

Figure 2: Industry's total final energy and non-energy consumption by fuel type under the Reference Case and REmap Case, 2015-2060

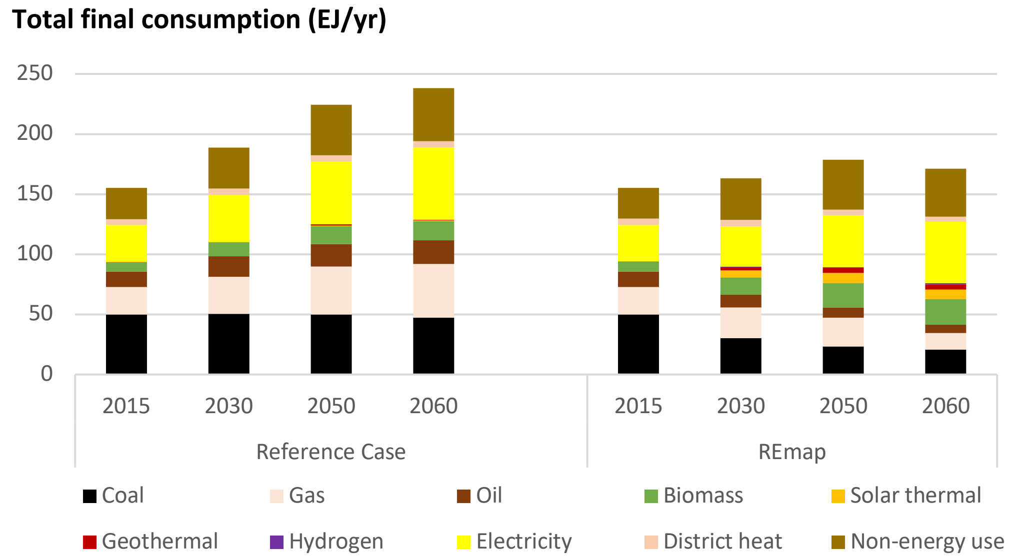


Figure 3: Industry's total CO_2 emissions by sector under the Reference Case and REmap Case, 2015-2060

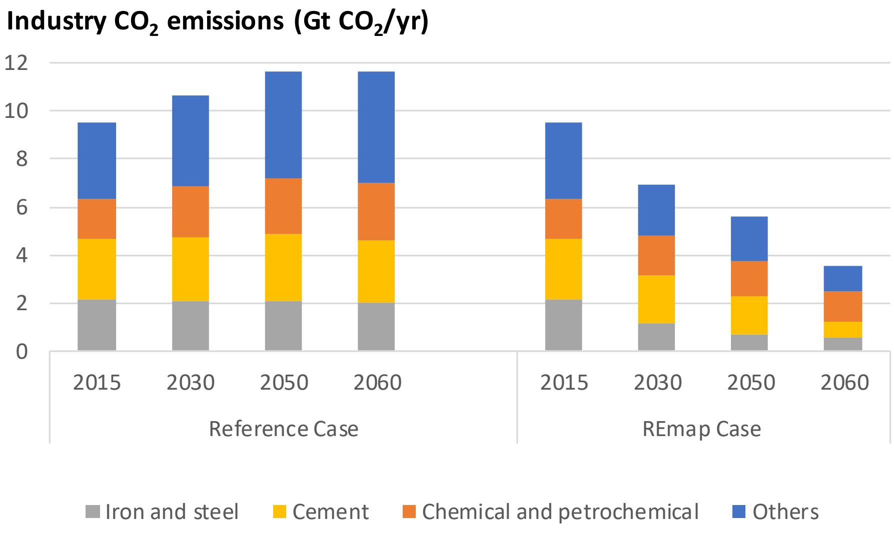
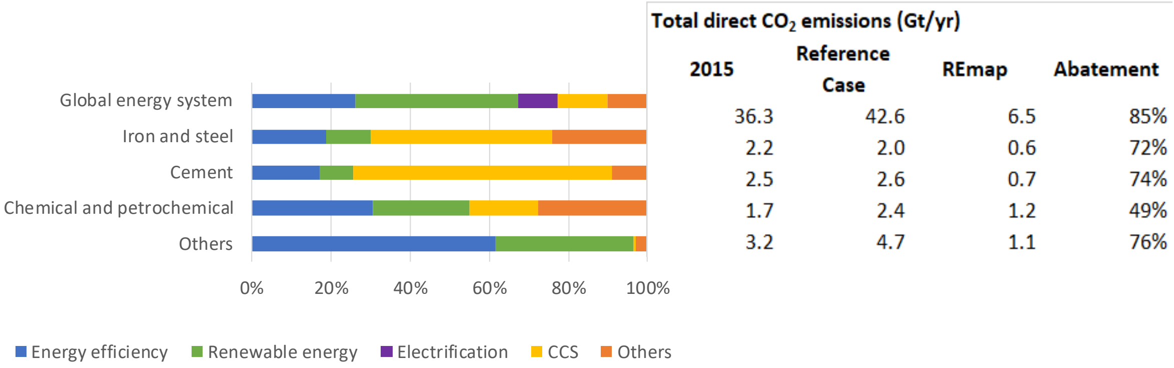


