+The role of RES and CCU in the energy consumption and decarbonization actions of Greek, Spanish, German and Dutch EIIs

Authors: Myrto Zeneli[1], Anatoli Rontogianni[1],, Aimilia Lympeti[1], Panagiotis Grammelis[1], Benedetta Di Costanzo[2], Rainer Janssen[2], Cosette Khawaja[2], Martijn Vis[5], Bas Davidis[5], Patrick Reumerman[5], Clara Jarauta-Córdoba[3], Asier Rueda[3] and Alessandro Carmona[3]
[1]*CERTH - Centre for Research and Technology Hellas / Chemical Process and Energy Resources Institute, Egialias 52, 15125 Marousi, Greece*
[2]*WIP Renewable Energies- Sylvensteinstraße 2, 81369j München*
[3]*CIRCE - Technology Center, Parque Empresarial Dinamiza, Ave. Ranillas 3D, 1st Floor, 50018 Zaragoza, Spain*
[5]*BTG - Biomass Technology Group BV, Josink Esweg 34, 7545 PN Enschede, Netherlands*

ABSTRACT

The European Union has set an ambitious target to be carbon neutral by 2050 by applying decarbonization actions across the whole spectrum of society and economic sectors. Energy intensive industries (EIIs) are at the forefront in this vision. The zero-carbon transition of EIIs by embracing climate friendly practices will be beneficial for the environment, but will also ensure the individual companies' long-term competitiveness. In this regard, innovative solutions are necessary to transform the way these sectors operate. The present work aims to address such issues by providing an overview of the European EIIs with a main emphasis in Germany, Greece, Spain and Netherlands. Numbers and statistics on several sectors, concerning energy consumption and GHG emissions profile are also presented. Moreover, ongoing decarbonisation actions, technological innovations, and commitments towards GHG emissions reduction are outlined. Finally, the overall challenges, barriers and potential measures towards the decarbonization of European industries are discussed.

KEYWORDS

Energy intensive industries; renewable energy technologies; carbon capture utilization and storage, industrial decarbonisation; technological innovations;

INTRODUCTION

The European Union new "Climate Law" is in line with Paris Agreement (PA), its new PA article 6 and the updated target for 2030 of CO_2 emissions reduction by at least 55% since 1990 level, along with the European Climate Law, the EU is committing to the groundbreaking target of carbon neutrality by 2050 (1). Energy intensive industries are at the forefront in this European leading decarbonisation strategy vision. The Energy-Intensive Industries (EIIs) ecosystem includes a wide range of sectors, i.e. non-ferrous metals, steel, aluminum, chemicals, fertilizers, cement, ceramics, lime, glass, paper and pulp. These sectors are characterized by a high energy intensity and are responsible for a large share of greenhouse gas (GHG) emissions produced mainly due to fuel combustion, electricity production and process emissions. Several decarbonization actions can be applied for all these sectors, such as the capture, utilization and storage (CCUS) of process emissions, use of renewable energy technologies for the electricity production instead of fossil fuels and increase of carbon neutral fuels in the fuel mix(2,3). The zero-carbon transition of EIIs by embracing climate friendly practices will be beneficial for the environment, but also will ensure the individual companies' long-term competitiveness. Nevertheless, many sectors have already picked to their efforts of reducing their GHG emissions without fulfilling their targets (4). In this regard, innovative solutions are necessary to transform the way these sectors operate. The paper presents the EIIs GHG emissions across different sectors, focusing in four different counties, i.e. Spain, Greece, Germany and The Netherlands. Specific technological innovations are summarized, whereas challenges for the widespread utilization and potential measures are elaborated for the EIIs ecosystem, which in terms of cycle of processes is reflected in the following pie-diagram.

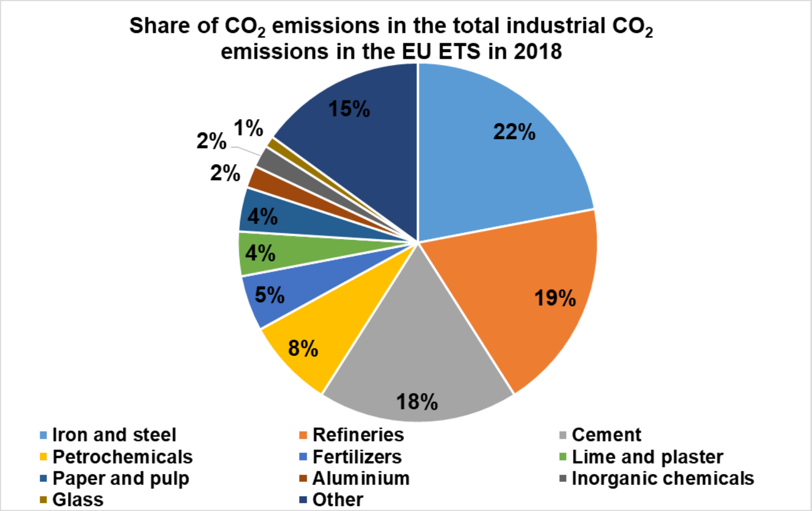


Figure 1. EIIs status in Europe (Source: EUTL, calculations CE De)

All four countries could be a representing reflection of the energy consumption of the intensive industry small and large-scale operations.

EIIs n Southern Europe: Greece and Spain

The EII sector is one of the most important industrial activities in Spain. According to the Spanish National Statistics Institute (INE) (5), it accounts around the 60% of the total energy consumption in Spain. Amongst the different sectors, the highest energy consumers are chemicals (14 %), iron & steel (15 %), non-ferrous metals – including alloys- (13 %), oil refining (8 %) and paper & pulp (6 %) (see

Figure 2).

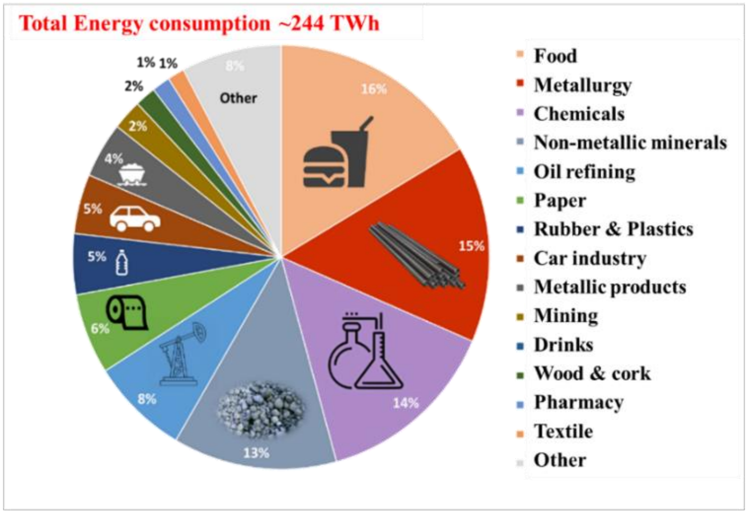


Figure 2. Energy consumption by sector – Spain. Reference year: 2019. (Source: INE)

Currently, almost all the energy required for the intensive processes for such sectors is provided by non-renewable sources, such as coal, oil and natural gas. Electricity plays a key role as well (ca. 22.6%), but renewable energies have a minor presence in the industrial energy landscape, with a share of less than 7%. In general, Spain follows the EU emission reduction target. A target set by the Spanish government is to reduce the GHG emissions by 23 % until 2030, taking as a reference 1990. The sectorial emission targets are not specified, except for the cement sector, which has set a decarbonisation roadmap.

