# Decarbonising Europe's energy intensive industries

# The Final Frontier


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In Memoriam
Henk Van den Abbeele (1948-2016)
*Chemist, Innovator and Entrepreneur*

*"There is a way out of every box, a solution to every puzzle; it's just a matter of finding it."*

Jean-Luc Picard

# Introduction

The goal of this report is to identify options for deep greenhouse gas emission reductions by EU energy intensive industries. This type of greenhouse gas mitigation should bring emissions in these sectors down by at least 80% in 2050 compared to 1990 levels. That would be consistent with the EU's long-term climate objective.

The main focus lies on innovative process technologies that significantly improve the emission performance compared to current (state-of-the-art) technologies. But moving towards decarbonisation in these industries forces us to look beyond process changes. The findings presented in this report therefore include other relevant options such as product and business innovations.

Researching the decarbonisation challenge for energy intensive industries cannot ignore the economic function these sectors have in the economy. This includes studying their current strengths and weaknesses. Most of the industries considered in this report have faced or are facing important economic challenges. Not all energy intensive industries can be covered within the scope of this study, and therefore, this report focuses on the most important parts of the chemical industry, the steel industry and the cement industry. Hence, the overwhelming majority of industrial greenhouse gas emissions from EU industrial sectors will be covered.

The analysis in this report starts with the assumption that mitigation options using only current technologies will not be able to address the decarbonisation challenge in time. Furthermore, the aforementioned economic challenges for sectors such as steel and cement might eclipse the needs and means for investments in breakthrough low-carbon technologies. The combination of both elements can truly give the impression of an unassailable frontier.

This report looks into the opportunities to break through this final frontier.

Chapter 1 analyses the major mitigation options in the chemicals industry, focusing particularly on petrochemicals and ammonia production for fertilisers. Chapter 2 addresses mitigation in the steel industry. Chapter 3 covers the cement industry. For each of the sectors, the results are discussed in an 'outlook and challenges'-section where a comprehensive approach towards deep emission reductions is presented. This takes into account the economic context under which each industry operates.

The report is concluded with an overarching assessment of all industries considered, and adds on a linkage with the public sector. This specifically includes an introduction to the forthcoming EU ETS innovation fund and suggestions for its design.

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# Executive Summary

**Between 1990 and 2013, EU industry contributed significantly to the economy-wide emission reductions in the EU. This report illustrates that further deep emission reductions, up to -80% or more (compared to 1990 levels) are possible in each of the industries considered. This transition will also enable opportunities that can enhance the competitiveness of European industry.**

However, tapping into the reduction potential will not be easy, as most of the low-hanging fruits have already been picked. Even if there still is potential to enhance existing processes using current technologies, this will not be sufficient to reach the deep mitigation goals. Furthermore most, if not all, of the energy intensive industries face major challenges regardless of future mitigation commitments. These include production and capacity surpluses, as well as increased competition with other regions around the world that have competitive advantages through lower cost fuels or larger sized domestic markets. These elements could hamper the potential to reduce emissions in the future. They can, on the other hand, also be an opportunity to focus on the climate friendly solutions that come with co-benefits, which would increase the economic performance and competitiveness of these industries.

This report shows that there is no *single* silver bullet that will break through the final frontier for deep emission reductions in energy intensive industries. **An economically attractive low-carbon transition will require the combination of three pillars. These are the process, product and business model transformations.**

In the chemical industry, the use of biomass waste as a feedstock for replacing most of the oil-based inputs will be an important element towards lower emission reductions. The cement industry seems to have a unique opportunity to use a specific type of CCS technology, which comes with important co-benefits. In the steel sector a new type of blast furnace that would negate the need for coking and sintering in hot iron production is currently being tested. This technology would be less costly to build and operate compared to conventional technologies. It can also reduce emissions by 20% and up to 80% with the availability of CCS.

Next to these breakthrough process technologies, also innovative products will have to play a key role in the industrial low-carbon transition. Development of new high-performing chemical compounds that can easily be assembled from bio-based feedstock will be essential. A promising and widely abundant clinker substitute, mentioned in this report, can reduce cement production emissions by 30%, while giving the same properties to cement as the commonly used Portland cement. Advanced material science leading to high performance and lightweight steel can open a market for steel producers, which targets downstream consumers in need of these types of steel for low-carbon performance of their products.

Finally, business model transitions will be essential to enable both economic and environmental benefits. Ammonia and fertiliser production can move from pure manufacturing into the direction of agricultural services, by benefiting from the use of emerging biotechnologies. The cement and steel industries will have to address the current (and possibly structural) overcapacity through rationalisation, modernisation and increased overall value added at lower sales volumes.

These industrial transitions cannot be seen as isolated issues and must instead be aligned with other major shifts in the EU economy that are expected over the next decades. The growth of renewable electricity can become an asset for industrial transformation. Electrification of ammonia and steel production open up for these processes to act as a battery, which consumes more electricity when plenty of renewables feed into the grid and reduces consumption at times of high demand and low renewable energy generation. These new services will, of course, need to be rewarded in future EU power markets. A paradigm shift towards higher levels of resource efficiency and a circular economy in the EU also matches well the industrial transitions mentioned in this report. Both the steel and the chemical sector have ample potential to increase re-usage and recycling of products. For the steel industry, this would fit nicely with the move towards higher levels of electric arc steel and away from blast furnace production. Finally, the anticipated electric vehicle revolution can have an impact on the availability of fossil fuel based feedstock for the chemical sector, through closures of refining capacity over the next decades. It will also further open a market for advanced lightweight steel in the automotive sector.

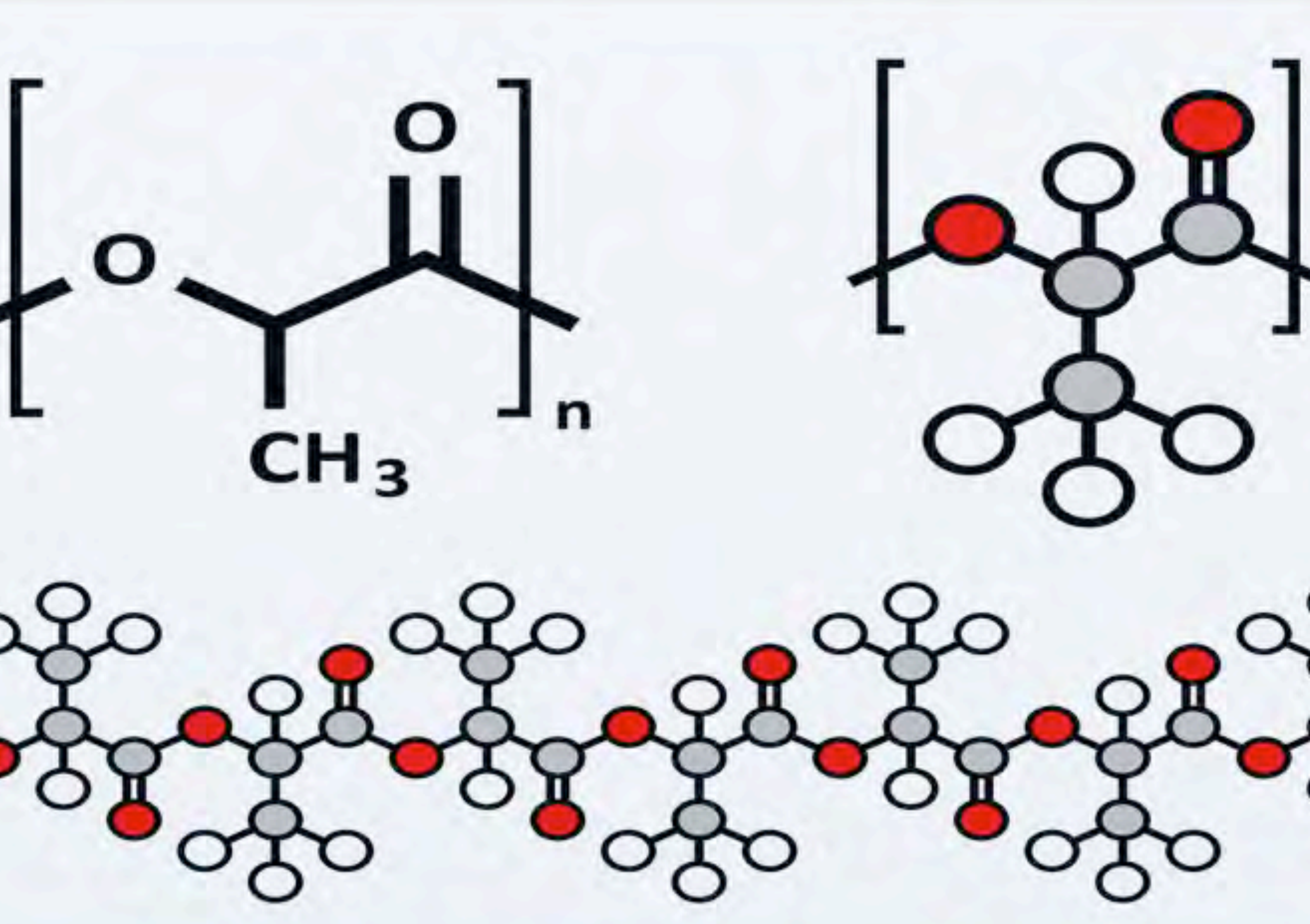
**The required transitions in energy intensive industries will not take place in the absence of smart and committed public policies.** First of all, governments will have to assist these industries through modernisation and rationalisation. The high capital intensity of investments in these sectors is a key barrier. For instance, sovereign loan guarantees can help reduce the cost of capital of these investments, in particular for sectors and companies that are currently underperforming. Government can also help to create markets for new low-carbon products through public procurement. Avoiding regulatory misalignment is a third element that requires evaluation, as to avoid punishing industries that move towards low-carbon processes or business models.

One of the more challenging parts of the industrial low-carbon transformation will be to bring promising low-carbon process technologies to the commercialisation stage. These new process technologies will need to be market-ready by 2030 to allow for deployment across the EU by 2050. Again, these investments will be capital intensive but also, due to their pioneering nature, risk intensive. **The proposed EU ETS Innovation Fund for the period 2020-2030 can become an important tool to**

**enable a timely commercialisation of these process technologies.** This report uses the knowledge gained through the above-mentioned sectorial analysis to highlight specific design options for the Innovation Fund. For instance, industrial demonstration process technologies that are eligible should also demonstrate economic (or other) co-benefits. This could enhance the success of future implementation and commercialisation. A milestone-based reward system can reduce the risk for both the public and private sector in the implementation of projects. Financing these projects will require a toolbox of instruments that match the needs of specific industries. Member States can consider new forms of co-financing, such as the use of public procurement. Finally, timely implementation of Innovation Fund projects will depend on streamlined State Aid guidelines that allow fast-track approval of co-financing by Member States.

To conclude, the authors of this report believe that the EU finds itself at an important moment in the history of its industrial development. Thanks to technological process and product innovations that are happening throughout the industries, achieving deep emission reductions can be possible over the next decades. Higher awareness in the public sector, that realising deep emission reductions will require a helping hand (e.g. through the EU ETS innovation fund), is essential.

**A full transition can only be guaranteed if there is a sustained effort by both the public and private sector to fully integrate the decarbonisation challenges within industrial policy, and hence make this both an economic and a low-carbon success.**




# -1-
# Chemicals Industry

# 1.1. Introduction

The EU chemical sector is one of the sectors in the EU economy that has made most progress in reducing greenhouse gas emissions. Since 1990, the sector's greenhouse gas emissions decreased by almost 60% - from more than 300 million tonnes $CO_2$-eq in 1990 to less than 150 million tonnes in 2013, as illustrated in figure 1.1.

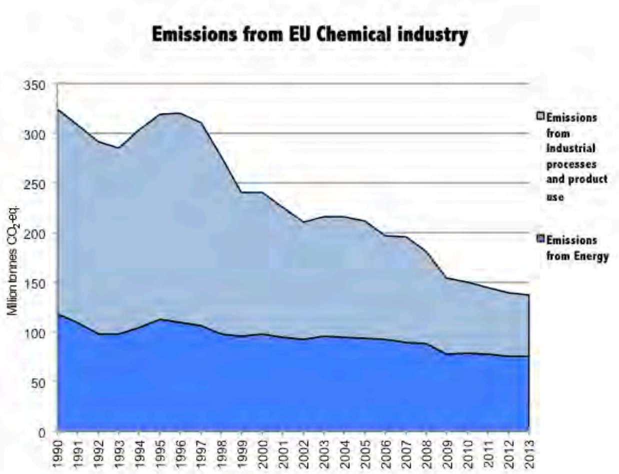



**Figure 1.1. Evolution of GHG emissions in the EU chemical industry between 1990 and 2013. [Mt $CO_2$-eq.] Source: EEA (2016).**

Most of this mitigation is due to reductions in process emissions, mainly of non-$CO_2$ greenhouse gases such as $N_2O$. In particular, the (process) greenhouse emissions from nitric acid production decreased by 90% between 1990 and 2013, and the process emissions from adipic acid production by almost 99% over the same period, as illustrated in figures 1.2 and 1.3.

At the same time the sector also managed to mitigate its energy related emissions following a reduction in fuel and power consumption of 24% between 1990 and 2013.

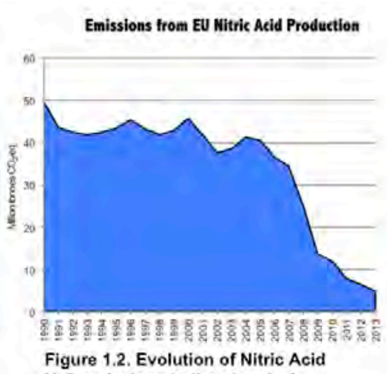



**Figure 1.2. Evolution of Nitric Acid $N_2O$ emissions in the chemical industry between 1990 and 2013. [Mton $CO_2$-eq.] Source: EEA (2016).**

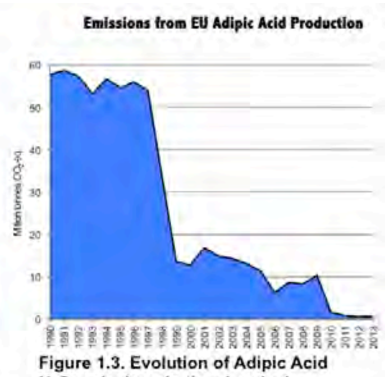



**Figure 1.3. Evolution of Adipic Acid $N_2O$ emissions in the chemical industry between 1990 and 2013. [Mton $CO_2$-eq.] Source: EEA (2016).**

These emission reductions are impressive, as the chemical sector managed to significantly increase its value added to the economy through growth in sales value (expressed in EUR) of almost 80% during the period 1994-2014. [1] Around 75% of sales take place inside EU.[2] The EU internal market is hence of major importance to the chemical sector. Nearly two thirds of the chemicals produced in the EU are supplied to other industrial sectors (such as packaging, automotive and electronic appliances) inside EU. This demonstrates the deeply connected and domestic value chain of the sector.

[1] CEFIC, 2016 p. 7
[2] id. p. 10

On the other hand, production growth has been stagnant over past 5 years.[3] Especially petrochemicals faced a sharp decline, while growth in specialty chemicals increased. This is illustrated by the recent, growing negative trade balance for petrochemicals, but also for basic inorganics (of which ammonium for fertilisers forms a significant part).[4] The main, and growing, competitors in these markets are the Middle-East, Russia, the US and China.

The next sections will analyse options that can reduce the total emissions of the chemical sector with 80% or more by 2050. Due to the size and complexity of the chemical sector, not all products and processes are covered in this report. However, by focusing on petrochemicals (in particular polymers and plastics) and ammonium production, the overwhelming majority of greenhouse gas emissions and hence mitigation in the chemical sector will be addressed.