Figure 4: CO_2 emissions reductions in REmap compared to Reference Case by technology, 2060



Total direct CO_2 emissions (Gt/yr)

2015	Reference Case	REmap	Abatement
36.3	42.6	6.5	85%
2.2	2.0	0.6	72%
2.5	2.6	0.7	74%
1.7	2.4	1.2	49%
3.2	4.7	1.1	76%

Figure 5: Breakdown of final renewable energy use in the industry sector, 2060

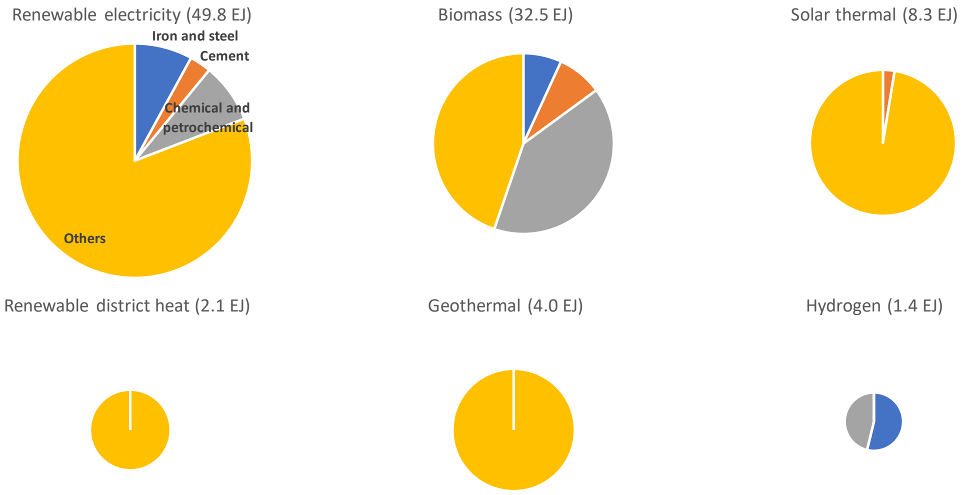
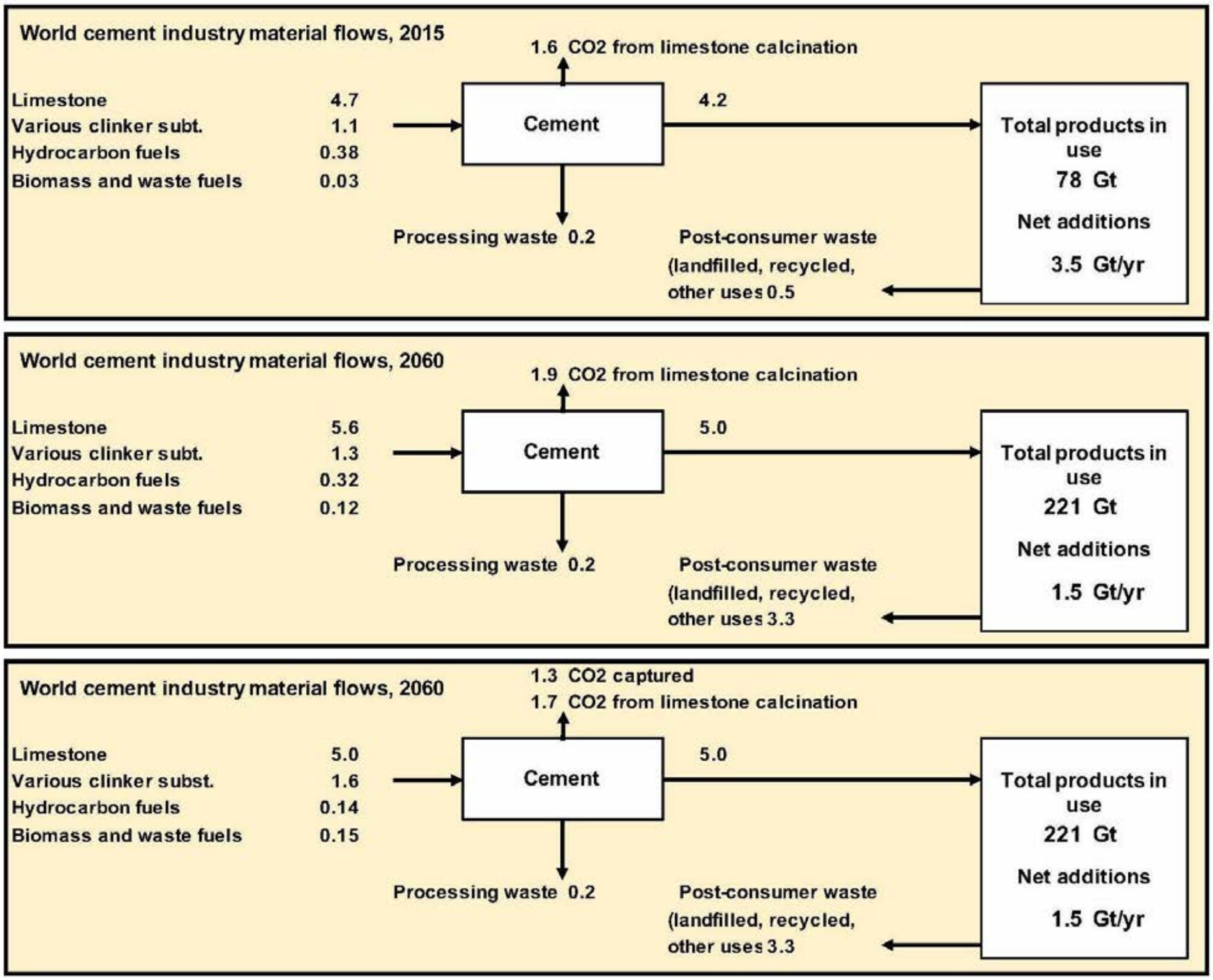
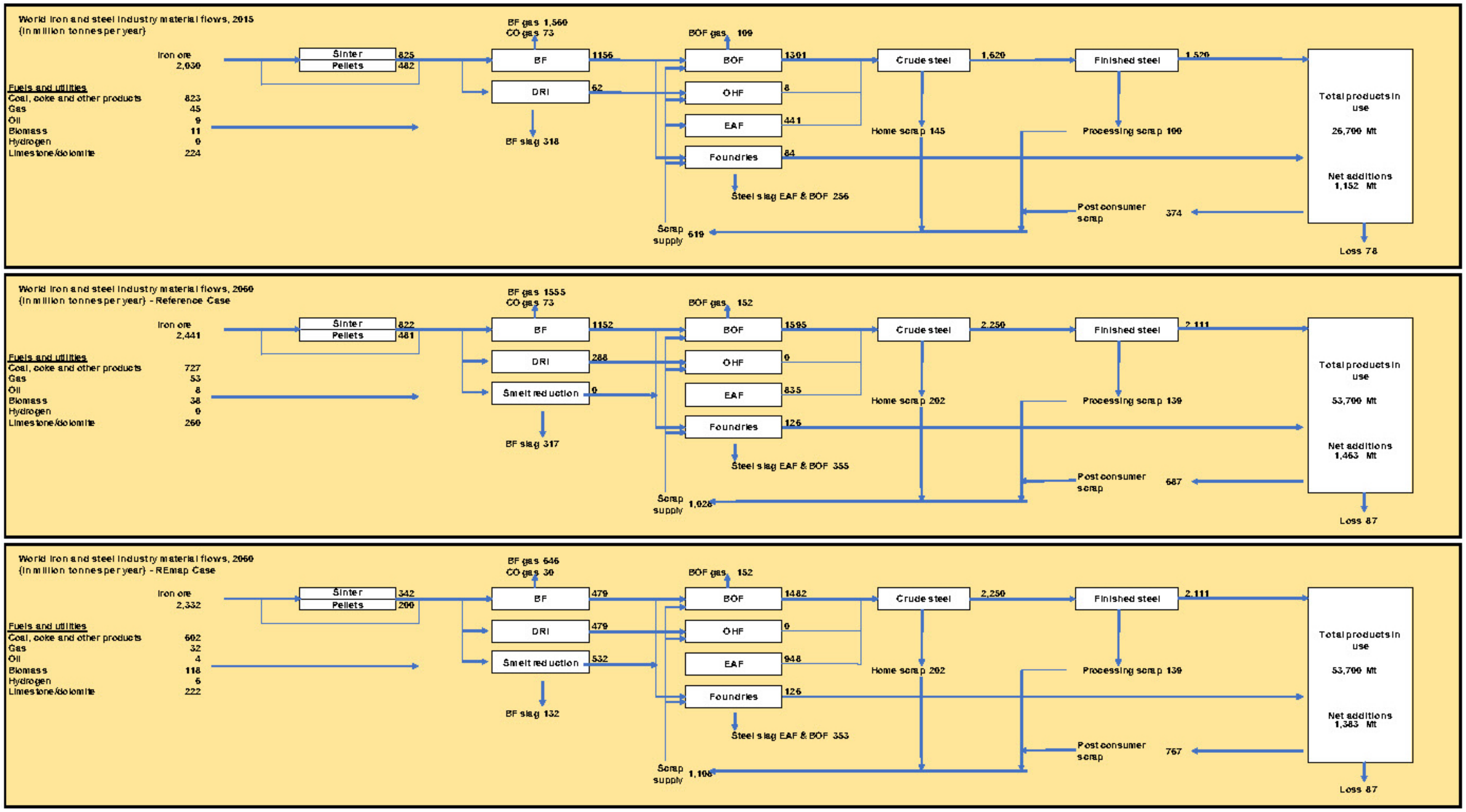