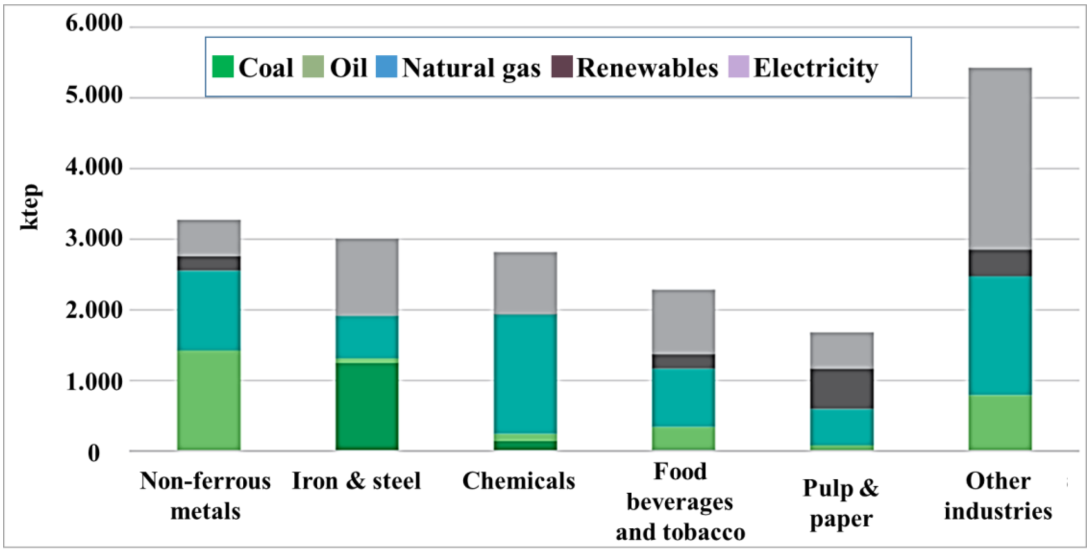


Figure 3. Energy consumption in EII sector – Spain (ktep). (Source: MITECO)

Some characteristics of energy-intensive industry make it difficult to decarbonize the sector. For example, primary production process equipment for primary production processes is characterized by high initial investment costs and is designed with a very long service life, e.g., up to 50 years in the case of cement plants. The industry has made numerous efforts in the past, mainly due to its own need to maintain its economic competitiveness (and thus reduce the energy and CO_2 costs associated with its activity). However, due to the characteristics of the sector, it still accounts for 23.5% of national energy consumption.(6)

Greece is not as heavily industrialized as other EU member states, however there is a significant presence and economic activity of several large EIIs, as well as several smaller companies. In some specific sectors, or sub-sectors the activity of Greek companies is actually relevant, even on the EU level. As shown in Table 1, the power and heat sectors are responsible for the largest share in the GHG emissions of the Greek EU-ETS sector, but they were able to reduce their emission by 16.56 Mt or 46.78% since 2015. Within the sectors focussed on in this paper, the aluminium (1.367 Mt CO2-eq in 2020) and cement (4.709 Mt-eq in 2020) are the largest contributors, as illustrated in
Figure *4*. The ceramic industry is responsible for the largest increase in GHG emissions in the period 2005 – 2015, however by observing the Figure 1, the sector has significantly decreased its CO_2 emissions since 2005.

Table 1. Overview of emissions of Greek EU-ETS sectors in 2020.

Sector	Operating installations	Mt CO_2 (2020)	% of all sectors	Mt CO_2 (2015)	Change
Aluminium	2	1.367	4.31%	1.282	6.61%
Cement	6	4.709	14.84%	5.523	-14.74%
Lime	13	0.229	0.72%	0.234	-2.23%
Ceramics	11	0.113	0.36%	0.072	57.33%
Fertilizer	2	0.235	0.74%	0.282	-16.67%
Ferrous Metals	5	0.468	1.47%	0.938	-50.14%
Glass	1	0.047	0.15%	0.047	0.06%
Pulp and Paper	8	0.07	0.22%	0.109	-35.89%
Inorganic Chemicals	1	0.022	0.07%	0.025	-9.65%
Mineral Oil	4	5.248	16.54%	5.517	-4.88%
Other	14	0.191	0.60%	0.258	-25.69%
Other Calcination Products	1	0.183	0.58%	0.172	6.35%
Power and Heat	39	18.845	59.40%	35.407	-46.78%
Total	107	31.727	100.00%	49.865	-36.37%

Source: EU-ETS reporting as collected in https://re4industry.eu/eiis-interactive-map/

Finally, in the period 2008-2010 there is a large fall in the CO_2 emissions of cement industry, which could easily assumed that is due to the economic crisis that faced Greece, which almost wiped out the construction industry and had as consequence the reduction of the cement production and therefore the reduction of the emissions in the production units.

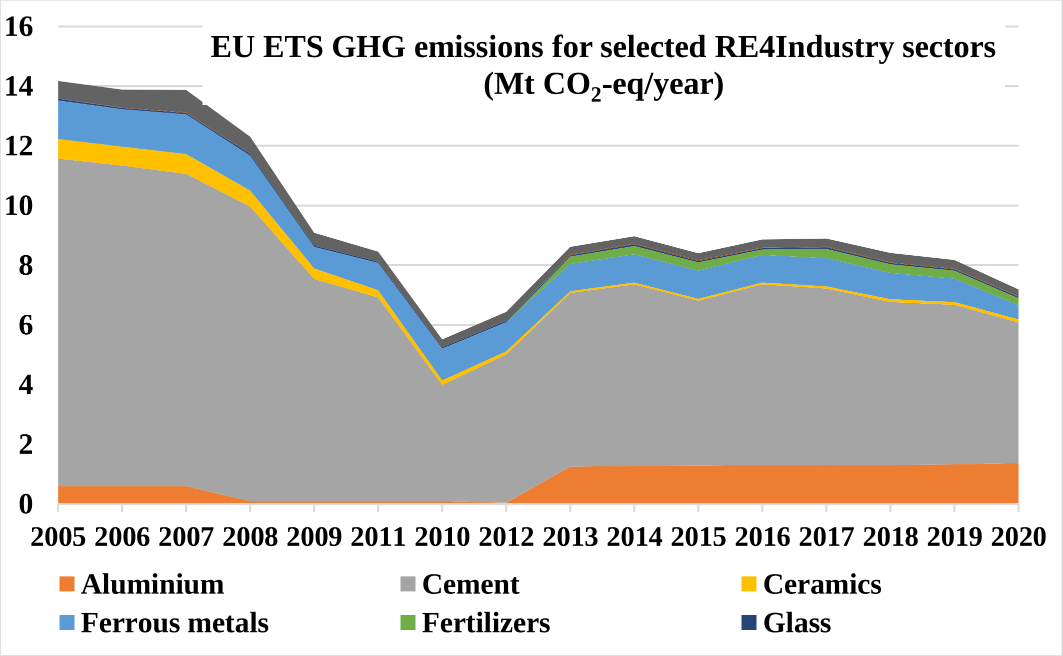


Figure 4. EU-ETS GHG emissions of selected energy-intensive sectors in Greece.

EIIs in Central Europe: Germany

Even though Germany has by far the highest share of industrial production in the European Union (EU), the energy intensity of its industrial sector is lower than the European average. In 2020 Germany recorded the highest value of sold industrial production, equivalent to 29% of the EU total, followed by Italy (18%) and France (12%). German EEIs generate annual sales of around 330 billion euros (18% of the sales of the entire manufacturing industry)(7) and employ around 880,000 people, equivalent to 15% of the workforce in the manufacturing sector. Every job in energy-intensive basic production secures about two jobs in other branches of industry and in the service sector. That means that EEIs generate about 2.5 million jobs in Germany (8).

The EEIs in Germany spend more than 17 billion euros on energy every year, for a net electricity consumption of 525 TWh (9). The figure below shows the distribution of the total emissions from individual industrial sectors. The iron and steel industry accounts for the largest share of industrial emissions at around 28%, followed by refineries (20%), cement clinker production (18%) and the chemical industry (15%).