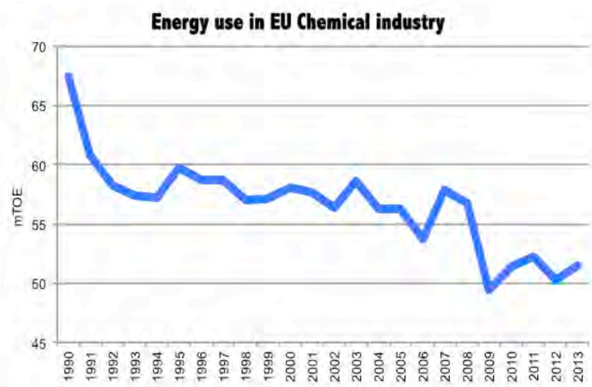



Figure 1.4. Evolution of energy use in the chemical industry between 1990 and 2013. [mTOE.]
Source: Eurostat (2016), CEFIC (2016).

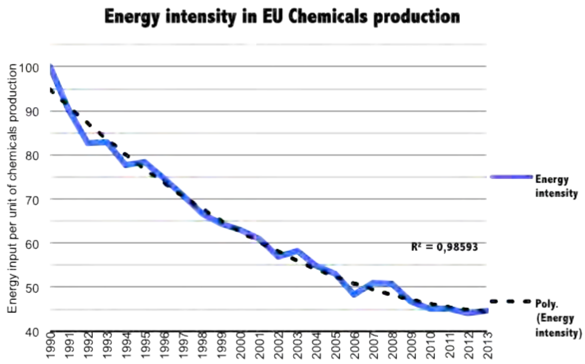



Figure 1.5. Evolution of index-based specific energy use in the chemical industry between 1990(=100) and 2013.
[Energy input/unit of chemicals production.]
Source: Eurostat (2016) and CEFIC (2016).

The chemical sector seems, with current emissions closing in to -60% compared to 1990, comes already close towards meeting the above-mentioned 2050 objectives. However, as shown in figures 1.2, 1.3, 1.4 and 1.5, the low hanging fruit in the form of non-$CO_2$ mitigation and efficiency improvements seems to be picked. Further emission reductions from energy and process efficiency are certainly possible, but such abatement opportunities will be fewer over time and likely also more expensive. Achieving further deep emission reductions, while maintaining sales volumes, will require a combination of (radical) new process technologies, innovative products, alternative feedstocks and business model revolutions.

[3] id p. 22
[4] id. p. 23

# 1.2. Petrochemicals

## 1.2.1. Mapping the sector

Petrochemicals are chemical products derived from petroleum products, such as crude oil or natural gas. The two most important petrochemicals are olefins (this includes ethylene, propylene and C4 products) and aromatics (including benzene, toluene and xylene isomers). An essential by-product is Pyrolysis gas (Pygas), consisting of aromatics and other high-octane chemicals. The olefins are the basis for polymers and oligomers used in plastics, resins, fibers, elastomers, lubricants, and gels. Aromatics are used as starting materials for a broad range of products such as clothing, pharmaceuticals, cosmetics, computers, paints, vehicle components, cooking utensils, household fabrics and sports equipment.

Steam cracking is the most important process to produce basic chemicals, through cracking long-chain hydrocarbons into short-chain hydrocarbons such as ethylene, propylene, butadiene, benzene aromatics and hydrogen. Benzene is produced through steam cracking and a reforming process. Most of the propylene in EU is produced with steam cracking, and the remainder in refineries in the catalytic cracking section, by dehydrogenation of propane and metathesis.[5] Aromatics are produced both in the chemical sector and the refinery sector. The EU chemical sector and the refineries are strongly integrated, with 59 crackers in total, 40 of which are integrated with refineries.[6] Also the feedstock for petrochemical production (in particular naphtha and liquid petroleum gas) comes from oil refineries through the refining process. In the EU, the main feedstock for petrochemical production is Naphtha (73%), followed by gas oil (10%) and gaseous feedstocks (17%) such as LPG (butane, propane) and ethane.[7] In the US and the Middle East, the main feedstock is ethane. Ethane is a component of natural gas and a relative cheap resource in these areas due to the recent exploration of shale gas in the US and the over-all abundance of gas resources in certain areas in the Middle East. The price of naphtha, on the other hand, follows the price of crude oil. This has led to a significant production cost difference between ethane based ethylene production and the European naphtha based production in the past years. However, this gap has narrowed due to the more recent collapse of oil prices. Also, Naphtha has an important economic advantage compared to ethane as a feedstock. The value of the by-products, such as propylene, crude C4's and Pygas from naphtha-based crackers, is much higher than those from ethane-based crackers.[8]

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[5] Ecofys et al., 2009a, p.22
[6] Mosquera, 2013, p. 9
[7] Ecofys et al, 2009a, p. 22
[8] Gonzalez, 2016

Among the olefins, ethylene has the highest production volume in EU's petrochemical sector. It is the basic input chemical for about 30% of all petrochemicals.[9] However, the EU has seen a steady decline in ethylene production over the past years[10], following the competitive disadvantage of ethane based ethylene production, and has led to closure of small inefficient plants in the EU[11].

Furthermore, current investment rates in ethylene production in the EU are significantly lower in comparison to investment rates in the US, Middle East and China. From an environmental perspective, Chinese investments are disconcerting. The cheapest feedstock available in China is coal, which generates significantly higher carbon emissions in the chemical conversion processes[12]. Furthermore, as growth in ethylene production and consumption is closely linked to GDP growth and industrialization, it is possible that China's slower economic growth could lead to overcapacities, as has been observed in the steel sector.[13] The latter could, in the absence of domestic Chinese market consolidation, lead to higher levels of export and compete more with EU based production.

Finding an exact and current estimate of the greenhouse gas emissions released in the production of petrochemicals as chemical subsector in the EU was not possible using public sources. Many processes are part of integrated chemicals production and hence have interconnected energy and feedstock streams. Furthermore, the production of the main feedstocks for the petrochemical sector (naphtha and LPG) is most likely covered by the emissions from the refining sector. Finally, as previously mentioned, some EU refineries have cracking installations for basic petrochemicals production. The emissions from these installations are also, most likely, covered by the emissions from the oil-refining sector. Figure 1.6 gives an indication of the greenhouse gas emissions related to petrochemicals production. The majority of the emissions are related to the production of high value chemicals (HVC) via cracking processes.

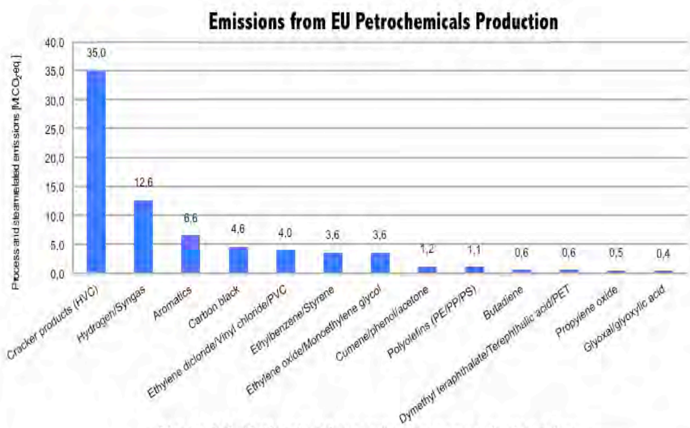


**Figure 1.6. Estimate of greenhouse gas emissions from petrochemicals production. [Mt $CO_2$-eq.] Source: Ecofys (2009).**

For the analysis of deep mitigation in the production of petrochemicals, two main options will be considered; Firstly, the replacement of fossil fuel based feedstock with biomass-based alternatives, and secondly, the potential of reducing the production volumes of some important petrochemical products through enhanced recycling.

[9] Ecofys et al, 2009a, p. 22
[10] Petrochemicals Europe, 2016
[11] Nexant 2014, p. 29
[12] Nexant, 2014, p. 18
[13] Spegele, 2015

# 1.2.2. The transition from petrochemicals to bio-based chemicals

Changing the feedstock from petroleum to bio-based feedstock using agricultural and forestry waste is an important option for further deep emission reductions in the production of petrochemicals. In theory, most petrochemicals and equivalent products can be constructed from a bio-based feedstock.

The flowchart in figure 1.8 illustrates the transformation using bio-based inputs such as starch, hemicellulose, cellulose, (plant based) oil and protein. The flowchart in figure 1.7 illustrates the transformation from crude oil and natural gas to final petrochemical products.

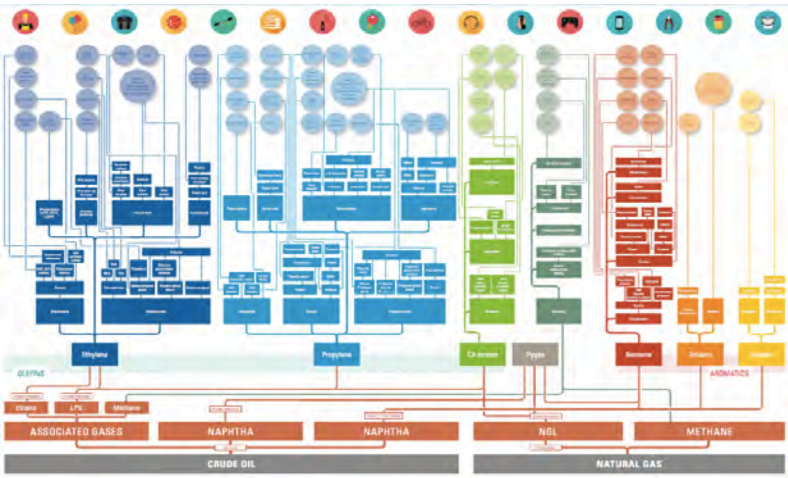


**Figure 1.7. Flowchart of petrochemical inputs, intermediate and final products. Source: Petrochemicals Europe (2014).**

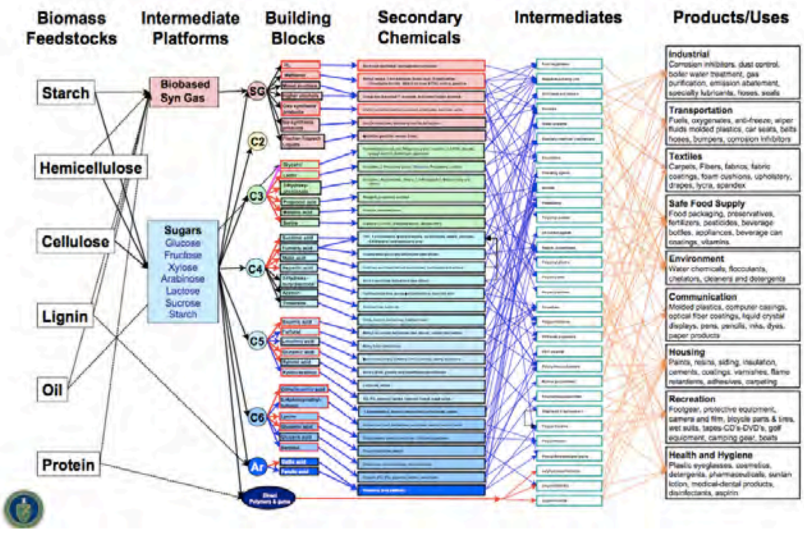


**Figure 1.8. Flowchart of bio-based chemicals' inputs, intermediates and final products. Source: Werpy & Petersen (2004).**

One of the major intermediate petrochemicals, ethylene, can be produced by using ethanol as a feedstock. Ethanol can, in turn, be produced through fermentation of sugars present in crops, such as sugar cane, corn and sugar beets. One hectare of sugar beets, the most interesting option in EU, is enough to produce 4.7 tonnes ethanol, which could be turned into 2.35 tonnes of ethylene. In Europe around 2 million hectares of land is used for cultivation of sugar beets, which would yield around 4.7 million tonnes of ethylene[14]. This would represent 1/5$^{th}$ of the total petroleum based ethylene production in the EU today. However, a full conversion from using the yields for the sugar industry

[14] Calculation based on data by CIBE (the International confederation of European Beet Growers), Bowen et al., 2010 and Cameron et al., 2012.

to ethanol production is highly unlikely. A conversion of half the annual yield could replace 10% of the current EU ethylene production. Reducing the use of oil as feedstock in this manner seems unlikely. The resources (in this case, sugar beets) are limited in Europe, and furthermore, production of ethanol at this scale competes with land use for sugar and animal feed production. The only large-scale conversion of ethanol to ethylene and polymers takes place in Brazil, mainly due to ample supply and relatively low cost of sugar cane.

A much more promising alternative is cellulosic ethanol conversion. Ligno-cellulose, which is present in biomass waste such as forestry and agriculture sector residues (or part of organic municipal waste), is converted to ethanol. As these feedstocks already are available they do not require replacement of existing land used for farming of other products, and the indirect greenhouse gas emissions will therefore be much lower than emissions from corn or sugar beet based ethanol. The transformation of lignocellulose to ethanol is conducted through usage of specific enzymes (enzymatic hydrolysis) or microbial and yeast based fermentation. Cellulosic ethanol is currently being produced in commercial scale in Europe, the US, Brazil and China in diverse first of their kind demonstration plants.

| Project | Country | Capacity [Million litres of ethanol/year] | Info | Status |
|---|---|---|---|---|
| **BEST project (Beta Renewables)** | Italy | 51 | NER 300 project, Novozymes enzyme technology | Operational since Oct 2013 |
| **Cometha** | Italy | 50 | EU FP7 project, cooperation with Novozymes, London Imperial College | Under development. Completed by 2018 |
| **Beta Renewables and Biochemtex** | Slovak Republic | 70 | Novozymes enzyme technology | Announced in 2014 |
| **Suomen Bioetanoli Oy** | Finland | 90 | Poet and DSM technologies | Announced in 2014 |
| **Inbicon Biomass Refinery Kalundborg (Small scale demo)** | Denmark | 5.4 | Cooperation with DONG energy | Operational |
| **Maabjerg Energy Concept (Full scale demo)** | Denmark | 80 | NER 300 support, DONG energy | Under development. Expected operational in 2018 |
| **Futurol (Small scale demo)** | France | 0.18 | Investors include Total energy | Operational since 2011 |
| **CEG plant Goswinowice** | Poland | 60 | NER 300 project | n.a. |

**Figure 1.9. EU demonstration projects on cellulosic conversion to ethanol. Source: European Biofuels Technology Platform (2015).**

The table in figure 1.9 gives an overview of the demonstration projects in operation or under development in Europe. Most of the projects aim to produce ethanol for use as biofuel and not as feedstock for the chemical sector. The main drivers for these producers are the EU's biofuels target and more stringent criteria on the sustainability of feedstock used in its production. Furthermore, EU capacity to valorise the ethanol to ethylene (and further up the value chain) at industrial scale seems limited at the moment. There is, however, no major technical barrier for biomass waste based ethanol to become an important petrochemical feedstock. The potential of wider application will depend on cost reductions, following R&D and scaling-up of lignocellulose based ethanol production. Therefore, the successful implementation of the current demonstration projects in the EU will be important.

Not all polymers need to be derived from (bio-based) ethylene. Production of Polylactic acid (PLA), a biodegradable thermoplastic with interesting applications in e.g. food packaging, also uses bio-based inputs. It can be produced from (corn) starch, but also from sugar beet pulp (a residue after sugar extraction) or lignocellulose. PLA is currently being produced at different plants around the world including in the EU. In 2010 Europe's first PLA pilot plant, a joint venture between Total and Galactic, was inaugurated in Belgium. Its goal is to demonstrate production of 1,500 tonnes of PLA per year.[15] At this moment, however, Europe seems to be lagging behind in the development of industrial scale PLA production compared to other regions in the world.[16]

In March 2016 Avantium and BASF announced a joint venture with the goal to produce furandicarboxylic acid (FDCA). FDCA is a key component in the production of the bio-based polymer polyethylene furanoate (PEF). PEF has potential to become an important product as it can replace polyethylene terephthalate (PET). PEF has, compared to PET, improved barrier properties for gases such as carbon dioxide and oxygen. Due to its higher mechanical strength, thinner PEF packaging can be produced. This implies that a lower amount of packaging material would be necessary. Therefore PEF looks suitable for the production of certain food and beverage packaging, for example films and plastic bottles. After usage PEF can be recycled. Both companies in the joint venture want to develop the process further and construct a reference plant for the production of FDCA with an annual capacity of up to 50,000 metric tons per year at the BASF site in Antwerp, Belgium.[17]

The above-mentioned examples show the potential of bio-based chemistry as an alternative for certain petrochemicals. This current innovation goal is now to further explore new and better production processes and products, ultimately aiming to replace most petroleum products by bio-based alternatives.