Figure 6: Material flows in the global cement sector under the REmap Case and the Reference Case, 2015 and 2060



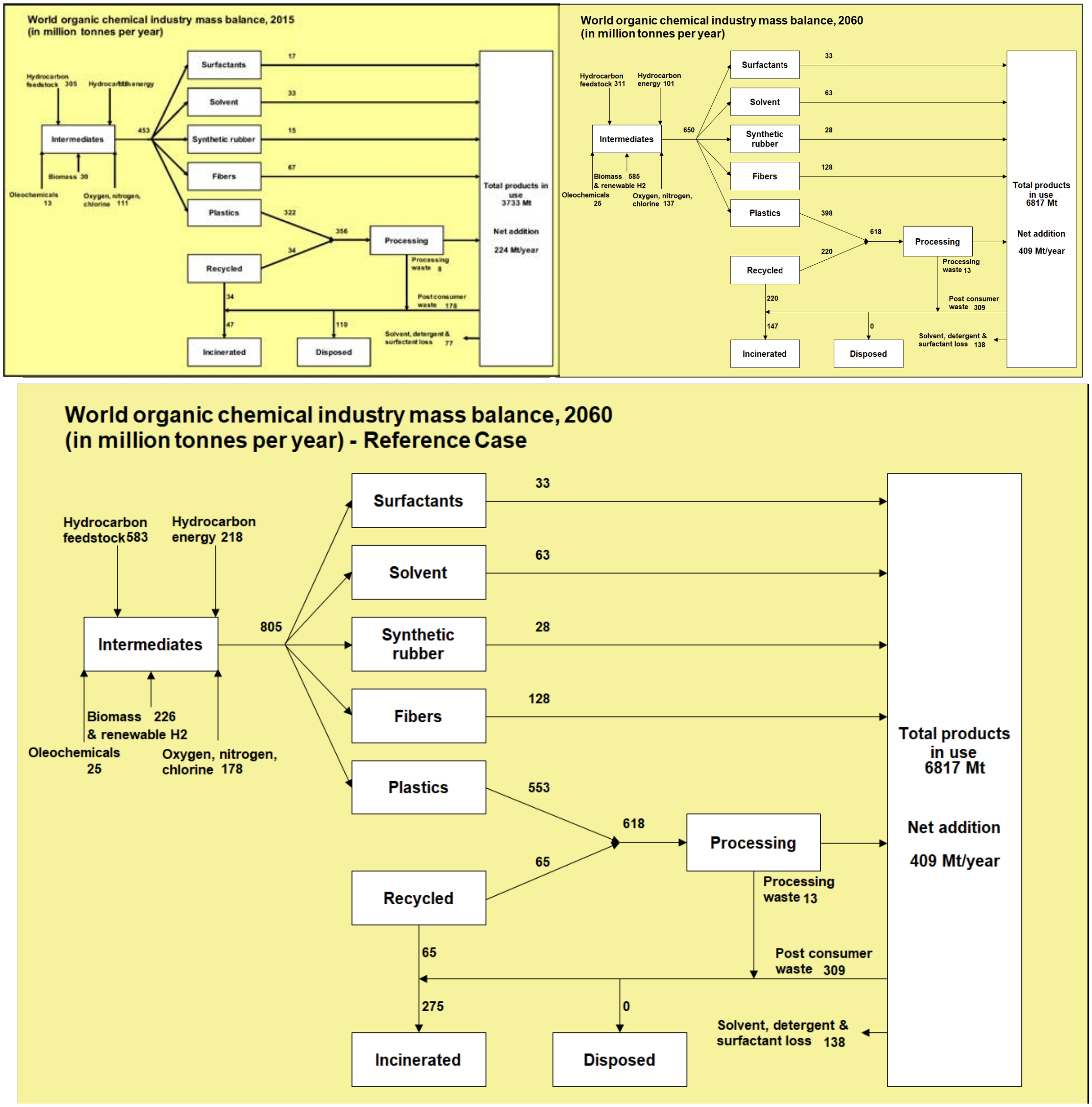
Sources and notes: Raw material inputs are based on IPTS/EC (2013a). It is assumed that 0.51 tonnes of CO2 per tonne of clinker is released. Energy demand related to the production of clinker substitutes is excluded. For all waste fuels, a lower heating value of 17.5 GJ/t is assumed, similar to biomass. For fossil fuels, the following lower heating values have been assumed (in GJ/t), coal: 25, gas: 37, oil: 44. Manufacturing losses (processing waste) is assumed as 4% throughout the entire 2015-2060 period based on Krausmann et al. (2017b). Post-consumer waste is estimated based on total cement entering the stock 50 years ago, i.e. the lifetime of concrete stocks based on Krausmann et al. (2017b) (range of 5-95 years). Total products in use is estimated as total production of cement minus processing waste and minus the cement leaving the stock as post-consumer waste.