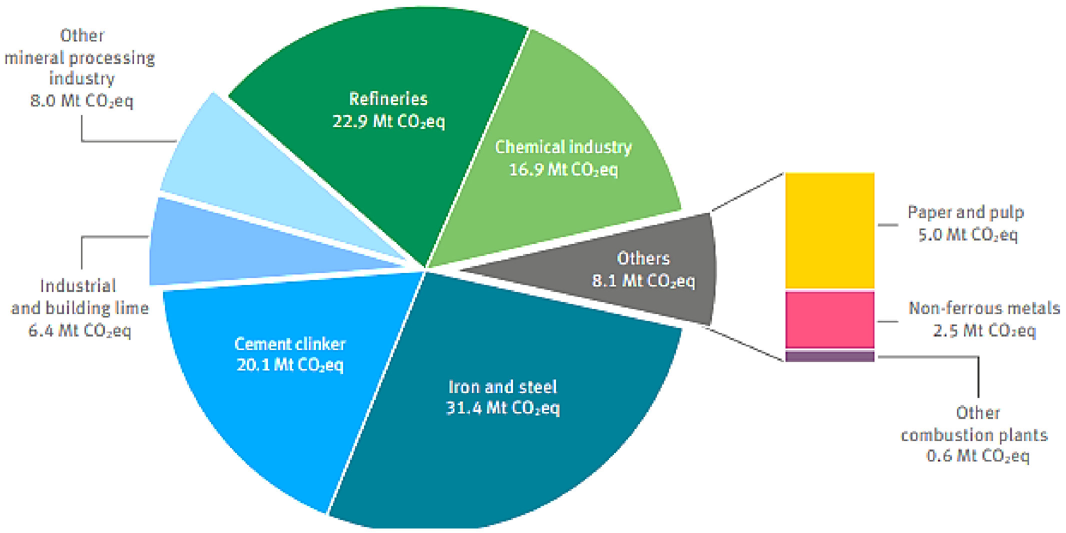


Figure 5. Distribution of emissions among individual industrial sectors in 2020. Source: German Emissions Trading Authority (DEHSt) (9), 2021.

Nevertheless, at the same time German EEIs invest heavily in energy-saving and emission-reducing production technologies. Between 1990 and 2012, they reduced their greenhouse gas emissions by a total of 31%, while increasing production by 42% and in 2020 emissions fell in almost all sectors, sometimes considerably, compared to the previous year, Figure 6.

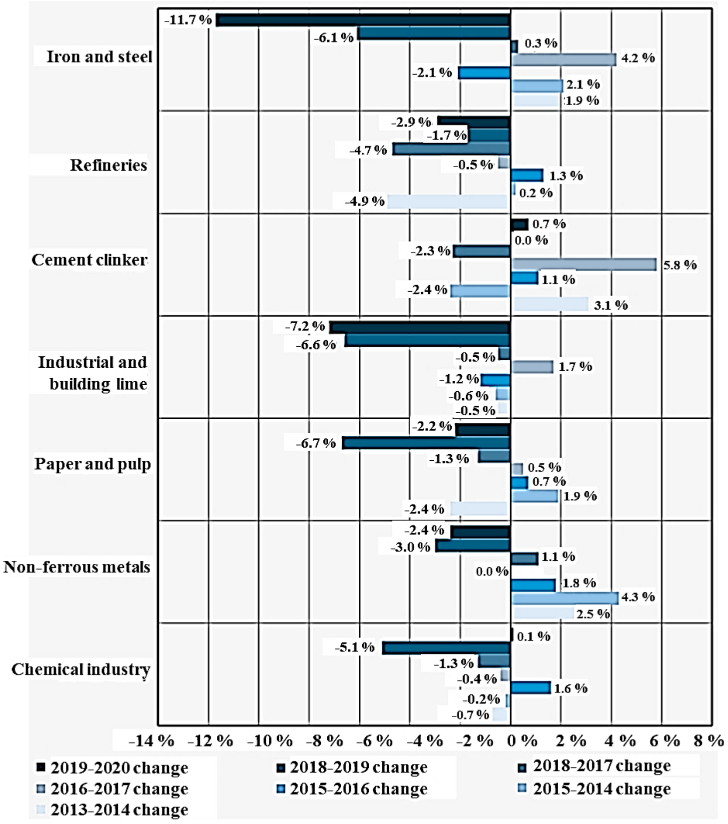


Figure 6. Annual emission changes in the industrial sectors in Germany since 2013 (10).

EIIs in Northern Europe: the Netherlands

The power and heat sectors are the major contributors of GHG emissions of the Dutch EU-ETS, but they have reduced their emissions by 17.32 Mton (or 34%) since 2015, *Table 2*.

Table 2. Emissions of the Dutch EU-ETS sectors in 2020 and their development since 2015.

Sector	Mt CO_2 –eq (2020)	% of all sectors	Mt CO_2 (increase since 2015)	Change
Aluminium	0.319	0.4 %	0.08	34 %
Cement	0.012	0.02 %	0.80	9 %
Ceramics	0.169	0.2 %	0.01	6 %
Construction Materials	0.377	0.5 %	0.02	5 %
Ferrous Metals	5.804	7.8 %	-0.53	-8 %
Fertilzer	5.069	6.8 %	-0.52	-9 %
Glass	0.422	0.6 %	-0.12	-22 %
Hydrogen Production	2.035	2.7 %	0.16	9 %
Inorganic Chemicals	0.601	0.8 %	-0.07	-11 %
Mineral Oil	10.253	13.8 %	-0.91	-8 %
Other	4.599	6.2 %	-0.93	-17 %
Other Chemicals	9.252	12.5 %	0.80	9 %
Other Non-Ferrous Metals	0.046	0.1 %	-0.01	-22 %
Petrochemical	0.491	0.7 %	0.172	-26 %

Power and Heat	33.676	45.4 %	-17.32	-34%
Pulp and Paper	0.981	1.3 %	-0.10	-9 %
Total	74.11	100.00%	-20.00	-21 %

Source: EU-ETS reporting as collected in https://re4industry.eu/eiis-interactive-map/

Within the sectors focused on in this paper, the other-chemicals (9.25 Mton CO_2-eq in 2020, ferrous metals (5.80 Mton) and fertiliser industry (5.07 Mton) are the largest contributors (*Figure 7*). The fertilizer industry is responsible for the largest increase in GHG emissions in the period 2005 – 2015; though these emissions stabilised from 2015 onwards. The large decrease of the emissions in the cement industry is directly related to the closure of the ENCI Maastricht plant that produced Portland clinker from its own marl mine.

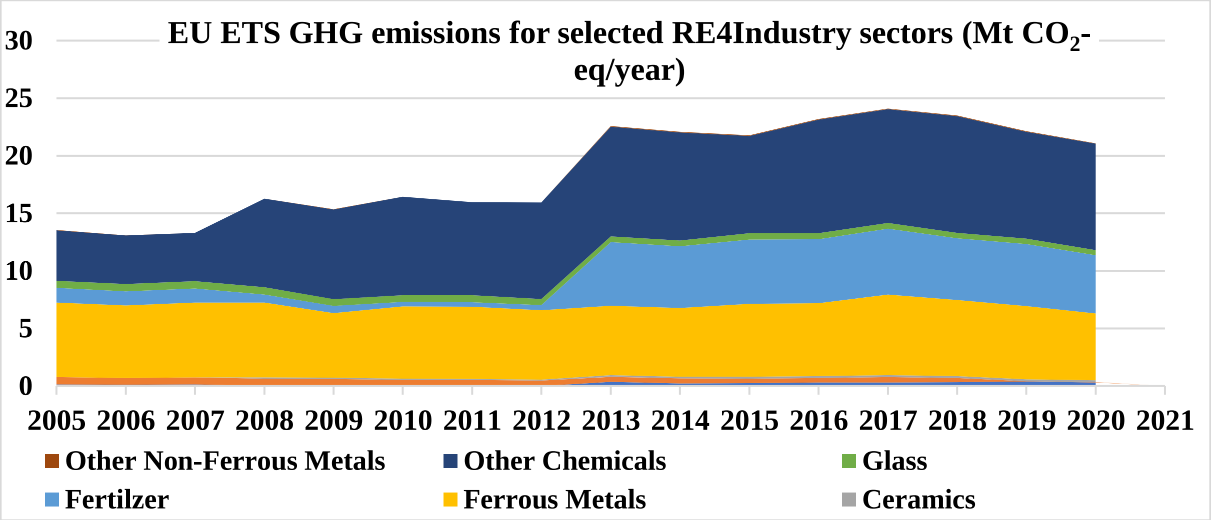


Figure 7. EU ETS GHG emissions of selected RE4Industry sectors in the Netherlands.