In the EU, the "bio-based industries" public private partnership is the flagship chemicals innovation initiative under Horizon 2020. It consists of in total €3.7 billions invested in bio-based innovation between 2014 and 2020. €975 millions comes from EU funds (Horizon 2020) and €2.7 billions from private investments. The main goal of the PPP is to replace at least 30% of petroleum based chemicals with bio-based and biodegradable alternatives until 2030. The new bio-based products will on average reduce $CO_2$ emissions by at least 50% compared to fossil alternatives. The bio-based products developed under the PPP also need to be comparable and/or superior to fossil-based products in terms of price, performance, availability and environmental

[15] See: http://www.total.com/en/energy-expertise/projects/biomass/futerro-renewable-plastics
[16] Nova-Institute, 2013
[17] Based on the press release by BASF, 15 March 2016, https://www.basf.com/en/company/news-and-media/news-releases/2016/03/p-16-153.html

benefits. Finally, the projects under the PPP seek to further develop the potential of waste, agricultural residues and forestry residues as input materials.[18]

**Selection of projects under the Bio-based industries public private partnership (Horizon 2020)**

The FIRST2RUN project under the PPP aims to demonstrate technological, economical and environmental sustainability at industrial scale of a first-of-kind value chain where low input and underutilized oil crops (i.e. cardoon) grown in arid and/or marginal lands and not in competition with food or feed, are exploited for the extraction of vegetable oils to be further converted into bio-monomers (mainly pelargonic and azelaic acids) as building blocks for high added value bioproducts, biolubricants, cosmetics, bioplastics, additives through the integration of chemical and biotechnological processes.

This demonstration bio-based refinery will, in particular, develop the application of sustainable, cost-effective and innovative catalytic and biocatalytic processes for the production of bio-building blocks from high oleic oils (such as azelaic acid, pelargonic acid and glycerol).

The "Greenlight" project will demonstrate the viability of the processing of lignin into carbon fiber and its structural composites with customized features (lightness, strength, cost-effectiveness) for the automotive industry with the aim to achieve a cost-efficient alternative to today's high-performing and relatively high-cost petroleum-based carbon fibre raw material (polyacrylo-nitrile, PAN).

Another project, VALCHEM, seeks to demonstrate a sustainable and integrated process whereby wood is transformed into lignin-based performance chemicals and mono-propylene glycol as the selected platform chemical. The aim is to show that this process can produce wood-based chemicals that are competitive with identical or similar-in-application products based on fossil raw materials in terms of quality and production cost.

The US4GREENCHEM project will design a bio-refinery concept for the complete valorisation of lignocellulosic biomass that is energy- and cost-efficient compared to petroleum-based production.

SMARTLI aims to demonstrate technologies and processes using lignin as raw material to produce biomaterials, such as components with improved properties for composites, plasticisers and different types (PU, PF, epoxy) of resins. The goal is to replace oil-based products with lignin based bioproducts (e.g. to substitute 25-75% of phenol in formaldehyde resins and to replace at least 50-70% of polyols in polyurethane foams).

The PROVIDES project will be important in order to reduce the cost of accessing lignocellulose in wood projects. Its ambition is to develop a radically new, sustainable and techno-economically feasible pulping technology for wood and agro-based lignocellulose raw materials based on deep eutectic solvents (DES). These DES will decompose lignin, hemicellulose and cellulose at low temperature and atmospheric pressure for further processing into materials and chemicals with a high added value.

Finally, the PULP2VALUE project is aiming to demonstrate an integrated and cost-effective cascading biorefinery system to refine sugar beet pulp (SBP), allowing for conversion of 65% of its dry mass into high value products (e.g. microcellulose fibers (MCF), arabinose and galacturonic acid).

Source: Biobased Industries PPP (2014) (http://www.bbi-europe.eu/projects)

All the above-mentioned examples show that, theoretically, significant parts of petrochemical production can be replaced with bio-based inputs. Further research and technological innovations will have to unlock new processes and materials that further replace current important petrochemical products and processes.

However, the fundamental question is whether there is enough sustainable biomass waste available in the EU to allow an almost complete transformation to bio-based

[18] Bio-based Industries Consortium, 2012

chemicals? That seems to be the case. The *CEFIC 2050 low-carbon roadmap European Chemistry for growth: Unlocking a competitive, low carbon and energy efficient future* examined literature addressing this question and concluded that by increasing the capture of forest residue an additional 600 PJ of forestry products could become available in 2020. In addition, in between 800-2100 PetaJoule (PJ)[19] could come from the use of straw.[20] Additional resources, not included in these estimates, could come from organic municipal, industrial and other agricultural waste. The current fossil fuel based inputs of the chemical sector, represent around 2000 PJ but have been declining since at least 1990.

While, there indeed is ample potential for biomass waste to replace the fossil fuel inputs to the chemical sector, this implies the condition that no, or a little part only, of these streams will be used for other energy production and production of transport fuels.

# 1.2.3. Link with the circular economy

Changing the feedstock towards bio-based input can, as discussed above, contribute significantly to deeper emission reductions in the production of petro-chemicals. It is also worth considering whether emissions can be reduced through higher levels of resource efficiency and through the circular economy.

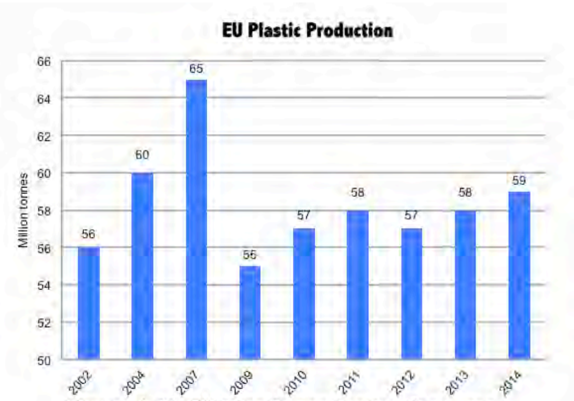


**Figure 1.10. EU Plastic production for some years between 2002 and 2014. [Mt.] Source: PlasticsEurope (2011-2015).**

The case of plastics is of particular interest because it is, as a group, a key petrochemical product. Furthermore, EU has an important potential in terms of reuse, recycling or recovery of many plastics. The EU produces 50-60 million tonnes plastics per year, most of which is used inside the region. Production has been relatively stable between 2002 and 2014, as illustrated in figure 1.10.

The main types of plastics are Polyethylene Terephthalate (PET) 7%, Polystyrene (PS &PS-E) 7%, Polyurethane (PUR) 7.5%, Polyvinylchloride (PVC) 10.3%, Polyethylene (LDPE & LLDPE) 17.2% and Polypropylene (PP) 19.2%. Most plastics are used for packaging (39.5%) followed by building and construction (20.1%), automotive (8.6%), electrical and electronic applications (5.7%) and agriculture (3.4%). The remainder (22.7%) is used for household appliances, furniture, sport goods and health and safety applications.[21]

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[19] 1 PetaJoule (PJ)=$10^{15}$ Joule
[20] CEFIC, 2013, p. 112
[21] PlasticsEurope, 2015

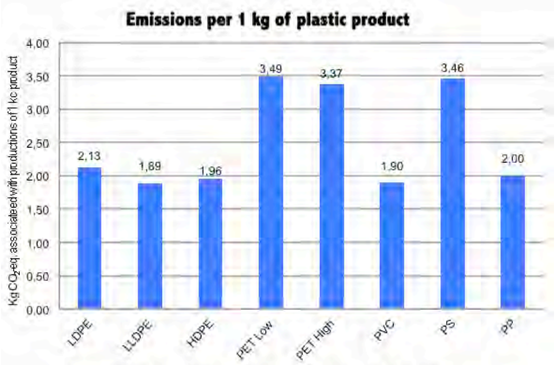


**Figure 1.11. Emissions per 1 kg of plastic product. [Kg $CO_2$-eq.]**
**Source: PlasticsEurope, from the relevant environmental product declarations of the European Plastics Manufacturers.**

During the production process of 1 kg plastics, between 1.9 and 3.5 kg of $CO_2$ are emitted depending on the type of plastic. This is illustrated in figure 1.11. Assuming an average[22] emission factor of 2.5 kg $CO_2$ per kg plastic produced, the total emissions associated with plastics production in the EU are around 145 million tonnes $CO_2$-eq. However, as some of the feedstock for plastics production is imported to the EU, all these emissions are not necessarily created inside EU.

A recent impact assessment by Deloitte for Plastic Recyclers Europe shows that there is significant potential in enhanced recycling of plastics in Europe. Applying current standards and proposed EU legislation on recycling will lead to important greenhouse gas emission reductions in the plastics sector over the next 10 years.[23] Figure 1.12 shows the assumed recycling rates by 2020 and 2025 for different sectors following implementation of existing or pending EU legislation.

Increased recycling performance could save up to 8 Mt of $CO_2$-eq emissions per year by 2020 and up to 13 Mt by 2025. It would reduce the GHG emissions from new (virgin) plastic production by almost 18 Mt in 2025, assuming current production levels.[24] There are ample opportunities in most sectors that use plastics to further increase these figures after 2025. Furthermore, increasing the recycling of plastics can have a positive effect on EU employment. By 2025, employment could increase considerably by 80,000 direct jobs and 120,000 indirect jobs. Finally, enhanced recycling will address the issue of resource leakage. In 2010, 13 million tonnes of plastic waste was separately collected in the EU. Nearly 25 % of that volume was exported overseas.[25]

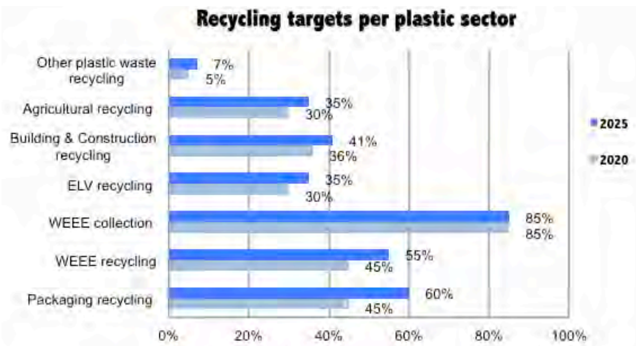


**Figure 1.12. Recycling targets per plastic sector. Source: Hestin et al. (2015).**

This brief and limited analysis on plastics' recycling indicates that there is indeed significant potential to replace part of the virgin plastics production (in the petrochemical sector) with recycled materials. Even with a move towards bio-based feedstock, this option will remain important because it will reduce pressure on the demand for these alternative input materials.

22 Taking into account that plastics with lower emission factor such as LDPE and PP dominate the volumes produced.
23 Hestin et al., 2015
24 Hestin et al., 2015, p. 36
25 Source: Eurostat. For a broader discussion, see http://ec.europa.eu/eurostat/statistics-explained/index.php/Recycling_–_secondary_material_price_indicator#Plastics

# 1.3. Ammonia and production of fertilisers

## 1.3.1. Mapping the sector

Ammonia is one the most important basic chemicals. Its most common use (approx. 80%) is in the production of fertilisers (e.g. urea). The EU's installed capacity can produce around 21 million tonnes of ammonia per year.[26] Making ammonia consists of two major stages: the manufacturing of hydrogen and the synthesis of ammonia (using nitrogen gas in the presence of a catalyst). The latter process through which nitrogen gas and hydrogen gas are reacted together to create ammonia is called the Haber-Bosch process. The whole process requires usage of a feedstock; in Europe, mainly natural gas is used.

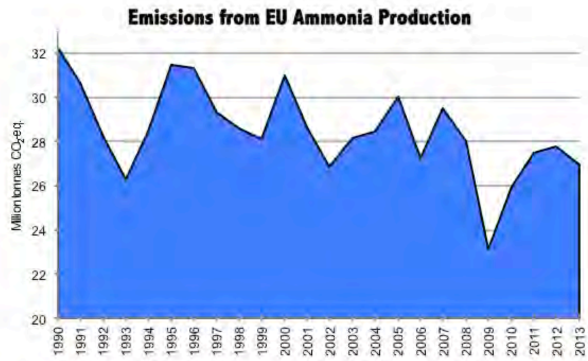


**Figure 1.13. Emissions from EU Ammonia production. [Mt $CO_2$-eq.] Source: EEA (2016).**

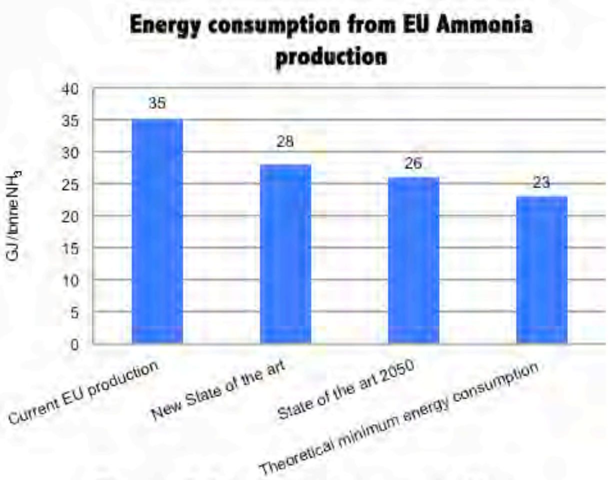


**Figure 1.14. Energy consumption from EU ammonia production. [GJ/tonne $NH_3$.] Source: CEFIC (2013).**

GHG (process) emissions from the production of ammonia (in 2013) stood at almost 27 million tonnes $CO_2$-eq (as shown in figure 1.13); representing around 20% of all GHG emissions from the chemical sector. Ammonia production related GHG emissions were 16.4% lower in 2013 compared to 1990. It is likely that the variation in emissions is more closely related to production volumes as opposed to process efficiency improvements. Between 2004 and 2011 the efficiency of ammonia production deteriorated slightly, as shown in figure 1.14.[27] Overall, the European ammonia production process installations are efficient. The current production efficiency is 35 GJ/t $NH_3$. New, state of the art, ammonia plants are, however, 20% more efficient with a specific energy usage of 28 GJ/t $NH_3$. This is already close to the theoretical minimal energy consumption of 23 GJ/t $NH_3$. By 2050, further improvement of process technologies could almost close this gap and

[26] Egenhofer et al., 2014, p.7
[27] CEFIC, 2013 p. 68

reach an energy consumption of 26 GJ/t $NH_3$[28]. If, in theory, by 2050 all existing European ammonia plants would be replaced by the expected state of the art at the time (at equal production levels), the emissions would be around 25% lower compared to today. Achieving 80-95% emission reduction by 2050 will hence be impossible using existing, but significantly improved, production processes.

Future deep emission reductions will therefore have to come from technological innovations that introduce radically different processes, as well as from business model innovations.