Figure 7: Material flows in the global iron and steel sector under the REmap Case and Reference Case, 2015 and 2060



Sources and notes: Foundry production based on AFS (2016). All other production volumes based on WSA (2016) unless otherwise stated. 120 kg and 50 kg of dolomite and limestone consumption per tonne pellet and sinter, respectively (Kuramochi et al., 2012) and 40 kg, 0-28 kg, 25-140 kg and 32-67 kg of dolomite and limestone consumption per tonne hot metal, basic oxygen furnace, electric arc furnace and smelt reduction steel, respectively (Link, 2008; IPTS/EC, 2013b). Iron ore demand for DRI at 1450 kg per tonne of iron (Sikstrom, 2013) and iron ore demand for smelt reduction 1500 kg per tonne of iron (Kuramochi et al., 2012). Pellet and sinter production as a share of the total iron ore input is assumed as 25% of all iron ore for pellet production and 935-965 kg pellet production per tonne of iron ore and, 50% of all iron ore is used for sinter production and 813 kg sinter production per tonne of iron ore (Corsten, 2009; IPTS/EC, 2013). 250-300 kg blast furnace slag per tonne of hot metal and 100-200 kg steel slag per tonne of basic oxygen furnace steel (IEA, 2007). 110-155 kg steel slag per tonne of electric arc furnace steel (Rohde et al., 2003; NSA, not dated). Scrap for basic oxygen furnace, electric arc furnace and casting as well as home scrap generation based on Horner (2014). 250 kg coke per tonne of hot metal and 6-8 GJ coke oven gas generated per tonne of coke with a density of 0.544 kg per Nm^3 and net calorific value of 17.5 GJ/Nm^3. 4 GJ of blast furnace gas is generated per tonne of hot metal with a density of 1.35 kg per Nm^3 and net calorific value of 4 MJ/Nm^3. 0-0.7 GJ basic oxygen furnace gas per tonne of steel with a density of 1.35 kg per Nm^3 and net calorific value of 6-8 MJ/Nm^3. Total products in use based on IEA (2007) and assuming a net growth of 0.8 Gt per year in 2005-2015 and 0.6 Gt per year in 2015-2060. Losses based on IEA (2007).

Figure 8: Material flows in the global organic chemical sector under the REmap Case and the Reference Case, 2015 and 2060



Sources and notes: Total hydrocarbon (coal, natural gas and gas oil/diesel/heavy fuel oil) feedstock and fuel input covers their consumption for steam cracking, ammonia, methanol and carbon production and their shares consumed in the organic chemical sector. Specific consumption and the net calorific value of hydrocarbon feedstocks and fuels are based on Weiss et al. (2008). Shares of their consumption for organic chemical sector are based on ammonia (90%) (Nexant, 2013), methanol (64%) (Alvarado, 2016), chlorine (65%) (WCC, 2017) and oxygen (25%) (IEA, 2007). All carbon black and steam cracking production is assumed to be consumed in the global organic chemical industry. Chemicals production in 2015 is based on ammonia (USGS, 2017), methanol (Argus, 2015), oxygen (IEA, 2007), chlorine (Kok, 2017), carbon black (Industry Experts, 2016), steam cracking products (OGJ, 2015) and oleochemicals (GVR, 2016). Current breakdown of their production routes (coal, gas, oil) and biomass input are based on Saygin et al. (2014) and by accounting for the production growth of bio-based chemicals between 2007 and 2017 based on Aeschelmann et al. (2015) and EuBP (2018). Production of final products, namely plastics (Plastics Europe, 2016), fibers (IC, 2017), synthetic rubber (RSB, 2018), solvents (IHS, 2013) and surfactants (Zoller and Sosis, 2006). Total processing and post-consumer waste are based on IEA (2007) and 2015 values are estimated based on production growth between 2004 and 2015. The post-consumer waste includes the 8 Mt plastics (4.8-12.7 Mt) that enter the ocean each year (Dunham, 2018). Total volume of plastics recycled 18% and total incinerated 25% of all generated plastic waste in 2015 (IEA, 2007; Geyer, Jambeck and Law, 2017) and rest is assumed to be landfilled. Processing and post-consumer waste is based on IEA (2007). Solvent, detergent and surfactant losses are based on IEA (2007). Total products in use is estimated by scaling up the growth in net additions between 2004 and 2015 based on IEA (2007). It is assumed by 2060, no plastics have been disposed, but either recycled or incinerated with energy recovery.