A summary of the CO_2 emissions is presented in Figure 8. As can be seen the highest producer is Germany, followed by Spain, then the Netherland, and, with Greece being the least important producer. All these, countries however should apply serious decarbonisation actions (RES along with CCUS technologies) to reduce their GHG emissions under the 2030 EU targets.

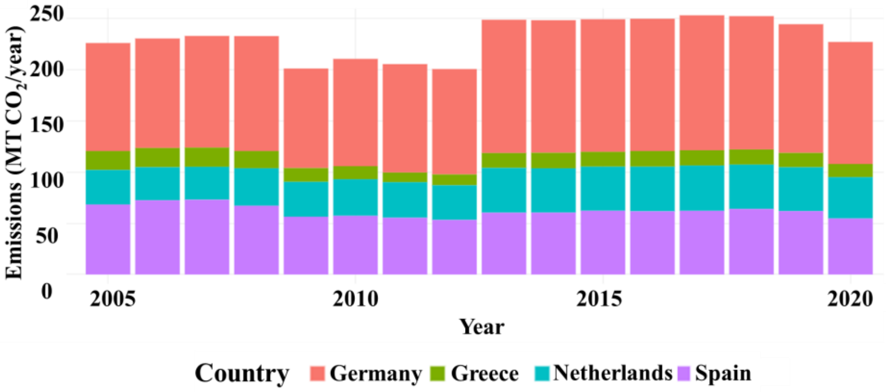


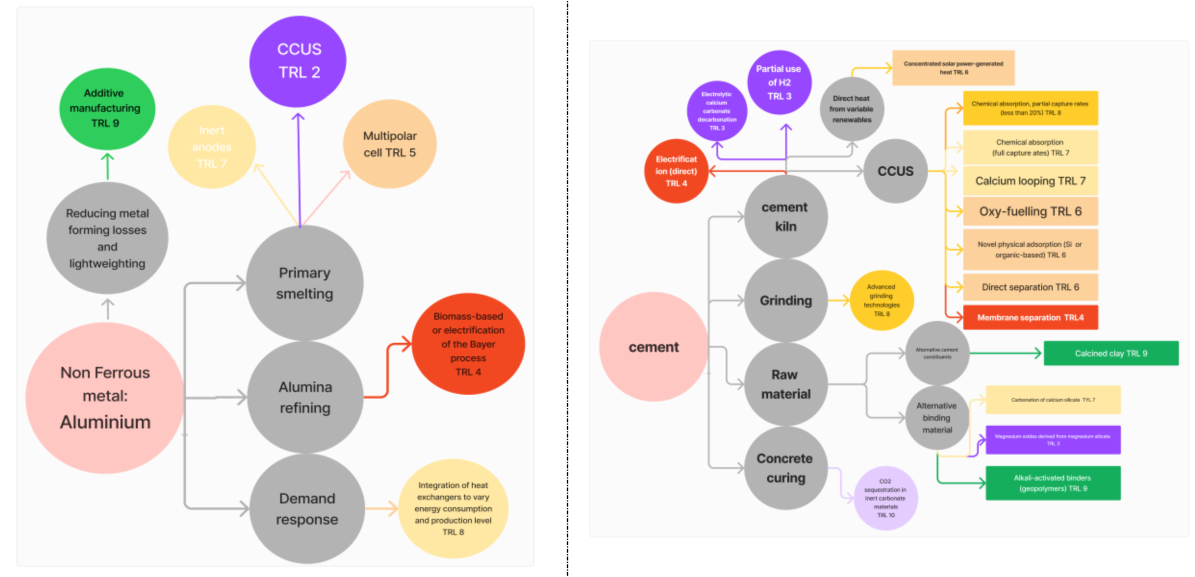
Figure 8. Industrial EU-ETS GHG emissions of the four different countries (2005-2020). Source: https://re4industry.eu/eiis-interactive-map

DECARBONIZATION ACTIONS ACROSS DIFFERENT SECTORS

Several decarbonisation actions can be applied across different sectors in order to achieve a clean energy transition. At a general context can be divided as:

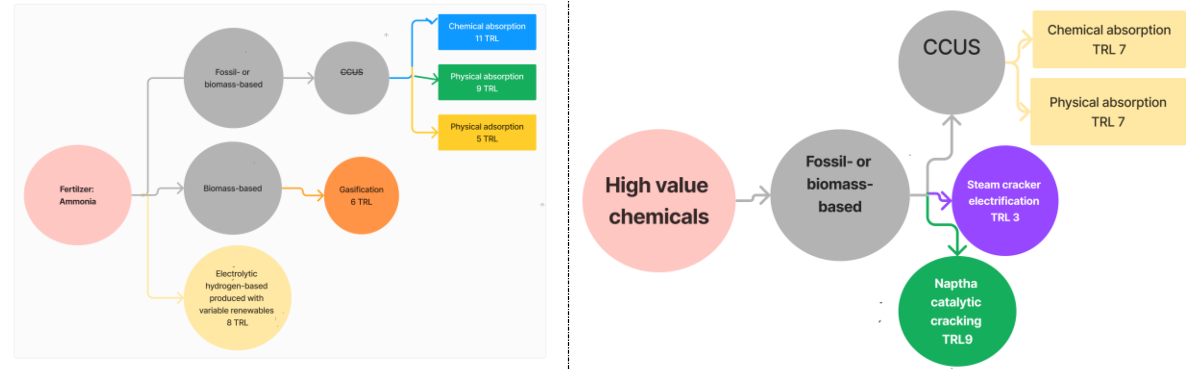
1. Electrification, which involves making processes for heat generation in EEIs run fully on green electricity. In fact, if the power supply is increasingly generated by renewable energy sources and greenhouse gas-neutral, emissions will be saved on a large scale.
2. The use of bio or synthetic fuels, which primarily consists of replacing fossil fuels, for example with biomass or greenhouse gas-neutral synthetic gases. But it should be noted that even if the use of biomass or bioenergy is generally a comparatively inexpensive and very effective option, the availability of biomass is limited, and it is also seen as a solution in other areas (residential heating, shipping and air traffic) to achieve climate neutrality. This raises the question as how to deal with scarcity and finite resources.
3. The use of Carbon Capture Utilisation (CCU) or Carbon Capture Storage (CCS). This approach consists of separating CO_2 from the exhaust gases of certain plants or from the air and then supplying it as a feedstock to other processes or alternatively to store it. CCU and CCS could become essential in some sectors, where there is a high percentage of unavoided process-related emissions (e.g. lime, cement).

The use of hydrogen also plays an important role, as a clean energy source. The aim in the future is to produce hydrogen in a greenhouse gas-neutral manner, for example through water electrolysis based on electricity from renewable sources. These renewable concepts corresponds to Power to X (PtX) technologies, a key future of the energy transition (11). Currently, however, hydrogen is still obtained from natural gas, which results in CO_2 emissions. Finally, various other approaches are examined, for example to make recycling processes more effective. This can be an important starting point, especially in the steel industry. Some specific innovations in energy technologies are summarized in the following, multi graph, concerning aluminium industry, cement industry, high value chemicals and ammonia industry all of which are the multi technology level technologies, from concepts or applications need to prototyped and applied (purple elements) till solutions commercially available.



Aluminium Industry, IEA

Cement Industry, IEA



Ammonium Industry, IEA

High Value Chemicals, IEA

Figure 9. Innovations across different EIIs sectors (12,13)

Decarbonization actions for non-ferrous industry

The non-ferrous metals industry is working hard to transition to a world where we rely on clean, renewable sources of energy by 2050. Non-ferrous metals are essential for many of the low-carbon projects widely known, like hybrid, electric and fuel cell vehicles, solar panels, wind turbines, and thermal systems. Future demand for these metals is expected to increase by 300% over current levels.

The sector has been making a lot of progress in terms of reducing its emissions over the past few decades. It's been especially successful in reducing direct and indirect GHG emissions by 60% since 90s. Meanwhile, the non-ferrous metal industry has fully embraced the circular economy since has already achieved high and increasingly recycling rates. The industry is highly electro-intensive though it has reduced its indirect greenhouse gas emissions significantly, through the increasing decarbonisation and renewable energy uptake in the European power sector. On the other hand, this points that non-ferrous metals industry is extremely sensitive to electricity prices, which affect its economic performance and competitiveness.

Table 3. Prospective technologies and pilot applications of EU Non-Ferrous metal industry.

EU Non-ferrous metal Industry	**Prospective technologies and pilot applications**
Aluminum	i. Wettable cathodes: wettable to the molten aluminium pad. The potential energy savings are estimated at up to 15-20 % (14) ii. Inert anodes: energy savings are estimated at up to 10-30 % (14,15) iii. Lower electrolysis temperature to around melting point, savings are could be around 5% (16) iv. High temperature carbothermic reduction of alumina: 20-30% more efficient compared to electrolysis (17) v. Chloride process (18) vi. Kaolin as raw material in the aluminium production could be a more efficient process by12- 46% (14) Carbon Capture Storage (CCS) technologies (19) vii. Karmøy Technology Pilot Plant, a new Hydro-developed technology uses 15% less energy (20)
Copper	i. Oxygen Flash Technique: a TRL 8 more efficient copper smelting (14) Copper extraction using electrolysis: a new low TRL metal production via molten electrolysis (14) ii. Alternative Fuels, like Hydrogen (14) or Biofuels (21) iii. Waste heat recovery – Aurubis: Heating extraction by copper smelting by-products (22) iv. Carbon Capture Storage (CCU) technologies
Silicon & ferroalloys	i. Organic Rankine Cycle: Transforming waste heat into electricity ii. Carbon capture and utilization (CCU): The Algae Project of Finnfjord AS (23) iii. Carbon Capture Storage (CCS)
Nickel	Electrification of various processes is considered as a long tern potential solution
Zink	i. Electrification of melting furnaces ii. Carbon Capture Storage (CCS) technologies (24)

For the energy transition and in the light of carbon neutrality, it is important to start using RES with greater intensity. A smart design of EU renewables and industrial policies could create α fertile ground for long-term contracts in renewables as a means of managing energy price volatility. In this direction, an extended use of renewable Power Purchase Agreements (PPAs) would be helpful. A related regulatory framework for PPAs direction and long-term power contracts would be essential for electro-intensive industries.

Further to the greening of the electricity, the European non-ferrous metals industry should also take steps to further reduce the carbon footprint of its heat requirements. Steps have already been taken in this direction by several industries: substitution of coal by natural gas, combined heat and power production, waste heat recovery and other energy efficiency measures. However, a further emissions reduction grows more complicated: the industry will have to evaluate different options that are already available on the table or will reach a high TRL in the future: further electrification, green hydrogen and renewable gases as a substitute for natural gas, biomass / bioenergy and others. On the following Table are described the most important pilot applications and prospective technologies of the main nonferrous metal.

Decarbonization of Cement and Lime Industry

Cement and lime industries are both of great importance of the EU’s economy. Construction and civil engineering require cement products, while the steel sector also needs lime for the production of building supplies, paints, plastics, and rubber. For these industries, the environmental sustainability is of utmost significance, and innovation involves the utilization of waste as a substitute for raw materials and fuels.

European lime industry takes several actions in order to reduce GHG, those could be divided in three main categories:

a. Fuel savings by up-scaling energy efficiency: Since 2010 European Lime industry has made a great amount of efforts in order to reduce emissions related to the calcination step of the process. It is estimated that by building new vertical kiln and retrofitting the existing could conclude 16% fuel reduction by 2050 [12]. The new vertical PFRK kilns consider to be the most energy efficient ones. Apart from the vertical kilts, energy heat recovery from the waste heat from the kilns but also during the exothermal reaction of hydration, could be used in drying limestone or in the milling process or in heating buildings and producing electricity. The economical attractiveness, taking into account the transportation cost due to the long distances from industrial areas, is something that has to be considered. Lastly, operating with more efficient motor systems could lead to fuel savings up to 10% furthermore the reduction of cooling air and optimizing grinding could lead to higher efficiency gains.
b. Fuel switching for lower carbon sources: The main alternatives are the wood powder firing and biomass gasification but also methanol, turpentine and tall oil may also be available for burning in lime kilns. In addition, lignin could also be used as fuel in lime production and finally the last decade the use of hydrogen is a potential and promising option. Also, wastes could be used as a fuel but not all types of kiln can process all types of waste, plus it is could be cost effective solution in relation with transport cost and unit prices of those fuels (25). Finally, hydrogen production using alkaline electrolysis is another developing technology.
c. CCU & CCS: Due to the fact that 70% of the total lime CO_2 emissions are produced during the reaction stage capturing CO_2 could be a sustainable yet not economical alternative in decarbonizing the lime industry.

European cement industry linked 50-60% of the total production cost to the energy usage costs. Thermal energy accounts for about 20–25% of the cement production cost The most energy intensive phase of the value chain is at the cement plant, where two critical materials are produced: clinker and cement. Cement production is a 24/7 process and is naturally energy intensive. Concrete on the contrary is a construction material with one of the lowest energy and carbon content, however, the manufacture of its key component, cement, is CO_2-intensive.

Carbon neutrality along the cement, concrete and clinker, value chain requires the deployment of existing and new technologies. On the following Table, the most important of them are recorded.

Table 4 Emissions Reductions Measurements in Cement Industry

Cement Industry Materials	Emissions Reductions Measurements
Clinker: its chemical process causes 60%-65% of cement manufacturing emissions	• Alternative Decarbonated Raw Materials like waste materials and by-products from other industries • Fuel Substitution with alternative locally available biomass fuels (21)

	• Thermal Efficiency kilns through converting preheater and other kiln types to pre-calciner kilns and by recovering heat from the cooler to generate up to 20% of electricity needs for the cement plant [13] • New types of Cement Clinkers can result in 20 – 30% CO_2 savings • CCU & CCS could fully eliminate its process emissions and potentially result in the future delivery of carbon negative concrete (26)
Cement: use of **low ratio clinker cements or even alternatives to** decrease emissions related to cement itself	• Low Clinker Cements: in 2021, 21% of the total substitutes are natural pozzolans, limestone or burnt oil shale and non-traditional substitutes such as calcined clay and silica (21)
Concrete	• Moving from small project site batching of concrete using bagged cement to industrialised processes along with data processing of needed amounts of the material, offers significant CO_2 emissions savings

Finally, the decarbonisation of electricity will play a key role in cement industry decarbonisation since it will result in emissions from generation of electricity used in clinker, cement and concrete production to be reduced to zero (26).

Decarbonization of chemical and fertilizer industry

The chemical industry has a crucial role in Europe's transformation to a more energy efficient and low carbon future. On these directions the sector has already made significant steps and has reduced its GHG emissions. However, further decarbonisation potentials need to be studied and implemented in order to succeed the carbon neutrality. Deep emissions reduction in Europe is technically possible through power supply decarbonisation and CCS integration with chemical processes in the 2030–2050 timeframe(27). A range of current and future technologies can sustain Europe's track record of energy and emissions intensity improvements: final energy demand can be maintained at a constant level, and emissions could be virtually eliminated with energy efficiency (33% of the total emissions reductions), CCS (25%), renewable electricity (20%) and fuel switching and measures to reduce nitrous oxide emissions (22%). To enable continuous and competitive production, access to large amounts of affordable and reliable energy and feedstock will be necessary, which can be challenging for renewables (28).
Some potential solutions of high TRL are identified in Table 5:

Table 5. Potential solutions of ethylene, methanol and chlorine.

Ethylene:	The production pathway of low-carbon ethylene is based on the previously described methanol production from hydrogen and CO_2 followed by the methanol to olefin process (MTO), which is currently commercially deployed, although commercial operations are located in China and no MTO plant is operated in Europe so far
Methanol:	Hydrogenation of CO_2 is used also in conventional methanol production by adding small amounts of CO_2 to adjust the CO/H_2 ratio of the syngas. Synthesis of methanol from CO and CO_2 are tied through the water gas shift reaction.

Chlorine:	Conversion of mercury cell plants to membrane cell technology, changing monopolar to bipolar membrane technology, and the retrofitting of membrane cell plants operating in 2010 to oxygen-depolarised cathodes technology

The use as feedstock forms a significant part of the use of fossil fuels and biomass in the chemical industry. Those GHG emissions can be reduced by efficient utilization of existing feedstock and the use of alternative feedstock. By using of renewable resources such as biomass, recycling, i.e. the use of secondary feedstock like industrial and post-consumer waste streams and use of other alternative feedstock such as the capture and utilization of CO_2.

Alternatives feedstock could be the recycled plastics. Three options for recycling of polymers are currently distinguished:

1. Back to polymer (=mechanical recycling): Collection and mechanically processing of waste plastics to produce recycled polymers.
2. Back to monomer (=feedstock recycling): Breaking down certain polymers into their monomers by means of a chemical process.
3. Back to feedstock (=feedstock recycling): Breaking down polymers into hydrocarbons or a mixture of carbon monoxide and hydrogen by means of a thermal process.

Utilization of captured carbon as feedstock comprises a broad range of processes involving its use in the fabrication or synthesis of products and the energy required must be produced "carbon-free" to avoid further production of CO_2 to generate the energy required. The utilization of CO_2 (CCU) could be developed in symbiosis with carbon capture and storage (CCS). If investments in pipeline infrastructure required for CCS are made, these could also serve as a feed-infrastructure for CCU applications, while the storage functionality delivered by CCS could ensure optimal use of the CCU-based plants. On the other hand, CCU could potentially accelerate improvements in capturing technologies, increase public acceptance for CCS and be an alternative for CCS in places where storage of CO_2 is not possible. In general, the investment cost of CCS is high and the attractiveness depends on CO_2 emissions volume, so, the larger the volumes of captured CO_2, the cheaper all the steps of CCS (27,29,30).

To sum up, the road to the decarbonisation of EU chemical industry is a really complex that can be solved and the solutions vary depending on the chemical sector, however the big steps and the large savings of CO_2 emission will come from the fertilizers that simultaneously are produced in large volumes and their production is carbon intensive. To this direction there are some large potentials that can be considered as game players. The first one is the use of hydrogen in the production of ammonia and methanol and the second is the use of biomass as feedstock. Regarding the use of hydrogen the generation of hydrogen is considered as one of the most energy-consuming processes so the possibility of using hydrogen from renewable energy sources could significantly reduce the fossil-fuel use and GHG footprint of these processes. So, although electrolytic water cleavage, which is a highly energy-intensive process and requires more energy is interesting from a GHG-saving perspective. However, from an economic perspective, the costs for hydrogen from electrolysis are currently roughly twice of those from gas steam reforming, so significant improvements to the energy efficiency and cost of these technologies are needed to make them economically viable. As far as concerns the use of biomass also is a game changer since has some important benefits. The first one is that the use of biomass will reduce the dependency on fossil fuels, which are the source of most GHG emissions in chemical processing. Also, that biomass material absorb CO_2 while growing, which can be used to counterbalance against emissions produced during manufacture or even during destruction or waste, and finally biomass sources are renewable, while fossil fuels are finite and likely to show larger price volatility in the future.

Taking into to account that almost the 75 % of the total European production **fertilizers** production is N fertilizers and that production of ammonia is responsible for the 30 Mt of the total 35 Mt of greenhouse emissions that produced the fertilizer industry in 2020, it is obvious that ammonia is the dominant emitter. Ammonia production is carried out in two stages, the Steam Methane Reforming (SMR) stage for the production of hydrogen, which is the feed material of hydrogen production and the Haber-Bosch stage where hydrogen produced and nitrogen react, producing ammonia (31).

The average energy efficiency for European fertilizers production plants is higher than the global average due to the use of relatively modern technology and reduced use of coal as main energy supply. The main driver for this is Europe's strict environmental legislation that pushed the past few years the European industry to invest steadily in order to increase its efficiency and reduce GHG emissions (32). As a consequence of this innovative advancements in technology, the European fertilizer industry's ammonia plants are among the most energy efficient worldwide, with the lowest GHG emissions, even though the production of nitrogen fertilizers, which reaches the 75% of total production, is characterized by high carbon-intensity. On average, 1.9 t of CO_2 are released on-site during the production of one ton of ammonia during the conventional method (33).

The European fertilizer industry has succeeded the last decades to drastically improve the energy efficiency of its production (Figure 10) so it is at a point where further investment in current technology is unlikely to take place. It is necessary the fertilizer industry to reinvent itself and go beyond current technology.

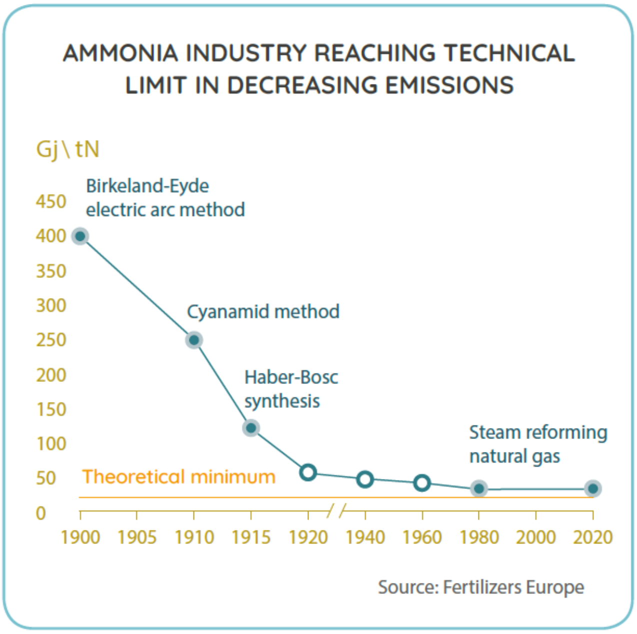


Figure 10. Fertilizer industry technical limit in decreasing emissions. Source: Fertilizers Europe (34)

So, despite the enormous strides made by the industry in recent years in reducing emissions, current production methods still remain energy intensive. In particular, SMR even though it is the least carbon intensive, still generates large amounts of CO_2. Through SMR, ammonia, the starting point for all mineral nitrogen fertilizers, is producing, forming a bridge between the nitrogen in the air and almost half of the food we eat. About 70% of ammonia is used for fertilizers, while the remainder is used for various industrial applications, such as plastics, explosives and synthetic fibers. So, ammonia makes an indispensable contribution to global agricultural systems through its use for fertilizers. Its production is an emissions and energy-intensive process, relying on fossil fuels, mainly natural gas with the global ammonia production accounts today for around 2% (8.6 EJ) of total final energy consumption (34).

CHALLENGES AND MEASURES

The case of Spain

Some of the most challenges have been detected through the contribution of the RE4Industry collaborative network, particularly, thanks to the Spanish Cluster & Committee. In Spain has development of specific regulation for by-products as feedstock due to the fact that there are legal issues related to difficulties to use/transport secondary-raw materials. For example, some residues are excluded because they do not fulfil the current waste laws.

Alternatives to produce electricity, in addition to renewable sources, such as nuclear power could play a role in the national electric landscape. Under that reason the nuclear power plants life is extended in order to secure the stabilization of electricity production.

Concerning the community, have been developed specific certifications for green products to increase awareness on those products and promote the production of circular added-value products and services. On this direction, acquisition of renewable energy should have more recognition by the authorities to stand out those EIIs that have put in place initiatives to decarbonize their processes.

There will be new costs related to the development of green energies in the EIIs facilities, like the common challenge of green hydrogen transport. There is uncertainty among EIIs about the current infrastructure that transports natural gas, which might be as well employed in the future to transport green hydrogen to the companies' site. Such type of infrastructure will allow to drive other projects (e.g., biofuels) required for the decarbonisation of industrial processes. Some EIIs might need huge amounts of fuels, assuring its supply will be a challenge, especially those produced from by-products or residues (eg. Biomass, biogas)

In the decarbonization plan saturation of electrical connection points in the network can be expected. Thus, investments will be required for the development of a new distribution system to buy/sell more electricity form the network. Overall, new funding options are required for the energy transition, including the integration of some technologies in current facilities, so-called as retrofitting, which might be not so obvious in some cases.

The case of the Netherlands

Achieving the goals of the Climate Agreement and the further transition to an emission-free economy in 2050 require a significant expansion of the energy infrastructure. Realizing this in a timely manner is complicated. Industrial companies, network operators, energy producers and regional governments have jointly drawn up Cluster Energy Strategies (CESs) in 2021, covering five specific areas with existing industrial clusters, while the sixth is related to various sectors located throughout the Netherlands. These CESs are further governed by the National Infrastructure Programme for Sustainable Industry (PIDI) and the multi-year programme infrastructure energy and climate MIEK.

Hydrogen and electrification play a major role in the decarbonisation plans of the Dutch industry. Both options depend strongly on the availability of large volumes of renewable electricity. The renewable electricity capacity planned to be produced on land is elaborated in the 30 Regional Energy Strategies (RES). The RES strategies are expected to result in 35 TWh/year renewable electricity production by 2030. However, most renewable electricity will have to be produced by wind parks at sea. According to the Climate Agreement wind parks at sea with a joint capacity of 11 GW will produce 49 TWh/year by 2030 (35). Given that in 2021 the capacity of wind at sea reached 2.5 GW and is expected to grow to 4.5 GW by 2030, a large effort still has to be made. The 35 TWh renewable electricity on land plus 49 TWh wind at sea as foreseen in the Dutch Climate Agreement of 2019 add up to 84 TWh of renewable electricity. This amount is well below the 128 TWh needed by the industry according to the Cluster Energy Strategies. Therefore, the advisory board "Additional Effort" as well as "Roadmap Electrification Industry" indicated that 45 TWh/year additional renewable electricity should be available by 2030, meaning that about 10 GW extra capacity of wind at sea should be realised, plus additional infrastructure to bring the electricity (or hydrogen if already converted at sea) to the (mainly industrial) users.

The case of Germany

Germany is one of the world's leading industrial locations. More than seven million employees in the manufacturing sector generate a fifth of the national value added. With the energy transition, Germany is pursuing an ambitious energy and climate policy. As part of the Paris climate agreement, Germany committed itself to taking steps to limit global warming to 1.5°C, and national commitments pledge an emissions reduction by 65 percent compared to 1990 levels by 2030 and climate neutrality by 2045.

With the industrial sector being responsible for a fifth of Germany's greenhouse gas emissions (and with EEIs generating the biggest share of these emissions), the decarbonisation of the sector is key to achieve long-term goal of greenhouse gas neutrality. In recent decades, German industry has already made great progress in reducing greenhouse gas emissions and reduced its greenhouse gas emissions by a third between 1990 and 2018, without losing its strong position on the world market. More than that, the industrial sector has committed to reducing emissions by around 56 million tons (around 29 per cent) by 2030 (compared to 2018levels)(36).

Nevertheless, further – and enormous – efforts still have to be made in order to achieve these objectives, and the previous chapters made clear that they cannot be achieved solely through further increases in energy efficiency: over the last ten years, the industrial sector has increased its efficiency, but without achieving a corresponding reduction in emissions. Rather, fundamental changes in production processes will be necessary.

However, there are two big impediments to these fundamental changes. First, about one-third of emissions from EEIs take the form of process-related emissions, which cannot be avoided using conventional production techniques due to the raw materials used and to the associated chemical reactions. A study(37) carried out in the framework of the Federal Ministry for Economic Affairs and Climate Action (BMWK)'s project "Energy transition in industry: potential, costs and interactions with the energy sector", demonstrates that the transformation of industry is technically possible, even though the challenges are great, because industrial production processes that have been tested and applied over decades have to be fundamentally changed, and because almost all of the emission-avoiding technologies are associated with high additional costs (38) . The second big challenge faced by German EEIs in their decarbonisation commitments lies in the fact that capital-intensive production plants have long operational lifespans (often with depreciation periods of 50 to 70 years). This means that in the coming investment cycle, renewed investment in conventional technologies could lead to stranded assets, i.e. to the early decommissioning of assets that have not yet been fully depreciated, and to the associated economic losses.

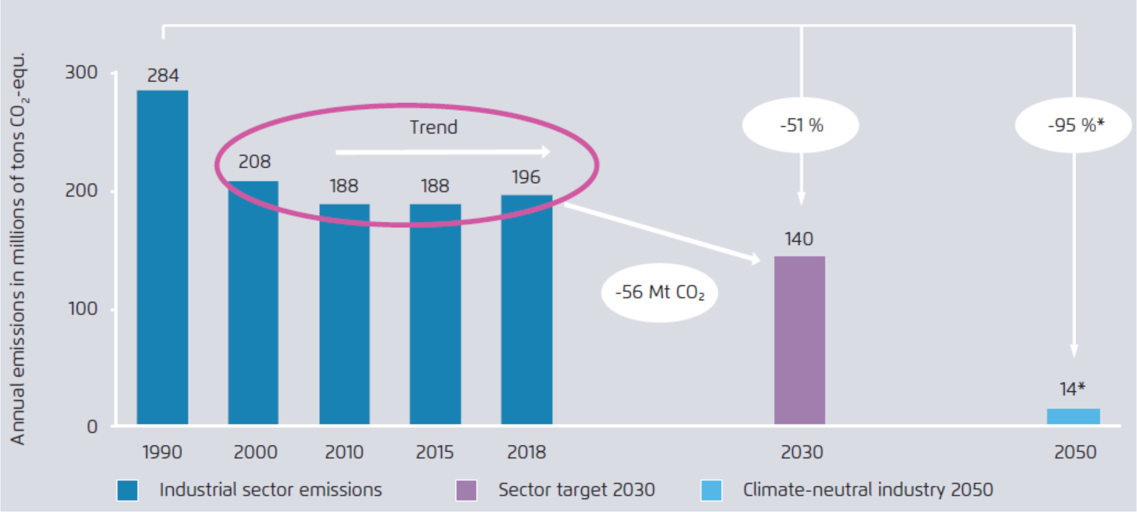


Figure 11. Emissions of the German industrial sector 1990-2018 and sector targets 2030/2050.(39)

The situation faced by the EEIs in Germany is alarming in this respect. In order to maintain current production levels, massive reinvestments into production plants will have to be made in the coming years. Some examples: by 2030, around 53 per cent of the blast furnaces in the steel industry, around 59 per cent of the steam crackers in the basic chemical industry and roughly 30 per cent of the cement kilns in the cement industry will need a reinvestment.

Companies will not make the necessary replacement investments if the long-term economic and regulatory conditions are uncertain. In light of increasing demands for climate protection, reinvesting in conventional, emission-intensive technologies faces a greater likelihood of being decommissioned early, increasing the risk associated with such endeavors. From the standpoint of companies as a rational economic actor, there are only two options: to invest in climate-neutral technologies in the next investment cycle, or to close down existing production plants at the end of their service lives and, if necessary, make new investments abroad, thus triggering massive job losses (the carbon leakage phenomenon, describes in the previous chapters) (40).

As illustrated above, technological potentials that could be harnessed to make the EEIs almost completely climate-neutral already exist today. But these technologies and production processes are still significantly more expensive today than conventional manufacturing processes and the additional costs cannot be passed on to customers because of fierce international competition. Therefore, to stimulate investment in these innovations now, industry actors need political signals that the government will actively support this transformation.

According to a study conducted by Agora Energiewende and Wuppertal Institute(39), the shift to low-carbon production processes requires a comprehensive new regulatory framework, with the following prerequisites:

- Industry actors need long-term, cross-party assurance that Germany will ensure internationally competitive energy prices for its EEIs.
- The new version of the EU state aid guidelines must be geared towards climate neutrality. National policy instruments to promote low-carbon technologies should not require individual approval from the European Commission, thus ensuring that the

supplemental investment and operation costs associated with such technologies can be financed over the long term.

- Necessary infrastructure, including power lines, hydrogen pipelines and CCS infrastructure (pipelines and ports as well as safe CO_2 storage facilities) must be reliably available in good time. To this end, planning approval must be granted quickly; this will require adjusting permitting rules and associated appeal procedures.

While the above regulatory provisions are important prerequisites, by themselves they cannot ensure the success of the transformation. Additional political measures and policy instruments are needed to encourage the shift to low-carbon production process, as those developed by Agora Energiewende and Wuppertal Institute and listed below.

1. Carbon price floor with border carbon adjustment: this option foresees introducing an increasing carbon price floor to the EU ETS, in order to provide a predictable price incentive. In addition, a carbon tax would be levied on imports, and exports to regions without carbon prices would receive tax credit equal to CO_2 costs.
2. Carbon Contract for Difference (CfD): under this policy instrument, when investing in key low-carbon technologies, companies would receive project-related subsidy payments based on avoided CO_2 emissions, thereby reducing project risks for industry actors. The amount of subsidy funding would be determined through an auction. Over the long term, the ability to participate in the auction should be available to all companies.
3. Green financing instruments: this instrument foresees reducing financing costs for investments in low-carbon technologies, either by offering below-market interest rates or indemnifying creditors for potential losses when projects are at the final stages of technology development.
4. Climate surcharge on end products: to help refinance other policy instruments mentioned here, a special charge would be levied on selected materials (steel, plastic, aluminum and cement), irrespective of emissions associated with their production.
5. Carbon price on end products: when products are sold to the end consumer, a charge would be levied based on the carbon content of the materials, thus offsetting the cost disadvantage of low-carbon products. This charge revenue could then be used to finance other instruments.
6. Green public procurement: public-sector entities would be required to fulfil sustainability requirements i.e. when developing infrastructure (e.g. buildings, bridges and railways) and procuring vehicles. This would create reliable demand for sustainably produced basic materials and end products (especially steel, cement and vehicles).
7. Quota for low-carbon materials: producers of consumer goods would be obliged to use fixed shares of low-carbon materials in their end products, thus guaranteeing demand for low-carbon materials.
8. Green hydrogen quota: natural gas providers would be required to sell a certain share of green hydrogen, thus ensuring the expansion of power-to-x technologies on the road to long-term decarbonisation.
9. Changes in construction and product standards: regulations and standards would be fundamentally revised and continuously adapted in order to simplify material efficiency and substitution and the use of new building materials in construction (e.g. cement based on alternative binders).

10. Standards for recyclable products: mmanufacturers would be obliged to design products so that recycling is simplified in order to close material loops and to reduce carbon-intensive primary production.

In conclusion, the competitiveness of the economy remains a key issue for Germany as an industrial power. The key challenge is to create a regulatory and policy framework that ensures the necessary technology shift without jeopardizing international competitiveness, while ensuring that there is open-technology competition for the best path. In view of the long investment cycles in industry, the regulatory course must be set in the next few years and it will be crucially important to develop a coherent set of instruments.

The case of Greece

Decarbonizing electricity – Renewable PPAs: High electricity prices is a major issue for the Greek EII sector. UNICEN – the Hellenic Union of Industrial Consumers of Energy – argues that the high electricity prices in Greece are a more structural issue, being heavily affected by the market organization. The Association has proposed a series of measures aiming to reform the Greek wholesale electricity market, among which is the expansion of renewable Power Purchase Agreements (PPAs) (41).

Although the cost of electricity from renewable electricity sources is constantly decreasing and in many cases has become competitive with fossil fuel options, the intermittent character of wind and solar energy requires that additional shaping and firming costs need to be taken into account for the renewable electricity sourcing and these pose additional risks for EIIs.

In order to solve this issue, the **"Green Pool"** concept has been proposed in a study commissioned by MYTILINEOS(42). In brief, the concept foresees that EIIs invest in new RESe production capacity, the production of which is aggregated trough the Green Pool, reducing the overall shaping and firming costs. The renewable electricity can be distributed to the EIIs on the basis of the renewable generation capacity they have brought into the pool. Any remaining shaping and firming costs can be subsidized through funds available from the Recovery and Resilience Facility. The Green Pool has been adopted by the Greek Government, becoming the basis of a proposal for the support of the EIIs sector in Greece. In early 2022, negotiations with the European Commission regarding the approval of the scheme are still ongoing. YPEN – the Ministry of Environment and Energy – anticipates the scheme to be launched in 2022, with an initial aim to cover 20 % of the EIIs' electricity demand through renewable PPAs. The anticipated level of public support is around 15 €/MWh.

Decarbonizing heat – biomass and renewable gases: On the one hand, the recent price hikes of both natural gas and CO_2 are actually a driver for decarbonisation all over Europe. On the other hand, EIIs are highly sensitive to energy costs and such increases can often make them to stop production altogether rather than switching to new alternatives.

Social opposition to renewable energy projects: Significant **social opposition** against several renewable energy projects in Greece has often been detected. This opposition most strongly materializes against wind farms that have been set for establishment in mountainous and/or touristic areas of Greece. To our knowledge, this activity has not directly impacted renewable electricity projects that have been planned with the explicit purpose to decarbonize the electricity supply to EIIs in Greece. More specific to the EII sector is the social opposition to initiatives related to the utilization of alternative, waste-derived fuels in the cement industry. The opposition is more evident in the Volos cement plant, due to its close proximity to a big population center and local air emissions issues. It should be noted that such issues are common in waste-to-energy projects in most countries of the world. Moreover, it would appear that there is less opposition to plans related to the utilization of "green waste" fractions, such as urban pruning, or other biomass assortments originating from post – fire forest management activities.

Company size and financial limitations: As a final note, it should be noted that many Greek EIIs are actually small or medium sized companies, with limited capacities to implement investments related to renewable energy uptake. On the other hand, it is evident that Greek companies with a strong position in their sectors are in fact willing to implement investments related to increased uptake of renewable energy.

CONCLUSIONS

In the era of accelerated zero-emission targets and climate change mitigation, four country models were studied of different industries volume. At this paper recorded the specific technological innovations, challenges and potentials of the main energy intensive industries operating in European South, Greece, Spain and European North, Germany and Netherlands. On the graph above are gathered the central options of each study country. Netherlands, going one step further has conducted a stakeholders coordination, Cluster Energy Strategies (CESs) network, in order to provide an organizational roadmap for the country. The introduction of decarbonization measures and in cases of such as those we examined, in different industries classifications indicates the common need of measurements and policies over the European net zero goals. Electrification, bio and synthetic fuel, CCU & CCS are the common energy perspective regarding the direct energy efficiency upscaling measurements.

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