## 1.3.2. Technological and business model revolutions for ammonia and fertiliser production

**Electrochemical production of ammonia**

Ammonia can also be produced without the use of fossil fuels. In fact, some of the first ammonia plants built around the world (around 1940) used electricity to generate hydrogen (through electrolysers) for the Haber-Bosch ammonia synthesis process. In most cases, these plants were connected to hydropower installations and had therefore access to plentiful and relatively cheap electricity. However, most of these plants were later closed as the natural gas (or even coal based) ammonia synthesis was more cost-effective. In particular high capital cost of the electrolysers made these processes less competitive. New types of electrolysers, splitting water into hydrogen gas and oxygen, in combination with cheap low-carbon electricity generation can make this process attractive again, especially if natural gas prices would significantly rise in the future.[29]

The so-called 'holy grail' of low-carbon ammonia production will be the 'solid state synthesis' process. Solid State Ammonia Synthesis (SSAS) combines the functions of the electrolyser and the Haber-Bosch synthesis loop into one process. Since the production step of separately producing hydrogen is eliminated, the technology can have significantly higher efficiency for ammonia synthesis and decreased capital costs. The SSAS process and equipment are still under development. There has, at laboratory scale, been considerable progress made in the development of solid-state electrochemical synthesis of ammonia technology to improve the rate of ammonia formation. In order to make a breakthrough in the field of solid-state ammonia

[28] CEFIC, 2013, pp. 67-69
[29] Holbrook and Leighty, 2009

synthesis, to increase the ammonia formation rate, continuing efforts to discover novel compounds are needed.[30]

Ammonia is also an excellent storage medium for hydrogen. In combination with ammonia fuels cells it can become an interesting technology for energy storage.[31] This is of high interest, since the decarbonisation of Europe's energy system will see a high amount of variable renewable energy sources come online over the next decades. That transition brings interesting business model opportunities for SSAS based ammonia producers. These could produce ammonia at times of high renewable energy generation and low wholesale electricity prices. Thereafter, the ammonia can be sold or used for fertiliser production or, at times of low renewable energy generation and high wholesale prices, be used to produce electricity. This new technology offers opportunities that do not exist with current processes. The fact that SSAS would work well with Europe's energy transition would make this a technology that deserves strong RD&D interest by policy makers and entrepreneurs. To achieve EU wide deployment by 2050, the next 10 to 15 years will be important to pilot, demonstrate and commercialise SSAS in the EU.

#### Use of bio-based waste

The gasification of bio-based waste to hydrogen is another option for replacing fossil fuels as feedstock for ammonia production. It can be done using existing technologies but requires high purity of the hydrogen produced. However, the process will consume more energy than its fossil fuel based alternative. [32] Furthermore, this process will consume a significant amount of biomass that hence will not be available for the aforementioned feedstock transition in the petrochemical sector.

Using bio-based waste can be more relevant downstream, in the production of fertilisers itself. The NEWFERT project, part of the Bio-based Industries PPP, seeks to enhance the nutrient recovery from bio-based waste for fertilizer production. Its goal is to develop a new value chain based on nutrient recovery bioprocesses from waste streams, and residues for manufacturing a new generation of bio-based fertilisers. This would enable the substitution of a significant percentage (at least 10%) of nitrogen and phosphorus with recycled components in commercial fertilisers.[33]

#### Business model revolutions in the fertiliser industry

The most important mitigation option would obviously be to reduce the use of fertilisers itself, while keeping the same crop yields. Not only would this have an impact on the production of ammonium, but lower use of fertilisers would also imply other major environmental benefits such as reduction in the eutrophication of surface

[30] Amar et al., 2011, p. 1860
[31] Lan et al., 2011, p. 1494
[32] CEFIC, 2013, p. 69
[33] Source: http://www.bbi-europe.eu/projects/newfert

waters. The main reason fertilisers are used is because agricultural crops cannot extract nitrogen, an essential element for their growth, directly from the air.

The University of Nottingham pioneered a bio-technology that allows almost any type of plant to obtain nitrogen directly from the atmosphere. The innovation (called N-Fix) is now further developed by its spin-off, Azotic technologies. Its technology is based on usage of the bacteria Gluconacetobacter diazotrophicus (Gd) for coating plant seeds in order to create a symbiotic relationship within the plant, enabling it to substitute the nitrogen it normally takes up from the soil with atmospheric nitrogen. This reduces the dependency on ammonia-based fertilisers. The first trials of this technology resulted in savings of around 50% of ammonia-based fertiliser for the same crop yields. This type of innovation looks promising as its global application could result in a significant reduction in the amount of fertiliser used on crops.[34]

The previous example is just one out of many ways the fertilising industry could transform over the upcoming decades. It is likely that similar and improved direct nitrogen fixation technologies emerge, if trials continue to be successful. With the prospect of that fertilisers' sale volumes might decrease significantly, this could be the time for the sector to rethink its business model. The fertilising business could hence move towards a manufacturing-service hybrid sector, where the volume of fertilisers sold becomes less important as more revenues will be generated through services provided to the agricultural sector. The latter could be expressed as a service with the goal to yield a certain amount of crop-productivity. There are ample innovations that are ready for wide scale application within this area, such as the use of drones that can image nitrogen deficient areas in a field in combination with focused micro dosing of fertiliser products.[35] These processes can also be almost completely automated, leading to higher productivity. These service-based fertilising technologies also have the potential to be exported for global application. It can therefore become an important European export product.

[34] Source: www.azotictechnologies.com

[35] Additional illustrative information on these types on innovation and their impact on the agriculture and fertilising industries can be found here http://blogs.edf.org/growingreturns/2015/08/19/3-ways-drones-can-help-take-agriculture-to-new-sustainability-heights/ and here http://www.bdlive.co.za/business/innovation/2016/01/19/drones-part-of-leap-in-agriculture-technology

# 1.4. Outlook and challenges

While the chemical sector already significantly reduced its emissions compared to 1990s levels, the biggest challenges ahead lie in realising emission reductions of more than 80% by 2050.

The analysis in the previous sections show that there are no impenetrable theoretical barriers for further deep emission reductions in the production of petrochemicals and ammonia production. Changing petroleum based inputs to bio-waste feedstock can eliminate most direct emissions in the petrochemical sector. Furthermore, important savings are possible by fully embracing recycling options in the production of plastics. New and promising electrochemical technologies can, if successfully demonstrated and commercially deployed, radically alter the production process of ammonia and related emissions. It is also likely that new agro-technologies such as direct nitrogen fixation and technological optimisation of fertiliser use will significantly reduce the need for ammonia in fertiliser production.

This transition to a low-$CO_2$ chemical industry will require three coordinated and radical evolutions over the next thirty years. These are process innovations in the chemical sector, supply chain enabling and optimisation in the agricultural and forestry sector and the downstream alignment with important consumers of chemical products.

The first important transition should occur in the production of chemicals itself. While there has been significant progress in developing and demonstrating the processes for turning biomass waste into ethanol, the downstream chemical processes that can turn biomass waste in high value chemicals are still under-explored. Important results from large-scale EU innovation projects are expected over the coming years, in particular the bio-based industries PPP. This initiative, together with other pilot and demonstration projects that seek to create important chemicals from biomass-waste, will be an essential step in allowing the cost-effective industrial scale commercialisation of these processes. The main goal will be to develop advanced enzymatic, catalytic and fermentation processes that reduce production costs as to make the bio-based chemicals economically competitive to oil based equivalents. Bio-based chemistry should also further research and develop alternative products with enhanced material or environmental properties compared to similar petrochemical products.

For ammonia production, the transition to advanced electrochemical processes looks promising but far from certain. Especially important is that these new processes can support the transition to high levels of renewable energy in the EU, through the application of demand response and energy storage in conjunction with advanced electricity based ammonia production. These multiple benefits should make advanced electricity based ammonia synthesis a prime target for EU research, development and demonstration support.

The second transition will need to occur in the agricultural and forestry sector. While the EU, in theory, can provide enough domestically acquired biomass waste to cover most the chemical sector demand, these supply chains are largely undeveloped. Replacing fossil fuel based chemicals with biomass waste will require development of a stable and cost-effective supply of waste streams from the agriculture and forestry sectors. This comes with the co-benefit of possibly generating additional revenues for EU's agriculture and forestry sectors. However, there can be intense competition for these resources from other sectors, such as electricity and biofuels production. Since the chemical sector will, if the processes are optimised, be able to generate much higher levels of value added to the economy from biomass waste compared to these other sectors, it should be given priority. For instance, the current target of renewable energy in transport (by means of biofuels) could be replaced by ambition levels to use biomass waste in the chemical sector, or further downstream under the form of product standards.

Replacing fossil fuel based feedstock by biomass-based alternatives could even become a necessity for the European chemical sector in the next decades. The accelerated growth of affordable electric vehicles can lead to an important and almost unavoidable disruption in the oil production and refining sectors in the period 2020-2040.[36] Bloomberg New Energy Finance predicts a displacement of 13 million barrels of crude oil per day by 2040.[37] This is six times more than the current oversupply on the oil markets and more than the current daily oil production of Saudi Arabia.[38] It is also comparable to the total EU daily refining capacity.[39] It is therefore possible that a future contraction in oil refining in the EU and beyond will reduce the availability of petrochemical feedstocks, in particular naphtha. The Benelux refining cluster is the region with the highest relative naphtha production rate (7.24%) in the EU due to the strong link with the petrochemical sector.[40] This is still a minor refining output compared to diesel and gasoline. If the demand for the two latter products drops significantly, a proportional reduction in naphtha production could indeed put pressure on the availability of feedstock for the petrochemical sector.

The final transition relates to the end consumers of chemical products. First of all, most (industrial) users of petrochemicals need to be willing to accept the use of bio-based alternatives. This is more likely to happen if these products can compete on costs with the fossil fuel based alternatives or have properties that exceed these of the alternatives. Public policy can help through demand creation by introducing

[36] Randall, 2016
[37] Bloomberg New Energy Finance, 2016
[38] https://ycharts.com/indicators/saudi_arabia_crude_oil_production
[39] Lukach et al., 2015, p. 70
[40] id. p. 95-96

product standards (e.g. eco-design) that require an increased use of bio-based chemicals over time. The latter can give the European bio-based chemistry a competitive advantage because the overwhelming majority of its consumers are located in the EU. Secondly, ambitious recycling goals will assist in cost-effectively reducing the emissions from in particular virgin plastics production in the short-term. In the long-term perspective, they will assist in mitigating pressure on the biomass waste supply chain. Finally, some sectors will have to rethink their business models to fit into a productive low-carbon society. For this, the fertilising sector, which is the biggest consumer of ammonia, is an interesting example. New agro-technologies such as direct fixation of nitrogen and targeted micro dosing of fertilisers could reshape the sector into one that not only provides fertilisers to the agricultural sector, but one that aims to provide a wide range of services to the agriculture sector towards achieving high crop yields.

A timely, ambitious and successful transition along these three pathways will not only secure a low-$CO_2$ chemical sector by 2050, it also has the potential to maintain or even enhance the competitiveness of the sector and make it less dependent on foreign fossil based resources.

# -2-
# Steel Industry

# 2.1. Introduction

In 2013, the total EU emissions from steelmaking were 166 MT $CO_2$-eq.[41] The EU steel industry saw a total GHG emissions decrease of 39% between 1990-2013 as shown in figure 2.1. Process emissions decreased with 38% and energy emissions decreased with 40% in that period.[42] Recent decarbonisation efforts have contributed to the mitigation, but economic recession and closure of EU steel plants also played a significant role in the decrease of overall emissions.[43]

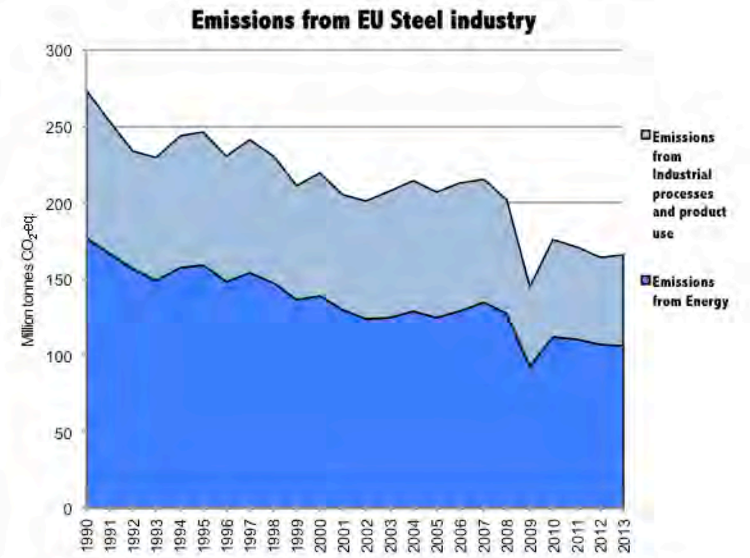


**Figure 2.1. Evolution of GHG emissions in the EU steel industry between 1990 and 2013. [Mt $CO_2$-eq.] Source: EEA (2016).**

Steelmaking is based on chemically reducing iron ore to iron- and steel products. The processes can be divided into primary production, using raw materials, or secondary production, using recycled steel scrap.

Primary production of crude steel is normally performed through the BF-BOF route. The first step is to produce iron out of coal and iron ore, which is performed in a blast furnace (BF). The iron is thereafter made into steel in a basic oxygen furnace (BOF). The BF-BOF route requires the creation of coke from coal and sintering of iron ore. The main $CO_2$ emissions occur in the blast furnace and to a lesser extent in the pre-production phase of coke and sinter manufacturing.[44] Other waste gases, such as CO, $CH_4$ and $H_2$, can be recovered and reused, for electricity generation and in the production process.[45] The BF-BOF steelmaking route includes production of coke, sinter and hot metal, and accounts for the great majority of $CO_2$ emission from steel production, as illustrated in figure 2.2. In EU, the BF-BOF route produces 1,888 tonnes $CO_2$ per tonne of steel produced.[46]

An available alternative to the BF-BOF route is the DRI-EAF route, where iron ore is reduced in solid state to DRI (Direct Reduced Iron) and thereafter melted in an EAF

[41] Emissions from industrial processes accounting for 36% and emissions from energy accounting for 64% out of the total emissions.
[42] EEA, 2016
[43] European Commission, 2016a
[44] Hasanbeigi, Prica and Arens, 2013, p. 93
[45] Ecofys, 2009b
[46] Eurofer, 2013, p. 33

(electric arc furnace). Most commonly, natural gas is used instead of coke as reducing agent. A very small amount of steel is produced through this route in the EU today.[47]

Secondary production is conducted in an electric arc furnace (EAF), where steel scrap is melted into new products.[48] As steel is 100% recyclable, the main resources needed are steel scrap and energy.[49] Scrap-EAF steel production mills have lower environmental impact and investment costs.[50] In EU, the EAF route produces 0,455 tonnes $CO_2$ per tonne of steel produced.[51] The route demands a great amount of electricity and EAF steelmaking accounts for for the main share of the sector's total electricity consumption, as illustrated in figure 2.3. The route should ideally be combined with renewable energy sources, in order to also minimize the indirect $CO_2$ emissions.