TABLES

Table 1: Overview of energy and climate roadmaps that focus on the energy-intensive industry sectors

Organisation	Year published	Region	Time frame	Technology scope	Reference
Chemical and petrochemical sector					
CEFIC	2013	EU	2010-2050	Energy and resource efficiency, fuel and feedstock substitution, non-CO_2 GHG abatement, CCS, decarbonizing power	CEFIC, 2013
IEA, ICCA, DECHEMA	2013	Global	2010-2050	Energy and resource efficiency from catalysis	IEA/ICCA/DECHEMA, 2013
CEFIC and DECHEMA	2017	EU	2015-2050	Energy and resource efficiency, fuel and feedstock substitution	DECHEMA, 2017
Iron and steel					
Eurofer	2013	EU	2010-2050	Energy and resource efficiency, fuel substitution, CCS	Eurofer, 2013
Cement					
WBCSD and IEA	2009	Global and regional	2006-2050	Energy and resource efficiency, fuel substitution, CCS	WBCSD and IEA, 2009
CEMBUREAU	2013	EU	2011-2050	Energy and resource efficiency, fuel substitution, CCS	CEMBUREAU, 2013

Notes: CEFIC: European Chemical Industry Council, IEA: International Energy Agency, ICCA: International Council of Chemical Associations, DECHEMA: DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e. V, Eurofer: The European Steel Association, WBCSD: World Business Council on Sustainable Development, CEMBUREAU: The European Cement Association.

Table 2: Production volume and energy consumption assumptions for bulk materials production, 2015-2060

	2015	Reference Case		REmap Case	
		2030	2060	2030	2060
Production volumes	(Mt/yr)	(Mt/yr)	(Mt/yr)	(Mt/yr)	(Mt/yr)
Blast furnace iron	1,183	1,149	1,152	788	518
Direct reduced iron	76	128	288	338	518
Smelt reduction iron	-	-	-	219	576
Primary steel	1,202	1,296	1,463	1,111	1,463
Secondary steel	409	556	788	741	788
Clinker	3,085	3,418	3,678	3,266	3,317
Cement	4,152	4,600	4,950	4,600	4,950
High-value chemicals	364	520	655	435	328
Ammonia	177	219	258	219	258
Methanol	70	165	218	165	218
Total plastics production	322	515	620	515	620
Total bio-based plastics production	2	20	61	69	151
Total recycled plastics	34	54	65	77	220
Specific final energy consumption	(GJ/t)	(GJ/t)	(GJ/t)	(GJ/t)	(GJ/t)
BOF steel	18.7	17.9	16.4	15.7	13.9
Scrap-EAF steel	2.7	2.6	2.4	2.3	2.0
DRI-EAF steel	12.8	12.2	11.2	10.7	9.5
Smelt reduction	-	-	-	14.0	12.0
Steel rolling	2.2	2.1	1.9	1.8	1.6
Clinker kilns	3.5	3.3	3.1	2.9	2.1
Cement grinding	0.3	0.3	0.3	0.3	0.2
High-value chemicals	30.0	28.7	26.2	25.1	20.4
Ammonia	20.0	19.1	17.5	16.7	13.6
Methanol	7.5	7.2	6.6	6.3	5.1

Notes: uses of fossil fuels as feedstock in the production of chemicals are excluded.

Table 3: Industry sector's renewable energy shares, 2015-2060

	2015	Reference Case			REmap		
		2030	2050	2060	2030	2050	2060
Only process heat	9%	10%	13%	14%	26%	38%	45%
Process heat, electricity & DHC	12%	17%	23%	22%	36%	53%	62%
Process heat, electricity, DHC & NEU	11%	15%	20%	20%	32%	47%	55%

Notes: NEU = non-energy use; DHC = district heating and cooling.