BF-BOF production currently (2013) accounts for around 61% of EU crude steel production, and EAF for the remaining 39%.[52] The scrap-EAF route emits around 1/4th as much $CO_2$ as the BF-BOF route, and if coke production is counted as a primary energy source and electricity is counted as a fuel source, the scrap-EAF route requires 1/3rd as much primary energy as the BF-BOF route.[53]

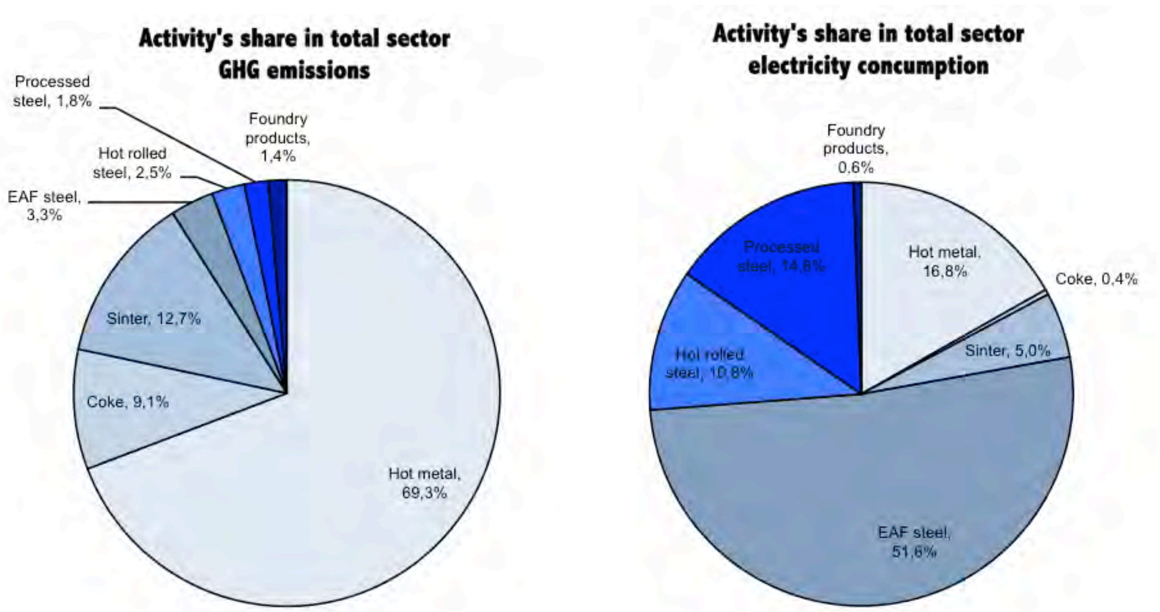


**Figure 2.2 and Figure 2.3. Activity's share in total sector GHG emissions and electricity consumption. Data refers to EU emissions year 2005-2008. Source: Ecofys (2009b).**

[47] World Steel Association, 2014a
[48] A smaller amount of scrap can be recycled also through the BF-BOF route.
[49] World Steel Association, 2014b
[50] Argenta and Bianchi Ferri, 2005. p. 1
[51] Eurofer, 2013, p.35
[52] Laplace Conceil and EFR, 2013
[53] University of Cambridge, 2007

Out of a total yearly EU production of around 170 MT crude steel, the main producer is Germany (39,7 MT[54]), following Italy (20,5 MT) and France (14,0 MT).[55]

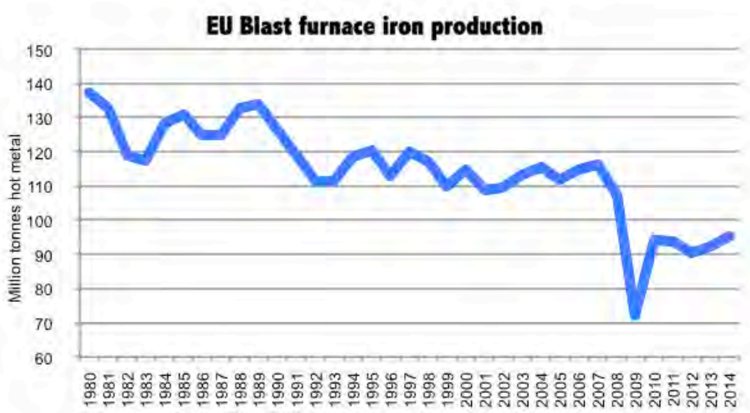


**Figure 2.4. EU BF iron production between 1980 and 2014.**
**Source: World Steel Association (2014).**

Figure 2.4 illustrates that EU blast furnace (BF) iron production has decreased from 137 MT to 95 MT between 1980 and 2014. The crisis years in the history of European steelmaking are visible and led to a reduction in over-all production capacity following closures of steel plants in Europe. The steel industry is currently struggling to cope with low steel prices due to overcapacity and strong international competition, in particular with China. China currently accounts for 50,3% of world steel production (2015) and has almost doubled its market share since year 2004.[56] The Chinese overcapacity is estimated to almost twice the total EU yearly production (350 million tonnes year 2015).[57] But overcapacity is not limited to China alone. According to Boston Consulting Group, European steel production (including Turkey) accounted for 14% of the world's overcapacity in steel year 2013, making Europe the second largest contributor to produced overcapacity after China (50%).[58]

While the emission reductions in the EU steel industry are already almost 40% below 1990 levels, and hence halfway towards -80% by 2050, future deep reductions will not be easy. Efficiency improvements in the BF-BOF route are still possible but will become smaller over time and less cost-effective. Other and more radical mitigation options will therefore have to be considered. The next section will look into three such approaches that can enable deep emission reductions in the steel sector by 2050. These are breakthrough low-carbon process technologies, product innovation and a business model transition.

[54] Data based on Jan-Nov 2015.
[55] European Commission, 2016b, p. 2
[56] European Commission, 2016b, p. 3
[57] European Commission, 2016b, p. 2
[58] The Boston Consulting Group, 2014, p. 6

# 2.2. Deep emissions reductions

## 2.2.1. Process innovations

Substantial emission reductions could, in theory, be achieved through breakthrough innovations in the production process. The most important initiative in this regard in the EU over the past decade has been the ULCOS programme – an initiative aiming to reduce $CO_2$ emissions from steelmaking with at least 50% per tonne steel produced. 48 EU organisations (including 10 steel and mining companies) have been involved in the project, since the launch in 2004. The programme focuses on iron ore based technologies and contains four different steelmaking routes built on breakthrough technologies, with mitigating effects illustrated in figure 2.5. None of the ULCOS technologies are currently available in commercial scale, but are still the key technologies available for decarbonisation of the EU steel industry, as they are being (more or less actively) developed inside the EU.[59]

### Electrolysis based steelmaking

Steelmaking through electrolysis would have a potential to reduce $CO_2$ emissions almost completely, as long as renewable electricity is used. Furthermore, electrolysis generates $O_2$ as off-gas, which can be sold for profit. It is a high-risk-high-reward technology, which could be very promising in the long-term, but is currently only available in laboratory scale in the EU. The technology is investigated under the ULCOS with the ULCOWIN project and in the United States at the MIT[60], with a long-term deployment not expected before 2040.

### Advanced DRI-EAF steelmaking

The DRI-EAF[61] route for steelmaking is more commonly used outside the EU. Large amounts of natural gas are needed in this process, and previous attempts of European implementation have turned out not to be financially viable[62]. The route is investigated in ULCORED (another ULCOS project), with a theoretical steel production capacity of 1 MT/year.[63] Without CCS, a 5% direct $CO_2$ emission reduction can be expected, and with CCS up to 80%. Deployment of the technology was initially expected around 2030, but the project seems to have progressed little during the past years.

[59] Ulcos, 2016a
[60] Kim, Paramore and Sadoway, 2011
[61] As previously explained, the route uses other reacting agents than coke for reduction of iron ore, and hence emits less $CO_2$ as a by-product. The route does not require any significant raw material refinement as the iron remains in solid form throughout the reaction, and the iron can later be converted into steel in an EAF.
[62] In 2012, natural gas prices were four times higher in the EU than in the US, and electricity prices almost twice as high. Source*:* CEPS, 2013, p. 63
[63] Croezen and Koreland, 2010

However, in April 2016, three Swedish actors[64] launched an initiative for further development of a similar technology. The project is based on the DRI-EAF route, but with hydrogen instead of natural gas as reactant for the DRI. The technology is expected to be deployed in Sweden around year 2030. Cost of hydrogen production is one of the major challenges to the project, and the initiative therefore aims to produce hydrogen through electrolysis, which requires extensive amounts of electricity. This could be provided by electricity that is currently being exported, as Sweden exports more than 20 TWh yearly (2015). However, there are no previous examples of successful large-scale hydrogen production though electrolysis.[65]

### Top Gas Recycling Blast Furnace

Another, until recently, promising process innovation is the ULCOS Top Gas Recycling Blast Furnace. The technology is based on the traditional blast furnace, but includes recovering and recycling of process off-gases. The off-gases are cleaned and reused in the production process. In combination with CCS, 60% $CO_2$ emission reductions could be reached, and 15% without CCS. An advantage with Top Gas Recycling is that it can be installed at current BF-BOF plants and does not require construction of new plants. Plants could therefore have a high production capacity, of up to 2MT/year.[66] Laboratory tests and pilot tests have been successfully conducted. The first large-scale demonstration project was planned to start in France in 2013, but the steel plant where the technology would have been implemented closed at the end of 2012.

### The HIsarna steelmaking process

The most advanced process innovation in the EU is HIsarna, another ULCOS project. It is a technology based on bath-smelting. It combines coal preheating and partial pyrolysis in a reactor, a melting cyclone for ore melting and a smelter vessel for final ore reduction and iron production. The HIsarna route does not require refinement of coal to coke and iron ore to sinter, but can use the raw materials directly in the process, allowing for more flexibility in the feedstock than the conventional BF-BOF route. The direct emissions from coking and sintering are hence avoided. Another benefit of this process streamlining is that steel production using the HIsarna technology can take place on a smaller area, allowing for brownfield development on or next to existing steel plants.

Overall, the process requires significantly less coal usage and thus reduces the amount of $CO_2$ emissions. Furthermore, it is a flexible process that allows partial substitution of coal by biomass, natural gas or even Hydrogen.[67] HIsarna can reduce $CO_2$ emissions by 20% compared to current blast furnace technologies. Due to the high and pure $CO_2$ concentration at the end of the process, CCS can relatively easy

[64] SSAB (steel producer), LKAB (mineral group, producing processed iron ore for steelmaking) and Vattenfall (state-owned electric power company).
[65] Vattenfall, 2016
[66] Croezen and Koreland, 2010
[67] Ulcos, 2016b

be applied at a later stage. This would result in emission reductions of around 80%[68].[69]

First hot iron production at HIsarna pilot in Ijmuiden, The Netherlands.
Source: Tata steel.

The HIsarna process has been successfully tested at the first pilot plant at Tata Steel's plant in Ijmuiden (Netherlands). An endurance test is expected to take place during the summer of 2016. After that, the goal is to build a first full size demonstration plant and have it operational between 2020 and 2025. At full scale the technology can produce around 0.5-1 Mt hot metal/year, which is comparable to a medium scale steel plant.[70]

A final and essential benefit of the HIsarna technology is that the capital expenditure (capex) for a new plant would be lower than an average EU blast furnace (incl. coking and sintering). Greenfield capex would be around 75% and brownfield capex around 65% compared to a traditional blast furnace. Also the cost to operate and maintain (opex) HIsarna would be lower; at only 90% compared to an average blast furnace.[71]

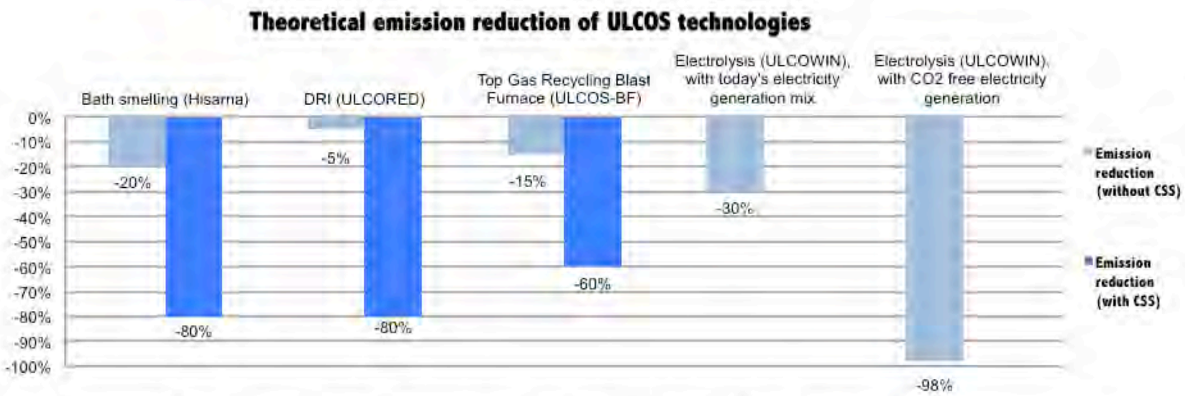


Figure 2.5. Theoretical emission reduction of ULCOS technologies, with and without CCS. Source: EUROFER (2013).

68 Some end-of-pipe solutions could mitigate inevitable emissions, or be a tool for the industry to gain extra development time for ideal processes. Most current scenarios for decarbonisation of the EU steel industry rely on the development of Carbon Capture and Storage (CCS). The basic technologies behind CCS are already available in commercial use, but as implementation requires huge investments and ideal geographic conditions, the technology has not yet been developed in the industry. The main potential for the technology is at plants with ideal infrastructure and geographic location, for example in close proximity to oil extraction fields that are no longer in use.
69 Eurofer (2013)
70 Croezen and Koreland, 2010, p. 32
71 Croezen and Koreland, 2010, p. 33

# 2.2.2. Product innovations

Product innovations could help reducing emissions and at the same time provide a great business opportunity to the EU steel industry. Furthermore, EU steel producers have difficulties to compete on low-value-high-volume products, and with a trend of low growth and high overcapacity, a possible solution is to turn to high value added products. Instead, the EU steel sector must compete on the basis of premium quality and cutting-edge technology.[72] EU steel producers could therefore look into differentiating their product portfolio and compete on other premises than volumes produced, in order to make best use of a product innovation based competitive advantage towards the rest of the world. Basically, this means that the steel sector needs to change production towards lower volumes with higher value added. Bringing high value products to the market requires extensive research; firstly in terms of technological development, and secondly in terms of market development and business opportunities.

Regarding technological development, the material properties of today's steel products could be drastically improved and material science is at the core of product development. One option would be to further explore new and better steel properties through using minute amounts of currently untapped rare-earth metals in the iron production process. This method is currently used to create stronger and lighter steel products.[73] Improved stiffness and ductility (at similar strength) of the steel product is another area to further explore with the help of material sciences, as less product improvement has been achieved in here.[74]

By creating these lightweight products with excellent physical properties the steel industry has a great opportunity to assist downstream consumers of steel (e.g. automotive and construction) to minimise their environmental footprint and, at the same time, improve their global competitiveness.

A new company called Nanosteel uses nano-technological processes to produce extra strong steel. The idea is to create stronger, rather than lighter, steel so that less volume of the material is needed in the final product.[75] For many manufacturing industries, such as the automotive industry, the final weight of the product is crucial as decreased weight decreases the fuel demand and thereby the emissions from each travel.[76] The automotive industry is currently facing the possibility of a major transformation, with the rapid development of heavier electric (battery powered) vehicles. Saving weight through lighter and stronger steel could extend the range of

[72] European Commission, 2016b, p. 8
[73] Highly recommended literature on this topic is the book " *The elements of power*" by David S. Abraham (2015). The author explains that less than 0.2% Vanadium, a rare earth commonly used in steel production, is needed to make the steel twice as strong and at the same time reducing the weight with 30%. Another rare-earth used for lightweight steel production Niobium.
[74] Allwood, 2016
[75] Nanosteel, 2016
[76] Research shows that fuel savings of 5,1% could be achievable by using on Advanced High-Strength Steel (AHSS) in a standard family car, due to the reduced weight of the vehicle. Source: Autoblog, 2011

electric vehicles. Therefore, the timing to research and develop highly advanced steel products could probably not be better. This explains why General Motors Ventures is one of the lead shareholders in NanoSteel. It invested upstream in the company's value chain.[77] The European steel industry could make similar acquisitions through forward vertical integration (by investing downstream in the value chain), in order to grasp these new market opportunities.

## 2.2.3. Business model transition

Next to process and product innovations, innovative business models also have potential to decrease emissions in the steel sector. The core idea is to optimise the usage of steel, given current economical and technological circumstances, by studying how EU steel is produced and consumed along the value chain. As previously discussed, and illustrated in figure 2.6, the scrap-EAF route enables major emission reductions in comparison to the conventional BF-BOF route. In combination with renewable energy sources, the scrap-EAF could reach almost zero-emission levels.[78] Moreover, the scrap-EAF route has only slightly higher capex (+8%) and opex (+14%) in comparison to the conventional BF-BOF route.[79]

Another benefit from moving to higher levels of scrap-EAF steel production is the smaller size of an EAF mill. Traditional and larger size blast furnace technology has little flexibility for ad hoc reductions in production volumes. With more and smaller steel plants, it would easier to balance the cyclical steel demand. This would make the EU steel industry less vulnerable to rapid market changes.

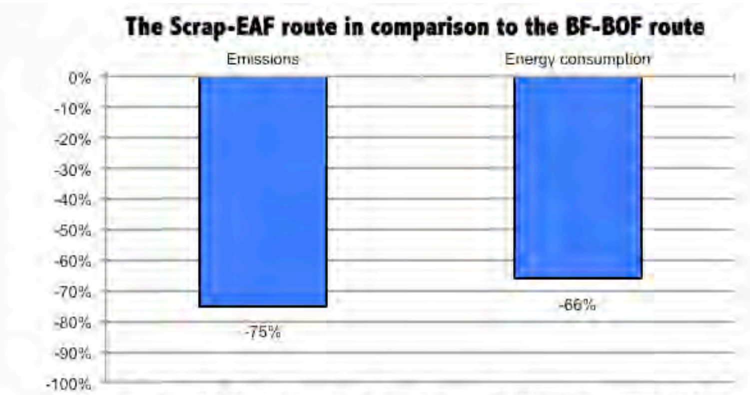


**Figure 2.6. Emissions and energy consumption of the scrap-EAF route, in relation to the BF-BOF route. Source: Allwood & Cullen et. al. (2012).**

EAF steel production can also be integrated with high levels of variable renewable energy. Electricity demand can be lower during times of high wholesale power prices and can be ramped up at times of low over-all electricity demand in combination with high renewable energy generation. The German primary aluminium producer TRIMET has been successfully experimenting with this new type of business model.[80]

[77] Nanosteel, 2016
[78] Birat et. al., 1999
[79] Eurofer, 2013, pp. 36-37
[80] See http://www.bloomberg.com/news/articles/2014-11-27/molten-aluminum-lakes-offer-power-storage-for-german-wind-farms

Limited scrap availability is frequently used as an argument against a paradigm shift towards the scrap-EAF route. Around 20% of scrap is generated within the steel industry, 40% during the manufacturing of components and 40% from product end-of-life, such as buildings or consumer goods.[81] Hence, around 60% of world scrap generation is still dependent on primary steel production, meaning that if all the world's BF-BOF plants would be replaced with scrap-EAF plants, there could be a shortage of scrap steel. However, a global shift to the scrap-EAF route could not be expected too soon – other regions, such as China and India, do not yet have enough scrap available to be likely to make any major change in production in the near future.

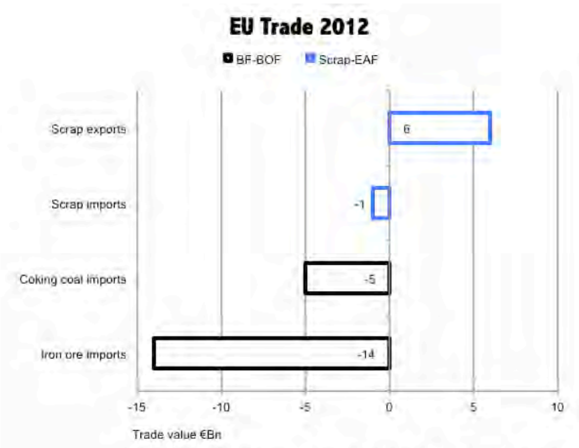


**Figure 2.7. Trade value of some EU imports and exports 2012. [€Bn.]**
**Source: Laplace Conceil and EFR (2013).**

The EU, on the other hand, has a great reservoir of scrap and does not risk future scrap shortages on the domestic market.[82] Currently, most of this scrap (see figure 2.8) is exported to regions outside of the EU. In 2014, the EU exported 16,86 million tonnes scrap, making it the world's leading scrap exporter. [83] This data suggests that there is, in fact, enough scrap availability inside the EU to allow for an increased secondary steel production through he scrap-EAF route. At the same time, EU is importing a large amount of iron ore and coking coal for BF-BOF steelmaking, and to a high cost, as illustrated in figure 2.7. In turn, most of these raw materials are imported from regions outside the EU.[84]

The scrap-EAF route could be a key to bringing the EU steel industry into the circular economy. By an increased downstream integration, the steel industry could change business model towards leasing steel products instead of selling them. Hence, the steel industry would also remain 'in control' of scrap recycling, and would no longer solely be selling steel, but instead offer a valuable service.

[81] Allwood and Cullen, 2012, pp. 53-54
[82] Laplace Conceil and EFR, 2013, p. 63
[83] Bureau of International Recycling, 2015, p. 7
[84] Croezen and Korteland, 2010

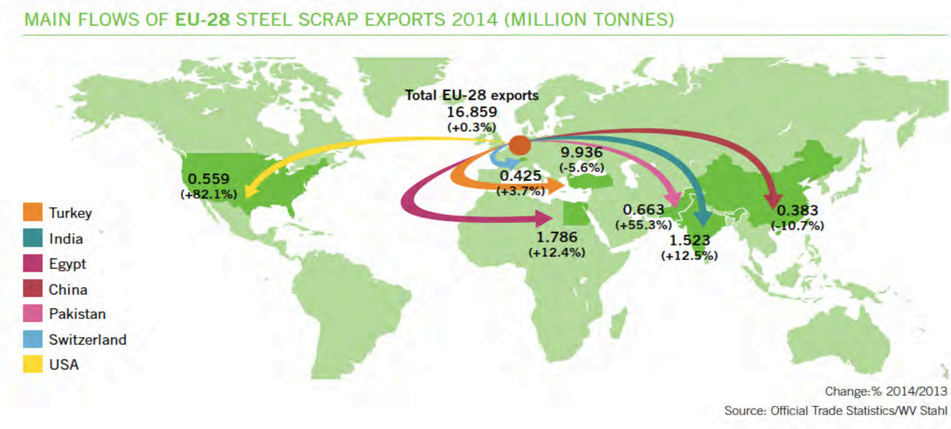


**Figure 2.8. EU steel scrap exports in 2014.**
**Source: Bureau of International Recycling (2015).**

There are still several issues with the EAF route, which have to be addressed; Firstly, the EAF route is today mainly used for products with lower quality sensitivity, such as reinforcement bars. The reason is that the scrap contains alloy elements, which are transferred into the steel product from the scrap through the EAF route. For production of steel products with high quality demand, for example sheets for the automobile industry, the BF-BOF route is therefore used instead.[85] However, other research suggests that that the quality of steel produced through the BF-BOF route and the EAF route are essentially the same.[86] If these steel quality issues are really due to the mixing of low and high quality of scrap, this should become a point of advanced research and development. In this case, lessons could be learned from innovation in secondary aluminium production. A recent project under the US Advanced Research Project Agency for Energy (ARPA-E) looks into light metals recycling innovation. Existing automated metals sorting technologies have difficulties distinguishing the different types of metal alloys. Hence, the recycling of light metals such as aluminium is mostly done by hand. This makes it an inefficient and expensive process. To address this problem, the Palo Alto Research Center (PARC) is developing an advanced diagnostic probe that would identify the composition of light metal scrap and hence lead to more cost-efficient sorting and recycling. The probe would even be able to separate scrap based on alloy quality and thus be able to obtain high-quality aluminium at low cost.[87]

Secondly, EU regulation (and in particular the EU ETS) does not encourage the steel industry to switch towards increased scrap-EAF production[88], even though it would make EU steel producers less dependent on import, enhance the move towards a circular economy and substantially decrease emissions. Steel production from scrap through the scrap-EAF route is both more capital efficient and energy efficient than steel production through the BF-BOF route. [89]

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[85] Ecofys, 2009b, p. 10
[86] Laplace Conceil and EFR, 2013
[87] See http://arpa-e.energy.gov/?q=slick-sheet-project/electrochemical-probe-rapid-scrap-metal-sorting
[88] In comparison to BOF steel production, the EAF steel production pays 54% of total regulation costs, even though it produces significantly less volumes than BOF steel production.
[89] Laplace Conceil and EFR, 2013, p. 65

# 2.3. Outlook and challenges

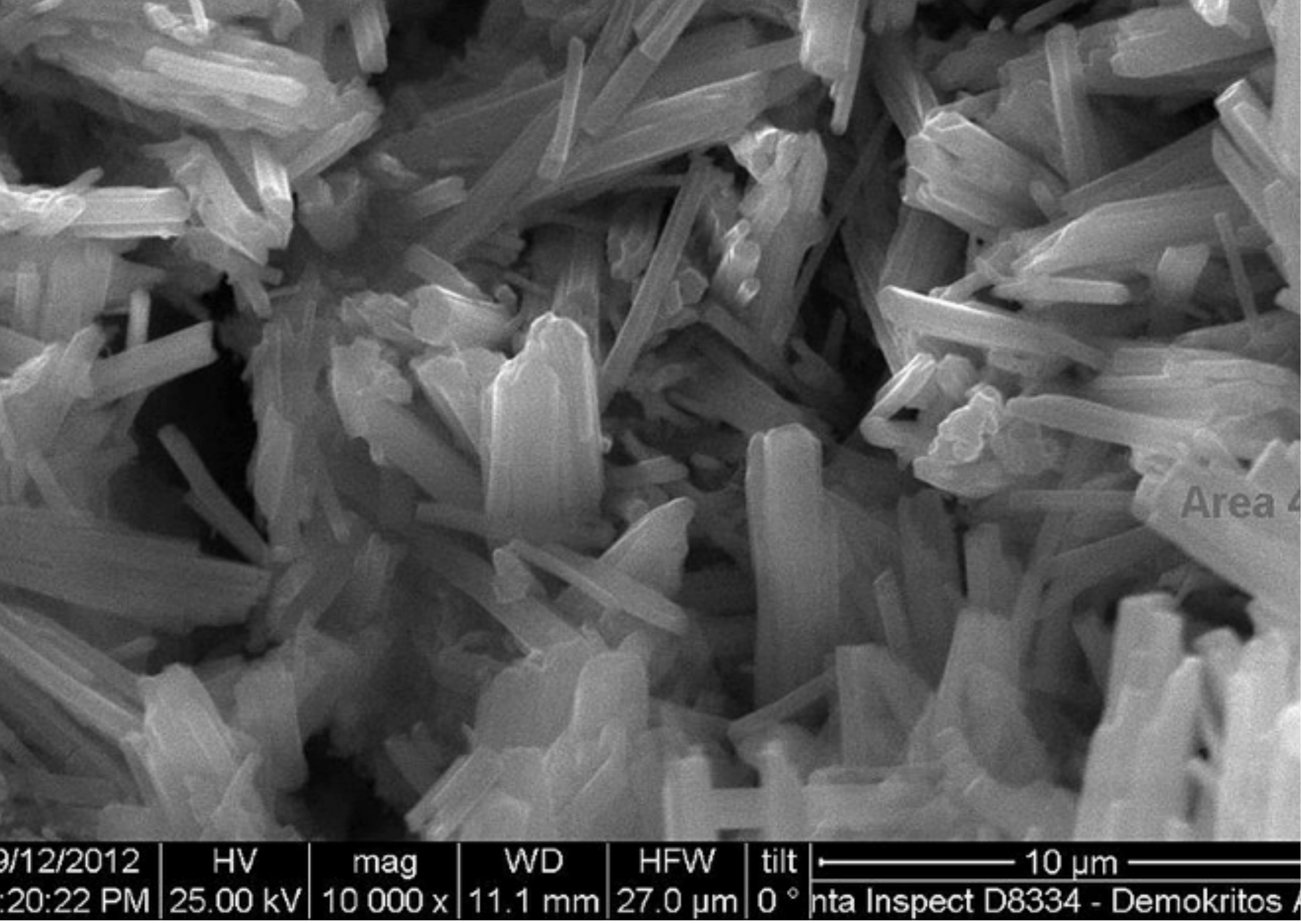
The EU steel sector currently faces multiple challenges. It struggles with low growth, falling steel prices and limited ability to reduce emissions in existing steel plants without major investments. Current market circumstances indicate that increased closure of EU steel plants is a possible likely scenario, and a challenge that the industry will have to face in one way or another. Meeting the 2050 emission reduction target will require that the currently used blast furnace steel technologies are replaced by breakthrough process technologies over the next 30 years[90]. This requires, a long-term industrial transition to be initiated. A low-carbon steel industry can be built in the EU through a combination of process innovation, product innovation and business and production model changes.

The ULCOS HIsarna process, with its expected low capex and opex in comparison to a traditional blast furnace, is the most promising technology available to date. While the technology will immediately reduce emissions with 20%, the use of CCS will make these reductions more substantial. However, the development of CCS will be more costly and demanding in terms of infrastructure and geographical conditions

Secondly, a growing market for 'green' or 'environmental' products creates several new business opportunities. The steel industry could increase profits by moving into high-value-low-volume products. High strength steel enables decreased steel volume and weight in the final product, which could both increase the product value for the customer and at the same time help decreasing the overall environmental footprint. Business opportunities arising from global market trends seldom pass by unattended, and if the EU steel industry does not capture the opportunity, other sectors or regions probably will.

Thirdly, a paradigm shift, from blast furnace steel to increased electric arc furnace production from scrap, would significantly help reducing emissions. The availability of renewable energy can be expected to grow during the upcoming decades. This will further lower the indirect emissions from electric arc steel production. EU is the world's biggest scrap exporter, and instead of importing iron ore and coke for primary steelmaking, the exported scrap could be used for secondary steelmaking instead. Furthermore, acquisitions or involvement along the value chain could give the industry higher control over the value chain, and a greater opportunity to move into the circular economy. It is important that steel producers that seek to move away from blast furnace steel production to electric arc based steel are not punished through higher regulatory costs. Steel manufacturers who seek to transition from blast furnace to electro-steel production could hence be given (EU-wide) priority protection against indirect carbon costs under the EU ETS.

[90] Acknowledging the current speed of R&D development in the EU, relevant technologies should have a pilot plant available already in year 2010 in order to be available in industrial scale demonstration plant until 2020-2030. The technologies must be commercially available latest by 2030, in order to achieve significant $CO_2$ reductions until 2050.




# -3-
# Cement Industry

# 3.1. Introduction

The EU cement industry's greenhouse gas emissions decreased by almost 40% between 1990 and 2013 (as shown in figure 3.1) from 164 million tonnes $CO_2$-eq. in 1990 to almost 103 million tonnes in 2013. The reductions occurred mainly due to lower production levels (-28% in 2013 compared to 1990, see figure 3.2) following the economic crisis in 2008, in particular in Southern European countries. However, the sector also managed to reduce the $CO_2$ intensity of its production processes by 12% in the same period (see figure 3.3). This reduction was enabled mainly thanks to a reduction in energy consumption, by means of efficiency improvements and increased use of biomass.

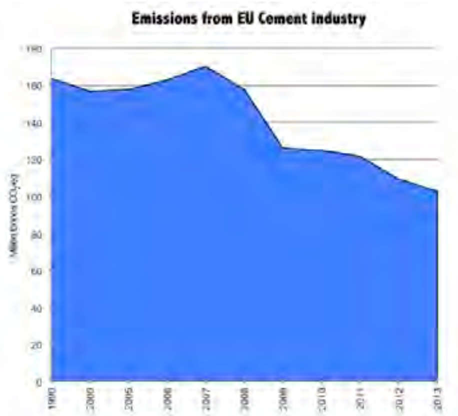



**Figure 3.1. Evolution of emissions from EU grey and white cement production for some years between 1990 and 2013. [Mt $CO_2$-eq.] Source: World Business Council for Sustainable Development (2015).**

More than half of the cement industry's $CO_2$ emissions are process emissions from the clinker production process, where limestone is heated to produce lime. Therefore, reducing the (limestone-based) clinker content or ratio in the cement produced is an important measure to reduce greenhouse gas emissions.

The main process routes for cement manufacturing are the dry, semi-dry, semi-wet and wet kiln processes. The latter two are significantly less energy efficient and have gradually been phased out in Europe. Yet, around 10% of cement in the EU is still produced using semi-wet and wet kilns.

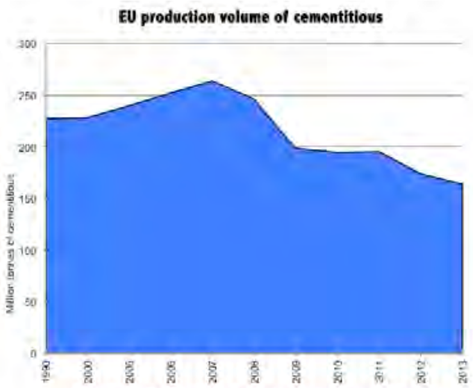



**Figure 3.2. Total production volume of grey and white cementitious for some years between 1990 and 2013. [Mt cementitious.] Source: World Business Council for Sustainable Development (2015).**

The EU cement market is a mature market, which will at best enjoy limited growth[91] in the future. The industry is very capital intensive (the ratio of investment cost to sales is of the order of 2 to 3, which is one of the highest in industry). However, lower clinker content in cement reduces the capital intensity.[92]

[91] © Boyer and Ponsard, 2013, p. 36
[92] id. p. 9

China is by far the largest cement producer[93], with production almost 14 times higher than the EU. There is increased speculation that the Chinese cement sector faces significant production and capacity surpluses[94], following the slow-down of domestic economic growth. All emerging economies have seen a significant growth in cement production over the past decade. Most of the cement production investments in new capacities in these emerging markets are likely modern, even in comparison to state of the art installations. This can explain the better energy performance of cement production outside the EU, as shown in figure 3.4. Indian cement production, in particular, is 20% more energy efficient than the European. This implies that there is still a relevant margin for EU producers to increase efficiency and reduce related $CO_2$ emissions.

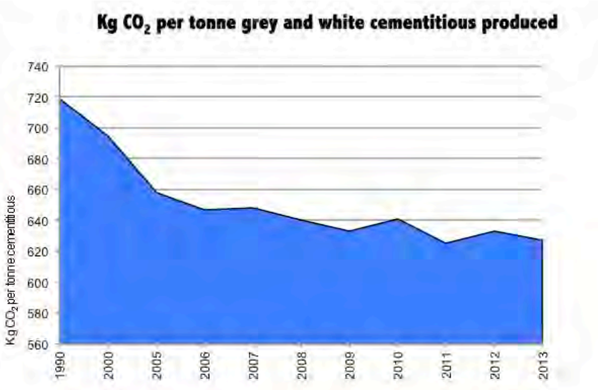



**Figure 3.3. Kg $CO_2$ per tonne grey and whilte cementitious produced for some years between 1990 and 2013. [Kg $CO_2$ per tonne cementitious.] Source: World Business Council for Sustainable Development (2015).**

Achieving deep emission reductions in the cement sector will require a portfolio of different approaches. The following section studies three options: process innovations, clinker substitution and downstream demand reduction.

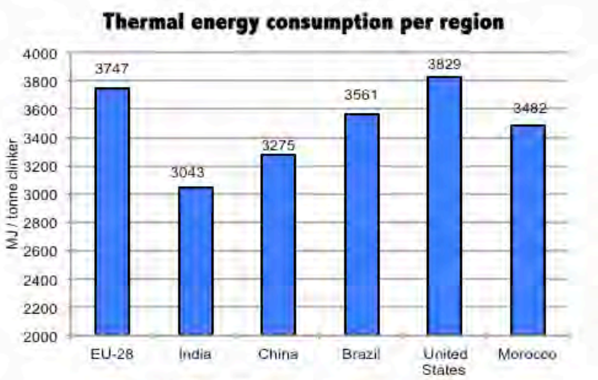



**Figure 3.4. Thermal energy consumption per region for grey clinker production. [MJ/t clinker.] Source: World Business Council for Sustainable Development (2015).**

[93] Producing around 2.18 Bn tonnes cement in 2012. http://www.globalcement.com/magazine/articles/796-china-first-in-cement
[94] http://www.scmp.com/business/article/1924670/what-will-happen-chinas-cement-production-30-times-us-and-steel-production

# 3.2. Deep emissions reductions

## 3.2.1. Process innovations

**Carbon Capture and Storage**

The chemical process in which limestone is calcinated to lime (i.e. the most important input material for clinker) will always lead to the production of $CO_2$ as a by-product. Hence, creation of $CO_2$ emissions is an unavoidable outcome of this process.

$CaCO_3$ (limestone) + Heat → CaO (lime) + $CO_2$

Therefore, reducing $CO_2$ emissions from clinker production will most likely require end-of-pipe measures such as carbon capture and storage (CCS). CCS in the cement industry has been studied for some time, but the research has not yet led to any operational pilot or demonstration plant. The most advanced CCS project in cement production is located at the Norcem plant in Brevik, Norway. However, this project has been delayed.[95]

There are three options for capturing $CO_2$ can at a cement plant. The first method is the post-combustion scrubbing of $CO_2$ in flue gases using amine solutions. The process requires high purity of $CO_2$ and therefore measures for $NO_2$, $SO_2$ and dust removal are needed. The second method is oxy-combustion. Here, oxygen is added to the combustion and calcination processes, in order to achieve high and pure concentrations of $CO_2$, which thereafter can be captured. This process requires additional energy for production of oxygen. It can influence the calcination process and lead to higher wear and tear in the kiln due to the higher temperatures reached with oxygenation.[96]

The third, and for the cement industry most promising, approach is capture through a Calcium looping cycle. It would use solid CaO (lime)-based sorbents to remove $CO_2$ from flue gases, producing a concentrated stream of $CO_2$ (up tot 95 %) suitable for storage. The scheme exploits the reversible gas-solid reaction between $CO_2$ and lime to form limestone. It has multiple potential benefits as a $CO_2$ capture process for both post- and pre-combustion applications. In theory, the overall cost of $CO_2$ capture would be low, due to the to the cheap sorbent (limestone) and the low energy penalty. These benefits are even more pronounced when the process is integrated into cement production (as opposed to integration in power production), where the

[95] As reported in The Guardian on 9 April 2015 http://www.theguardian.com/environment/2015/apr/09/carbon-capture-dream-norway-beset-by-delays-fears-doubt-europe

[96] Barker et al., 2009, pp. 89-90

use of the spent sorbent (lime) can result in around 50% reduction of the energy required in cement production.[97]

Since June 2013, Calcium looping carbon capture is being tested in at the Taiwan Cement Company's (TCC) cement plant in Hualien, Taiwan. It is the largest test facility worldwide for this technology, with a capacity to capture around 1 tonne per hour of $CO_2$ from 3.1 tonnes per hour of flue gas produced by the cement plant. The facility has a capture rate of around 85% and requires a make-up of limestone of around 0.2 tonnes per hour. The current $CO_2$ capture cost for the pilot plant is around US$40 per tonne (with heat integration).[98]

**Limestone reduction through electrolysis**

Molten carbonate electrolytic synthesis could be an interesting, but untested and speculative, process to avoid $CO_2$ emissions in the production of lime. The process would operate as a reverse of molten carbonate fuel cells by using electrical energy to drive the process of lime generation.[99] The process has been demonstrated at laboratory scale. The interesting element here is that the $CO_2$ produced (in the transition from limestone to lime) is further reduced (at high temperatures) in the electrolysis process inside molten carbonate. Depending on the temperature, this results in carbon-monoxide (CO) or pure carbon. The process could be economically viable in larger scale through valorisation of CO as feedstock in chemical processes.

As far as the authors are aware, there are currently no plans to apply this technology on pilot or demonstration scale. On the other hand, molten salt (and molten metal) electrochemistry is a growing research field with promising applications for e.g. grid scale energy storage.[100]

## 3.2.2. Enhanced clinker substitution

Using clinker substitutes in the production of cement is an important option to reduce process $CO_2$ emissions in cement production. The currently most common clinker substitutes are granulated blast furnace slag, fly ash material from coal fired power production, silica fume (by-product from production of silicon), natural occurring pozolans (e.g. volcanic ashes, pumices, clays and shale) and even limestone itself. It is possible to produce cement with high levels (up to 95%) of clinker substitutes.[101] Figure 3.5 below illustrates the use of different clinker substitutes in the EU between 1990 and 2013, as percentage of cement volume.

[97] Dean et al., 2011, p. 837 and 851. For a detailed analysis of the specific economic benefits of calcium looping in cement production see id. p. 843
[98] Global CCS Institute, 2014
[99] Licht et al. 2012. Interestingly, the authors of this paper propose a process using solar-thermal and solar-electricity to produce clinker without $CO_2$ emissions.
[100] http://news.mit.edu/2016/battery-molten-metals-0112
[101] http://lowcarboneconomy.cembureau.eu/index.php?page=clinker-substitution offers a good introduction into clinker substitutes and their relevance and potential in reducing $CO_2$ emissions in cement production

The total use of clinker substitutes in the EU slightly increased in the period 1990-2013, from 22% to 26% (see figure 3.6).

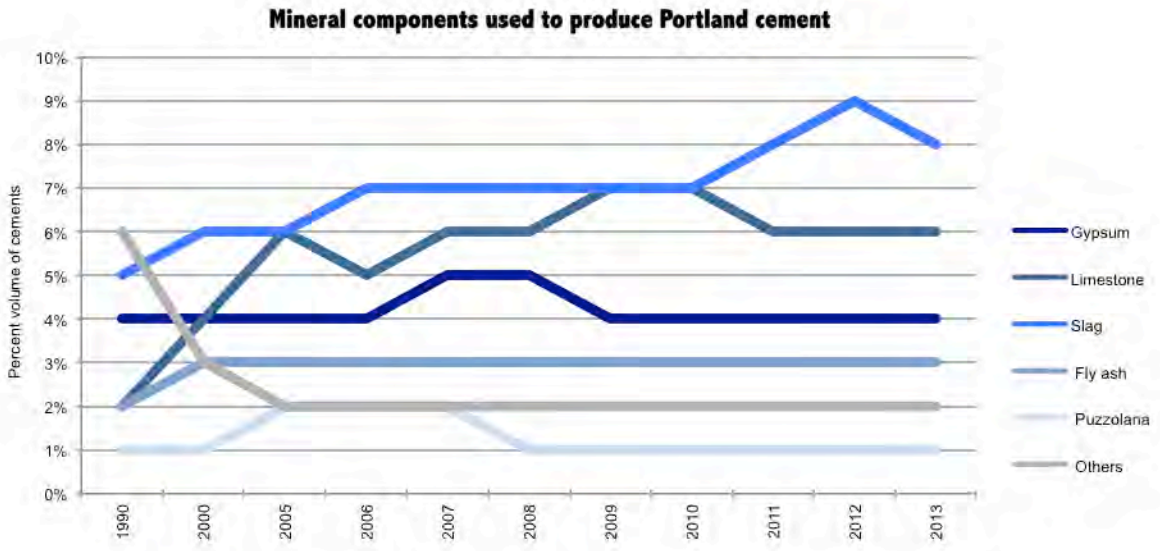



**Figure 3.5. Mineral components used to produce Portland cement for some years between 1990 and 2013. [% volume of cements.] Source: World Business Council for Sustainable Development (2015).**

Significantly increasing the use of clinker substitutes could, in theory, bring an important contribution to deep emission reductions in the cement sector. There are two constraints to this approach. First of all, increased use of substitutes can alter the properties of cement, generating different material properties and applications. The latter can require introduction of new cement standards. These new products will also require acceptance by customers downstream to hence enable a viable market for these products to emerge. Secondly, the substitutes will need to be available in sufficient quantities at different locations in the EU, as to allow cost-effective integration in the cement production supply chain.[102]

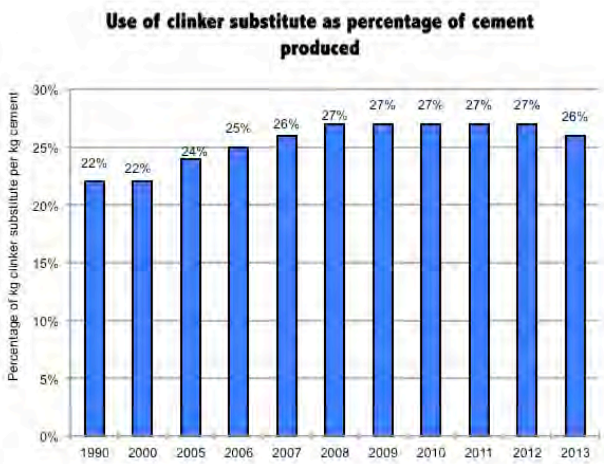



**Figure 3.6. EU use of clinker substitute as percentage of cement produced, for some years between 1990 and 2013. [Percentage of kg clinker substitute per kg cement.] Source: World Business Council for Sustainable Development (2015).**

The potential for increased use of blast furnace slag seems limited. Currently around 82% of slag produced is treated[103] so that it can be used as clinker substitute. Almost

[102] Cembureau, 2012
[103] Blast furnace slag requires quenching to allow the formation of a crystalline structure that give the slag cementitious properties. Around 4 million tonnes of 23.5 million tonnes slag in in 2010 (based on data from 13 major iron and steel producers in the EU) is not treated in this manner.

all of the slag produced is used for construction purposes; 66% of slag is used for cement production or as addition to concrete, 23% goes to road construction, and the remainder is temporarily stored. [104] Pozzolans, from volcanic origin, are geographically concentrated in limited and specific locations, preventing wide scale application across the EU. Limestone, a widely available resource, could be used to a higher extent as substitute but will hit technical limitations related to the material properties of cement. However, more research into how higher levels of limestone could be added to cement while keeping the same or similar material properties could partially address this issue.

There are other options to substitute clinker beyond the ones mention above, but most of them will have similar resource limitations. For instance, there seems to be potential for increased use of kaolin clays, which are currently exploited for ceramics and applications in paper and chemical sector. These clays need thermal treatment[105] before they obtain the properties under the form of metakaolinite (or aluminosilicate) a clinker substitute.[106] There are currently no direct estimates of how much of these resources could be further exploited in Europe to replace clinker.

Magnesite, a mineral used for making magnesium oxide cement, is only available in relative small quantities in the EU; Estimated at 80 million tonnes (Mt) in Greece, 35 Mt in Slovakia, 15 Mt in Austria and 10 Mt in Spain.[107] Hence, the material is not available in sufficient amounts to replace large parts of current Portland cement production.

Enhanced landfill mining (ELFM) in the EU can also produce an interesting clinker substitute. ELFM is currently defined as *"the safe conditioning, excavation and integrated valorization of (historic and/or future) landfilled waste streams as both materials (Waste-to-Material) and energy (Waste-to-Energy), using innovative transformation technologies and respecting the most stringent social and ecological criteria".*[108] One of the technologies explored with ELFM is the use of gas-plasma technology that turns part of the recovered waste into syngas. What remains after the process is called "plasmarok®", a geo-polymer that can be used as clinker substitute. Full implementation of ELFM in the EU could produce 250-840 million tonnes of plasmarok® over a period of 20-30 years. Jones et al. estimate that this would correspond to a reduction of 3 to 11 Mt of $CO_2$ per year in the EU (or between 3 to 11% of current EU cement emissions).[109]

The final and most promising example is replacing clinker using three relatively reasonably abundant alternative resources (Belite, Ye'elimite and Ferrite). Research

[104] Euroslag, 2011
[105] dehydroxylation at around 1000˚C
[106] Ilić et al., 2010, p. 1
[107] Source: http://www.statista.com/statistics/264953/global-reserves-of-magnesium-by-major-countries/ Most magnesite can be found in Russia (650 Mt) and China (500 Mt).
[108] Jones et al., 2013, p. 4
[109] id. p.10

by Li et al. (2007) demonstrated that these new types of clinker can be produced at temperatures of 1300˚C (i.e. 100 to 200 ˚C lower than traditional clinker production), and can be used to make cements that perform similar to Portland cement in testing. The $CO_2$ emissions in the production process are expected to be up to 30% lower compared to traditional clinker.[110] The process and product is currently further developed under the name Aether®. The first trials confirm the aforementioned findings. Furthermore Aether® cement can be produced in kilns designed for making Portland cement clinker, reducing the need for new capital intensive investments. Two year of tests showed that the cements are of quality that at least matches of otherwise equivalent portland cement.[111]

### 3.2.2. Downstream innovations

The most common application of cement is as a binding agent in concrete and mortars. Cement acts as the binder that sets to bind all the other materials (e.g. sand and aggregates) that are part of concrete or mortar together. Concrete typically needs only 10-15% cement in volume to set. Innovations that reduce the amount of concrete needed (e.g. for achieving a similar level of compressive strength) or the amount of cement needed to bind concrete will have a direct impact on the total emissions of the cement sector.

Using nanotechnology, the fundamental structure of concrete can be modified to enhance the bulk materials properties. For instance, nano-silica in concrete acts as a nucleation site to accelerate the hydration of cement. It also assists in filling the pores in concrete to give it higher packing density, which leads to higher strength with lesser porosity. While more research is needed on the state and dispersion of nano-silica in concrete, major benefits that can come with this technology. These include the reduction of cement consumption for specific grades of concrete, but also an early and high compressive strength and durability of the concrete.[112] The multiple benefits of advanced material science, such as nano-technology, make it an area that can be prioritised with the goal to further reduce $CO_2$ emissions through optimalisation of the use of cement in concrete and mortars.

To further reduce the consumption of cement, the design stage for infrastructure and buildings will have to further prioritise material and resource efficiency. This includes advanced training and tools for architects and civil engineers, with the aim of minimising the use of inputs such as concrete, while at the same time giving buildings and constructions the same (or improved) levels of strength and resilience. For instance, the use of 3D printing[113] in construction allows for new constructions that could meet these criteria.

[110] Li et al., 2007, p.1 and pp. 11-12
[111] Quillin et al., 2014
[112] Singh et al., 2013, pp. 1074-1075
[113] For illustrative example of use of 3D printing with concrete see: http://www.gizmag.com/berkeley-researchers-pioneer-powder-based-concrete-3d-printing/36515/

# 3.3. Outlook and challenges

The combination of modernisation, process and innovations and smart use of materials can dramatically reduce the emissions from the industry over the next decades.

The EU cement industry still has ample opportunities to reduce its energy consumption. In particular, the use of older production technologies will have to be phased out. Closing older and inefficient production sites, especially as the market has a production surplus, and modernising other plants will make the sector more resilient against carbon leakage.[114] Further efficiencies can be achieved through optimal restructuring following recent mergers in the EU.[115] These transitions will not be straightforward and will require public support to a certain extent. One measure could be to reduce cost of capital for capital-intensive modernisation investments though government backed loan guarantees.

At this moment, a dramatic increase in use of low-carbon alternatives for clinker looks unlikely. There is, however, significant potential for clinker substitution in the future. The development of low-carbon cements using alternative materials could serve niche markets with compatible product requirements. The main challenge will be to find substitute materials that are available in abundance, and deliver a product with properties equivalent to ordinary Portland cement. The Aether® cement seems to combine all these characteristics and is therefore extremely promising. It will need to gain a significant market share in order to achieve its potential of around 30% emission reductions compared to regular clinker at an economy wide scale. In this area, the public sector can help by supporting the development of supply chains for alternative inputs into the production process. Governments can also assist in market creation by using the power of public procurement. For instance, new large-scale infrastructure projects in the EU could make utilisation of low-carbon cement obligatory. Finally, product standards that allow safe application of new cement types should, if needed, be developed timely to allow market uptake as early as possible.

Regarding radical process innovations, the use of the calcium looping CCS technology looks very promising. Due to its close affinity with clinker production itself, it is one of the few (if not only) CCS options with potential to be economically viable, even at a low carbon price. It has potential to capture more than 80% of the cement production emissions. The economic viability of this technology can be further increased through industrial symbiosis, where over time cement and steel production

[114] For instance, closure of all of WET/shaft kiln and set-wet semi-dry kiln would lead to almost 13 million tonnes of $CO_2$ reductions while enhancing the over-all performance of the industry.
[115] © Boyer and Ponsard, 2013, p. 45

are combined at the same site, preferable with cost-effective connections to storage sites.

Finally, downstream innovation leading to lower consumption of (higher quality) concrete is an area that deserves further R&D investments. Emerging front-end technologies such as nano-technology and 3D printing most probably be applied towards further achieving lower emissions from the cement industry.

# -4-
# Breaking through the Final Frontier

# 4.1. Introduction

Between 1990 and 2013, the EU industry has contributed significantly to the current economy wide emission reductions in the EU. This report demonstrates that, in each of the sectors, considered further deep emission reductions to -80% or more (compared to 1990) are possible. However, tapping into that potential will not be easy. Most low-hanging fruits have already been picked, and if there is still potential to enhance existing processes this will not be sufficient to reach the deep mitigation goals. Furthermore most, if not all, of the energy intensive industries face major challenges regardless of future mitigation commitments. These include production and capacity surpluses and increased competition with other regions around the world that have competitive advantages through lower cost fuels or larger sized domestic markets. These elements could hamper the potential to reduce emissions in the future. They can, on the other hand, also be an opportunity to focus on climate friendly solutions that come with co-benefits, which would increase the economic performance and competitiveness of these industries.

This report shows that there will be no *single* silver bullet that will break through the final frontier for deep emission reductions in energy intensive industries. For the sectors considered in this report, the conclusion is that an economic attractive low-carbon transition will require the combination of three approaches. These are specifically process, product and business model innovations and transformations and will need to take place over the next 30 years.

In the chemical industry, the use of biomass waste as a feedstock that will replace most of the oil-based inputs will be an important element towards lower emission reductions. The cement industry seems to have a unique opportunity to use a specific type of CCS technology that comes with important co-benefits. In the steel sector, a new type of blast furnace that would negate the need for coking and sintering in hot iron production is currently being tested. This technology would be less costly to build and operate compared to conventional technologies. It can also reduce emissions by 20% and up to 80% with the use of CCS.

Next to these breakthrough process technologies, also innovative products will have to play an important role in the industrial low-carbon transition. The development of new high-performing chemical compounds that can easily be assembled from bio-based feedstock will be essential. A promising and widely abundant clinker substitute, mentioned in this report, can reduce cement production emissions by 30% while giving the same properties to cement as the commonly Portland cement. Advanced material science leading to high performance and lightweight steel can open the market for steel producers towards downstream consumers that need these types of steel for low-carbon performance of their products.

Finally, business model transitions will be crucial to enable both economic and environmental benefits. Ammonia and fertiliser production can move from pure manufacturing into a more agriculture services direction by benefiting from the use of emerging biotechnologies. Cement and steel will have to address the current (and maybe structural) overcapacity through rationalisation, modernisation and increased overall value added at lower sales volumes.

These industrial transitions cannot be seen as isolated issues and must instead be aligned with other major shifts in the EU economy expected over the next decades. The growth of renewable electricity can become an asset for industrial transformation. Electrification of ammonia and steel production open the option for these processes to act like a battery, which consumes more electricity when plenty of renewables feed into the grid and reduces consumption at times of high demand and low renewable energy generation. These new services will, of course, need to be rewarded in future EU power markets. A paradigm shift towards higher levels of resource efficiency and a circular economy in the EU do also match well the industrial transitions mentioned in this report. Both the steel and the chemical sector have ample potential to increase re-usage and recycling of products. For steel this would fit nicely with the move towards higher levels of electric arc steel and away from blast furnace production. Finally, the anticipated electric vehicle revolution can have an impact on the availability of fossil fuel based feedstock for the chemical sector, through closures of refining capacity over the next decades. It will also further open a market for advanced lightweight steel in the automotive sector.

The required transitions in energy intensive industries will not take place in the absence of smart and committed public policies. First of all, governments will have to assist these industries through their modernisation and rationalisation. The high capital intensity of investments these sectors is a key barrier here. For instance, sovereign loan guarantees can help reduce the cost of capital of these investments, in particular for sectors and companies that are underperforming at the moment. Governments can also help to create markets for new low-carbon products through public procurement. Avoiding regulatory misalignment is a third element that requires evaluation, as to avoid punishing industries that move to low-carbon processes or business models.

One of the most challenging parts of the industrial low-carbon transformation will be to bring promising low-carbon process technologies to the commercialisation stage. These new process technologies will need to be market-ready by 2030 to allow for their deployment across the EU by 2050. Again, these investments will be capital intensive but also, due to their pioneering nature, risk intensive. The proposed EU ETS innovation fund for the period 2020-2030 can become an important tool to enable a timely commercialisation of these process technologies. The next section will consider some of the important design options that can help the fund achieve this goal.

# 4.2. The EU ETS Innovation Fund

## 4.2.1. Building upon the NER 300

In 2008, as part of the legislative review of the EU ETS for the period 2013-2020, a new entrants reserve containing 300 million allowances to be auctioned under the EU ETS New Entrants Reserve (NER 300) was established. The revenues generated through this reserve were aimed at financing low-carbon energy demonstration projects. The programme was conceived as a catalyst for the demonstration of carbon capture and storage (CCS) and innovative renewable energy (RES) technologies on a commercial scale within the European Union.

**Locations of NER 300 projects across the EU.**
**Source: European Commission.**

An important goal for the NER 300 is to leverage a considerable amount of private investment and national co-funding across the EU. The funds from the sales of EU ETS allowances will be distributed to projects selected through two rounds of calls for proposals. The disbursement of the funds will depend on the successful completion of these projects and their performance in reducing CO2 emissions.

Under the two separate calls for proposals the European Commission made funding awards for a total value of €2.1 billion to 38 renewable energy projects and one carbon and capture project[116]. In this process the Commission used the expertise of the European Investment Bank (EIB) to evaluate proposals submitted by Member States. The EIB also sold the NER allowances on behalf of the European Commission. The Bank also manages the revenues and the payment of funds to Member States during project implementation.[117]

In October 2014, the European Union's head of state and government agreed to continue this NER concept after 2020. It was agreed to also expand it to 400 million allowances and to include demonstration projects from energy intensive industries. As from 2020, the fund will be called the EU ETS *Innovation Fund*.

[116] The carbon capture and storage project seems likely to be cancelled. http://www.theguardian.com/environment/2016/jan/21/axing-ccs-support-puts-uk-climate-policy-at-risk-lawmakers-hear
[117] Source http://ec.europa.eu/clima/policies/lowcarbon/ner300/

# 4.2.2. Designing the Innovation Fund

In July 2015, the European Commission proposed specific amendments to the current EU ETS, to become operational as from 2021. The innovation fund is part of this proposal as both an extension and amendment to the NER 300. This includes extending the fund to industrial demonstration projects and the innovation to link financial awards to milestone achievements in the projects' implementation. The Commission also considers replacing the current non-reimbursable performance-based grant by a financial instrument such as a guarantee or equity participation.[118] This section will build upon the Commission's proposal and further consider three critical parts for the design of the Innovation Fund:

- The technical criteria for access to the fund.
- Financial mechanisms and governance of the fund.
- The fund's relation with national co-financing and state aid.

**Technical criteria for access to the fund**

First of all, it is important that the fund lets a wide range of different technologies compete against each other. This avoids the risks associated with so-called 'picking the winners'. However, avoiding picking winners does not mean that technological criteria should be absent in the funds' design. For instance, broad spectrum and performance based criteria for access such as at least 20-25% GHG mitigation compared to current Best Available Technologies for industrial installations or a significant reduction in the Levelized Cost of Electricity (LCOE) for energy technologies can be considered.

Furthermore, in order to increase the likelihood of future deployment and commercialization of low-carbon breakthrough technologies it is relevant to include "co-benefit" criteria such as increased productivity, other cost savings, low-carbon product and business model innovation linked to these breakthrough technologies. The history of industrial economics shows that enabling the improvement of these business bottom lines increases the likelihood of the technology becoming widely adopted. This report shows that the most promising breakthrough technologies in the steel, cement and chemicals industries do have co-beneficial features beyond the reduction of greenhouse gas emissions.

**Financial mechanisms and governance of the fund**

Regarding the disbursement of the fund, it seems preferable that a financing toolbox is developed and used, due to the diverse nature of sizes, types and risk-profiles of likely projects. This toolbox could consist of two types of instruments; loans and grants. Grants, including equity participation, should be used with projects that carry a high project risk. Risk mitigation for the funder and grantee can be mitigated

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[118] See the executive summary of the European Commission's Impact Assessment Accompanying the document "Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC to enhance cost-effective emission reductions and low- carbon investments" http://ec.europa.eu/clima/policies/ets/revision/docs/swd_2015_136_en.pdf

through a gradual and milestone achievement based release of funding. Loans, including loan guarantees, can be more appropriate in case companies have difficulty with balance sheet financing or to reduce the cost of (additional) capital. Each of these instruments would come with a specific set of conditions.

The proposed milestone based funding approach is a smart improvement over the current NER 300 design. The latter did not reduce project risk because the final release of funding was linked and partially timed to the full implementation of the projects and the rate of actual $CO_2$ mitigation. Two iconic examples that successfully used performance milestone criteria are the US Advanced Research Project Agency – Energy (ARPA-E) and NASA's Commercial Orbital Transportation Services (COTS) programme. The ARPA-E, modelled on the Defence Advanced Research Projects Agency (DARPA), seeks to advance high-potential, high-impact energy technologies that are too early for private-sector investment. Since 2009, ARPA-E has funded over 360 potentially transformational energy technology projects, including projects that aim to significantly reduce energy use and greenhouse gas emissions in energy intensive industries (e.g. the non-ferrous metals and chemical sectors).[119] NASA's COTS programme, established in 2005, has the goal to stimulate the development and demonstration of commercial rocket launch and orbital transportation capabilities, including resupply missions to the international space station.[120] Both programmes share another interesting feature that can be relevant for the governance of the EU ETS Innovation Fund. ARPA-E and NASA COTS programmes have lean management structures and streamlined administrative procedures. This lean structure is compensated through the use of highly skilled and experienced management. It limits the administrative burden for participating companies and allows for fast-track decisions during the selection and implementation phase of the projects.

**Space X Dragon capsule on its way to the International Space Station. A successful example of the milestone based NASA COTS-programme. Source: NASA.**

The EU also has KIC Inno-energy[121]. This is an EU supported private company with the goal to assist businesses develop innovative energy products, services, and solutions that have high commercial potential. It follows similar lean management principles, aiming to increase its innovation enabling potential.

[119] http://arpa-e.energy.gov
[120] https://www.nasa.gov/commercial-orbital-transportation-services-cots
[121] http://www.kic-innoenergy.com/about/about-kic-innoenergy/

**The relation with Member States' co-financing and State Aid**

Lack of adequate and timely co-financing by Member States seemed to have been one of the issues under the current NER 300 programme. This issue can be mitigated if the European Commission provides clarity on environmental state aid well before the innovation fund comes online. In particular a State Aid waiver or fast-track procedure, under certain specific conditions, could be considered.

Member States should also be able to use a broad range of tools to provide co-financing. One interesting example could be the use of public procurement to advance market access for e.g. low-carbon steel or cement in large infrastructure projects. The latter could also become a requirement at EU level for the use of EU infrastructure support mechanisms such as EFSI.

# 4.3. Towards an integrated and enlightened EU industrial policy

To be successful, the EU ETS Innovation Fund will need to be embedded in a broader, ambitious and consistent EU wide vision on the future of EU energy intensive industry, including its decarbonisation. The authors of this report believe that the EU finds itself at an important moment in the history of its industrial development. Thanks to technological process and product innovations that are created throughout the industries, achieving deep emission reductions can be possible over the next decades. Higher awareness in the public sector, that realising deep emission reductions will require a helping hand (e.g. through the EU ETS innovation fund), is essential. A full transition can only be guaranteed if there is a sustained effort by both the public and private sector to fully integrate the decarbonisation challenges within industrial policy, and hence make this both an economic and low-carbon success story.

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