Table 4: Monitoring technology progress by sector, 2000-2060

	Tech. type	Installed capacity, history and REmap						Growth index of installed capacity under REmap			Mitig. costs	CO_2 mitig. 2060	Capacity indicators
		Unit	2000	2015/16	2030	2050	2060	2000-16	2016-30	2030-60	[USD/t CO_2]	[Gt CO_2/yr]	[-]
DRI with renewable hydrogen	RE	EJ/yr	-	-	0.2	0.5	0.7	-	-	4.4	65-190	0.1	1,125 DRI plants fully operating with renewable hydrogen. All DRI plants in operation today in India is around 500
Smelting reduction	EE - heat	Mt/yr	-	2	219	390	532	-	2	2.0	5-45	0.01	625 smelting reduction plants
CO_2 captured from iron production	CCS	Mt/yr	-	0.8	305	602	729	-	0.8	1.8	50-150	0.7	900 CCS plants with the size of the single plant in operation today in Abu Dhabi
Biomass use in blast furnaces	RE	Mt/yr	9.0	10.8	60.2	109.8	113.7	9.0	10.8	1.0	-50-50	0.2	1,125 blast furnaces meeting one-third of their fuel demand with biofuels
Clinker-to-cement ratio	OTH	%	82.5	74.3	71.0	67.0	67.0	82.5	74.3	0.9	35-75	0.2	1,600 Mt clinker substitute required. Current availability of the typical substitutes is around 1,000 Mt
CO_2 captured from cement production	CCS	Mt/yr	-	-	327	513	1,327	-	-	4.1	35-70	1.3	440 clinker kilns with a CCS plant
Clinker kilns biomass and alternative fuels	RE	EJ/yr	0.2	0.4	1.4	2.6	2.6	0.2	0.4	1.8	-15- -65	0.1	3,900 clinker kilns meeting more than one third of their total energy demand from biomass and alternative fuels
Bio-based chemicals	RE	Mt/yr	-	13	69	127	151	-	5.5	2.2	100-300	1.1	One quarter of all plastics from biomass raw materials
Renewable hydrogen based ammonia production	RE	Mt/yr	-	-	4	13	18	-	-	4.1	20-130	0.08	40 ammonia plants running entirely based on renewable hydrogen
CO_2 captured from gas ammonia production	CCS	Mt/yr	-	1.7	50	100	200	-	1.7	4.0	100-200	0.2	425 ammonia plants retrofitted with CCS. Today 1.7 Mt CO_2 emissions are captured from 2 fertilizer plants
Renewable process heating (incl. waste)	RE	EJ/yr	6.8	8.1	23	34	35	6.8	8.1	1.4	40-125	2.0	45% of all process heat supplied from renewables compared to 10% today
Recycled steel production	OTH	Mt/yr	286	409	741	880	900	286	409	1.5	-25-35	0.5	200,000 ship loads each year to carry steel scrap
Recycled aluminium production	OTH	Mt/yr	8	26	46	69	77	8	26	1.7	-35-25	0.1	19,000 ship loads each year to carry aluminium scrap
Recycled plastics	OTH	Mt/yr	8	12	77	141	220	8	12	1.8	20-60	0.3	Plastics recycled equivalent to the total weight of 11 trillion ½ liter PET bottles
Energy management systems ISO 50001	EE - heat	Index (2015=1)	-	1.00	0.84	0.73	0.72	-	1.00	0.8	25-45	2.3	1% annual improvements in industrial energy efficiency (including baseline improvements)
Efficient motors and industrial electricity systems	EE – elec	Index (2015=1)	-	1.00	0.84	0.73	0.72	-	1.00	0.8	-80-40	1.7	

Notes: Emissions reductions total 10.9 Gt, including 8.1 Gt from fuel use (see Figure 4) 1.1 Gt from carbon stored in chemicals and 1.7 Gt from electricity use efficiency. RE: Renewable energy technologies; EE - heat, - fuel, - elec: Energy efficiency measures; ELEC: electrification that improves energy efficiency; CCS: carbon capture and storage OTH: material efficiency improvements and other low-carbon strategies such as modal shift in transport. Source: IRENA (2017b)

Table 5: Overview of initiatives for decarbonisation of the bulk material producing industry sectors. Source: IRENA (2016;2017b)

Name	Scope	Technology / Sector	Stakeholders	Region
Cement Sustainability Initiative	23 major cement producers with operations in more than 100 countries, aiming to explore sustainable development means	Cement sector energy efficiency and alternative fuels	Private sector	Global, 100 countries
CEM Corporate Sourcing Campaign	Seeks to accomplish higher uses of renewables	Company level for renewable energy	Inter-governmental and private sector	CEM member countries
RE100	Global initiative of influential businesses committed to 100 % renewable electricity, working to massively increase demand for renewable energy	Company level for renewable energy	Private sector	Global
Lawrence Berkeley National Laboratory – China Energy Group	Collaboration between the Chinese and the US government and nongovernment partners to gain an in-depth understanding of China's industrial sector and its energy use and energy efficiency	Energy efficiency in energy-intensive sectors	Government and non-government	China
Sustainable Energy Financing Facilities (SEFFs) of the European Bank for Reconstruction and Development (EBRD)	Credit lines to local financial institutions that seek to develop sustainable energy financing as a permanent area of business for energy efficiency and small-scale renewable energy	Energy efficiency and renewable energy in various industry sectors	Finance and private sectors	South East Europe, Central Europe and Baltic States, Eastern Europe and Caucasus, Central Asia
Business Environmental Leadership Council (BELC)	Largest US-based group of corporations focused on addressing the challenges of climate change and supporting mandatory climate policy	Company level driven by climate change mitigation	Private sector	US
GCCSI	International member-led organisation whose mission is to accelerate the deployment of CCS in tackling climate change and providing energy security	Cement	Private sector, development banks, 6 governments	Global
WWF Climate Savers	Works in partnership with companies to set and meet goals to reduce carbon emissions, advance projects to protect their resources from climate impacts, and ensure the sustainability of their core business. Corporations partner with WWF to establish ambitious targets to voluntarily reduce their GHG emissions within a defined timeframe	Company level driven by climate change mitigation	NGO, private sector	Global
Ultra –Low CO_2 Steelmaking (ULCOS)	Consortium of 48 companies and organisations that have launched a cooperative R&D initiative to enable drastic reduction in CO_2 emissions from steel production. Aim is to reduce CO_2 emissions of today's best routes by at least 50%	Iron and steel sector, energy efficiency, renewables, CCS, electrification	Private sector and academia	Europe
Global management consultant companies	Public and private advisory bodies that contribute to data collection and benchmarking initiatives in the industry sector	All industry sectors for benchmarking energy use	Private sector	Global
SHIP Plants	Data collection about technology, performance and cost about solar thermal use for process heating	Solar process heat	Private sector	Global
IEA Technology Collaboration Programmes (TCPs)	Pre-commercial technology information exchange to support innovation for energy security, economic growth and environmental protection, by exchanging precommercial technology information.	All large energy using industries and all low-carbon technologies	Intergovernmental and academia	IEA member countries

COLORADO SCHOOL OF MINES
PAYNE INSTITUTE

ABOUT THE AUTHORS

Dolf Gielen is director for technology and innovation at the International Renewable Energy Agency since 2011. He holds a PhD from Delft University of Technology in Delft, the Netherlands. He has studied Chemical Engineering at Eindhoven University of Technology and Environmental Sciences at Utrecht University in the Netherlands. Prior to joining IRENA he has worked for the International Energy Agency and the United Nations. Gielen spent two years as a fellow at the National Institute for Environmental Studies in Japan. He has coauthored more than 100 papers in peer reviewed journals and contributed to numerous books and research reports. Gielen is a non-resident fellow of the Payne Institute at Colorado School of Mines.

Deger Saygin works as the director of the SHURA Energy Transition Center. In his former role at the International Renewable Energy Agency, Deger developed and led the global renewable energy roadmap programme between 2013 and 2017. This programme has assisted the world’s 70 largest energy using countries in accelerating the use of renewable energy and energy efficiency technologies to operationalise the goals of the seventh Sustainable Development Goal and the Paris Agreement. Prior to joining IRENA, Deger worked as a researcher at Utrecht University carrying out projects for intergovernmental organisations, countries and the private sector about more sustainable uses of energy and resources in the manufacturing industry. It is also where he received his PhD. He received his undergraduate degree in environmental engineering from the Middle East Technical University in Ankara.

ABOUT THE PAYNE INSTITUTE

The mission of the Payne Institute at Colorado School of Mines is to provide world-class scientific insights, helping to inform and shape public policy on earth resources, energy, and the environment. The Institute was established with an endowment from Jim and Arlene Payne, and seeks to link the strong scientific and engineering research and expertise at Mines with issues related to public policy and national security.

The Payne Institute Commentary Series offers independent insights and research on a wide range of topics related to energy, natural resources, and environmental policy. The series accommodates three categories, namely: Viewpoints, Essays, and Working Papers.

For more information, visit PayneInstitute.MINES.edu.

@payneinstitute

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT