UNECE

ESCWA

TECHNOLOGY BRIEF

CARBON NEUTRAL ENERGY INTENSIVE INDUSTRIES

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Disclaimer
The publication does not necessarily reflect the position of the reviewers and partners listed above who helped develop this publication.

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Executive Summary

To avoid the worst impacts of climate change, the United Nations Economic Commission for Europe (UNECE) and the Economic Commission for Western Asia (ECWA) are exploring opportunities to achieve carbon neutrality within energy intensive industries across the region.

Energy intensive industries are one of the key greenhouse gas emitters, accounting for about 25% of total CO_2 emissions globally and 66% of the industrial sector. Cement, iron and steel, and chemicals and petrochemicals industries are singled out as the most significant industrial CO_2 emitters, with shares in the sector reaching 27%, 25%, and 14%, respectively. The decarbonisation of these industries is a top priority to attain carbon neutrality and Paris Agreement targets.

Plenty of challenges remain to achieve carbon neutrality in the industrial sector. They include a wide range of difficult to replace energy intensive carbon emitting industrial processes. They also have low-profit margins for commodity products in a globally competitive environment and the expected rise of demand for carbon intensive materials in sectors such as buildings, transport, and health care.

This brief explores the best ways for energy-intensive industries to transition to a carbon-neutral economy while maintaining or improving their global competitiveness. With the emergence of the EU Green Deal, plans for climate neutrality in energy intensive industries are inevitable. These plans should include investing in realistic technological solutions and aligning action in different key areas such as industry, policy, economy, and research. Cement, iron and steel, and chemicals and petrochemicals industries are the backbones of modern economies. While their emissions are high, they play a pivotal role in low-carbon post-Covid recovery.

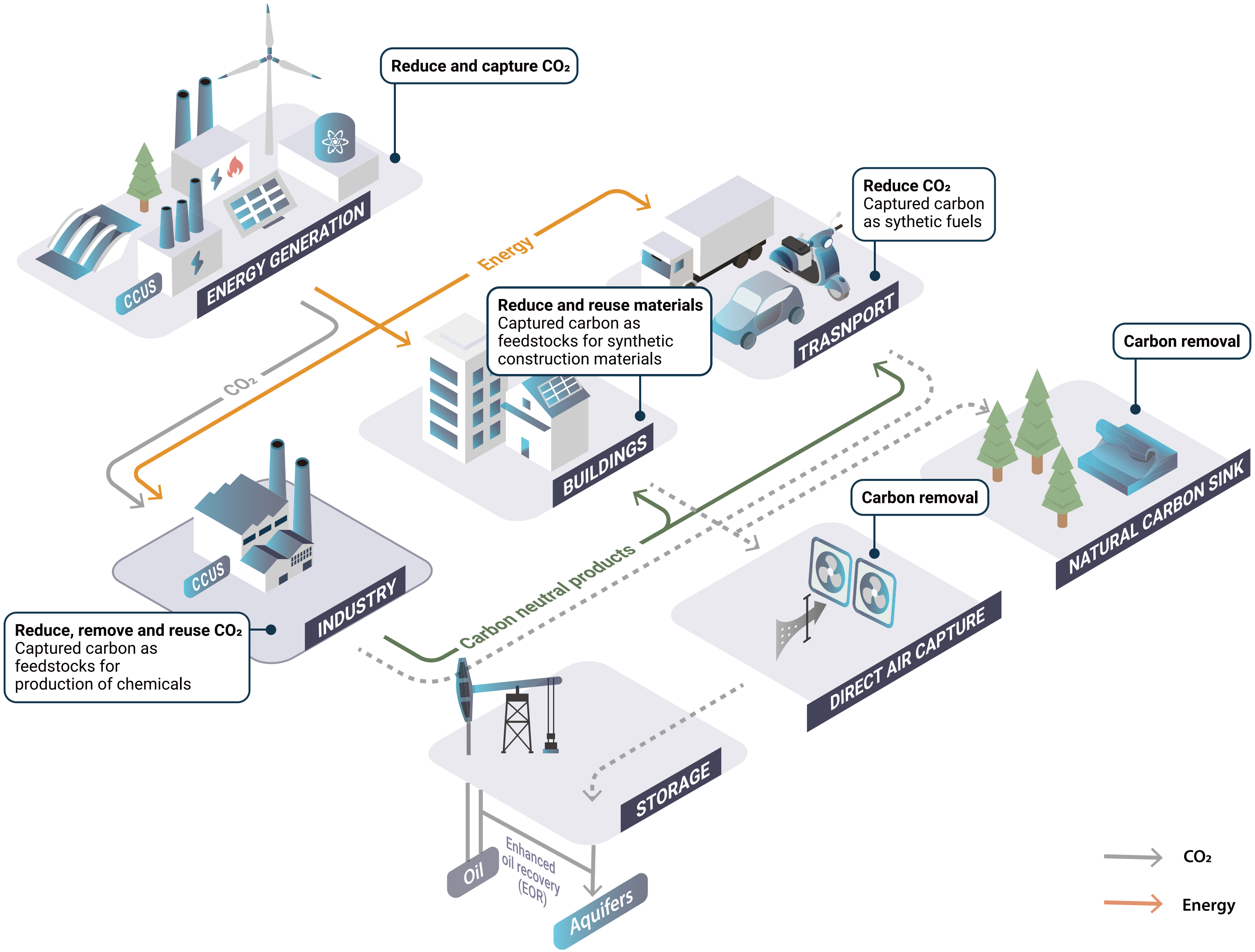
The solutions presented in this brief fall into two categories: technology-based solutions and concept-based solutions. Technology-based solutions include carbon capture, utilisation, and storage (CCUS); hydrogen; industrial energy efficiency; nuclear power and heat; and electrification coupled with increased renewables. The concept-based solutions include Circular Carbon Economy (CCE) and Industrial Clusters approach. The CCE concept encompasses reducing, capturing, recycling, and removing carbon (CO_2) and methane (CH_4) (Fig.1).

Energy intensive industries deserve particular interest as their large carbon footprints make their transformation towards a carbon neutral form of production challenging. To further narrow the gap, shaping structural shifts throughout the value chain and applying a systemic approach to circular carbon economy and industrial clusters across the region is required.

International cooperation is essential to support all countries across the ESCWA and UNECE regions to accelerate energy transition and attain carbon neutral energy intensive industries. Different countries and sub-regions require different solutions based on their socio-economic and political circumstances as well as access to natural resources.

ESCWA and UNECE continues to play the role of an honest broker and offer a neutral platform for inclusive and transparent dialogue, exchanges of best practices and lessons learned, and consensus building on effective approaches to achieving carbon neutrality.

Figure 1 Circular Carbon Economy



Key Takeaways

Deploy technology solutions for carbon neutral industries

Countries need to support and encourage innovation and research and development to advance development and deployment of low- and zero-carbon technologies. Industrial energy efficiency, carbon capture, use and storage (CCUS), hydrogen, nuclear power and heat, and electrification are key to achieving carbon neutral industries.

Embrace the concepts of circular carbon economy and industrial clusters

Circular carbon economy that relies on carbon reduction, capture, reuse and removal combined with an industrial cluster approach is a means of creating sustainable jobs and provision of a low-carbon stimulus to economies. This is possible through investments from the EU Innovation Fund and other government and private sector initiatives.

Develop policy framework and institutional capacity to support transition to carbon neutral industries

Clear regulatory frameworks that allow commercialisation of low- and zero-carbon solutions and decarbonisation of energy intensive industries are necessary. Legislation needs to be adapted and include new regulations applicable across all energy intensive industries, such as taxing carbon emissions from industries, code of practice for adoption of CCUS etc.

Attract financing and promote public-private partnership (PPP)

Financing projects at an early stage is necessary to scale favourable conditions and allow earlier commercialisation of low- and zero-carbon solutions. Investments need to be directed towards modernization and decarbonisation of energy intensive industries. There is a need for inclusive multi-stakeholder initiatives that are strengthened by public-private partnerships.

Promote regional cooperation to share best practices and lessons learned

A sub-regional approach to share knowledge and best practices is needed to accelerate existing efforts, improve cost efficiencies for large infrastructure projects and promote projects of common interest.

1. Status of Energy-Intensive Industries

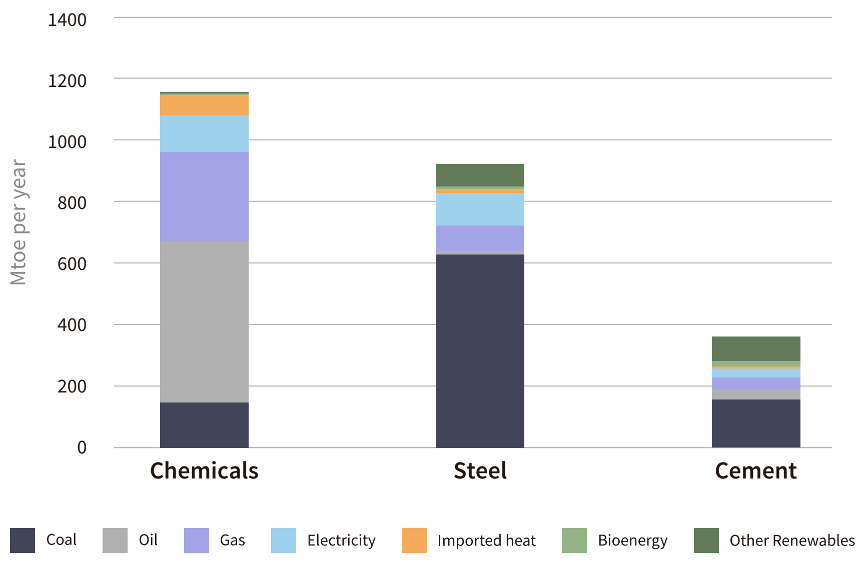
Energy-intensive industries are one of the key greenhouse gas emitters, accounting for about 25% of total CO_2 emissions globally and 66% of the industrial sector. Decarbonisation of energy-intensive industries is thus a key milestone in attaining carbon neutrality.

Energy intensive industries are characterised by a high energy intensity, measured in energy consumed per unit value (kWh/$) and/or high carbon intensity in carbon emissions per unit value (CO_2e/$). Their energy usage makes up a significant part of production costs. They are the starting point of many industrial value chains providing both raw and processed materials.

This brief is focusing on three sectors: steel, chemicals, and cement. These three sectors produce the basic materials for infrastructure, buildings, machinery, and consumer goods. Cement, iron and steel, and chemicals and petrochemicals industries are singled out as the most significant industrial CO_2 emitters, with shares in the sector reaching 27%, 25%, and 14%, respectively.

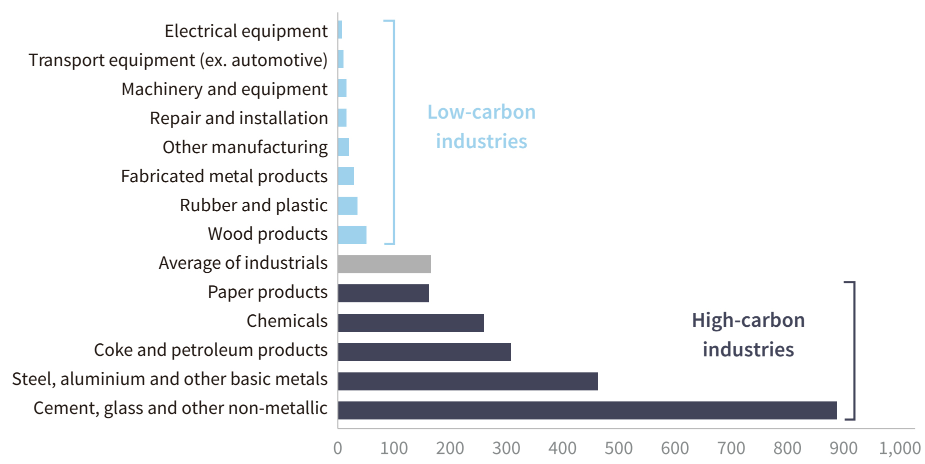
To support the transition toward carbon neutrality and a circular carbon economy by 2050, energy intensive industries require modernized infrastructure, modified industrial processes, and low-carbon technologies. Deploying cleaner technology solutions and a concept of circular carbon economy across hard-to-abate industries is expected to reduce costs, improve their competitiveness and market readiness, and create green and sustainable jobs.

Figure 2 Total energy demand by sector



***Source**: IEA, 2021*

Figure 3 High and Low Carbon Industries



***Source**: Lombard Odier, Kaminker and Höhne-Sparborth, 2020*

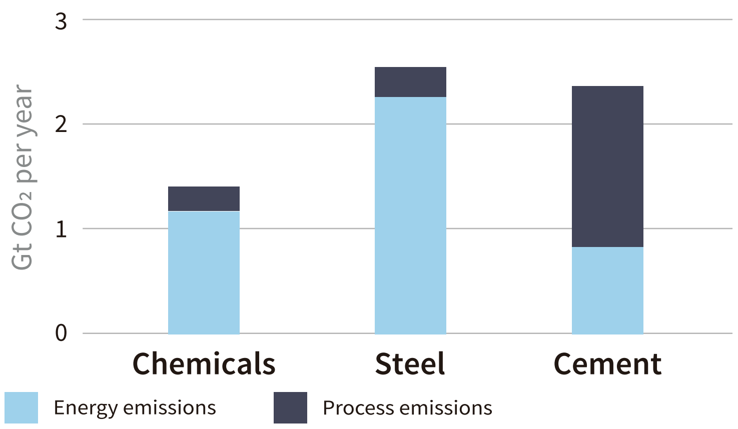
2. Technological Pathways to the Decarbonisation of Selected Energy-Intensive Industries

This chapter provides a concise overview of selected energy-intensive industry sectors—focusing on the decarbonisation of the manufacturing processes of cement, steel and chemicals.

The decarbonisation of energy intensive industries is a top priority to attain carbon neutrality and Paris Agreement targets. However, decarbonisation of the production of cement, steel and chemicals is challenging and in some cases technically impossible.

Energy intensive industries require high temperatures and chemical processes that are today most efficiently reached by burning fossil fuels resulting in a high carbon footprint of these sectors. In addition, CO_2 emissions are also often a by-product of the chemical transformation processes in the production of cement, steel and chemicals. Fossil fuel is also used as a feedstock in chemical transformation reactions and manufacturing. Hence, decarbonising energy intensive industries is technically not possible as it would require alternative chemical processes that deliver a desired output without emitting CO_2 as a by-product. But it is possible to attain carbon neutral energy intensive industries by embracing both emissions reductions that would significantly decrease the carbon footprint of energy intensive industries paired with renewable energy procurement and carbon removals through technology and nature-based solutions.

Figure 4 Share of CO_2 emissions



Source: IEA, 2021

Technology solutions for carbon neutral energy intensive industries

Industrial energy efficiency to reduce, substitute and compensate for emissions through machinery replacement for higher efficiency, installation of heating control system and waste heat recovery. (Pathways to Effectively Decarbonise Industry).

Electrification of heat coupled with renewable energy or nuclear power to power furnaces by electricity instead of burning fossil fuels.

Biomass as a fuel and feedstock. Charcoal or biogas could replace traditional fossil fuels in the industrial processes to attain a carbon neutral effect.

Carbon capture, use and storage (CCUS) is a solution to capture CO_2 and either store it underground or transform it into something useful such ethanol or raw materials to be used in the chemical or cement sector.

Hydrogen Hydrogen is carbon neutral energy vector that can be used as a fuel in a furnace, feedstock in production of chemicals or as a reactant in industrial chemical processes.

Circularity is a concept of achieving sustainable production and consumption by embracing innovative solutions that encourage reuse and recycling of materials and resources across the whole value chain.

Many of these technology solutions are still at early stages of development and are costly compared to traditional predominantly fossil-fuel based production methods. Policy support, research and development, and financing would be required to commercialize these technology solutions. There is a need for pilot plants, demonstration plants and scale-up of carbon-neutral industrial plants that deploy these technology solutions.

3. Target Industries

Cement industry

Cement is a widely used construction material in the world. It is the second-most-consumed product globally after potable water. The cement industry alone is responsible for almost 7% of the world's emissions (roughly 2.5-3.0 $GtCO_2$/yr per IEA). In comparison to other energy intensive industries, cement production generates about 7kg of CO_2 per revenue dollar, compared to 1.5kg in steel production and 0.3 kg in chemicals production.

According to IEA, the global demand for cement is expected to increase 12-23% by 2050. If the industry does not embrace technology solutions to cut its carbon footprint this anticipated growth will result in even larger GHG emissions.

Overview

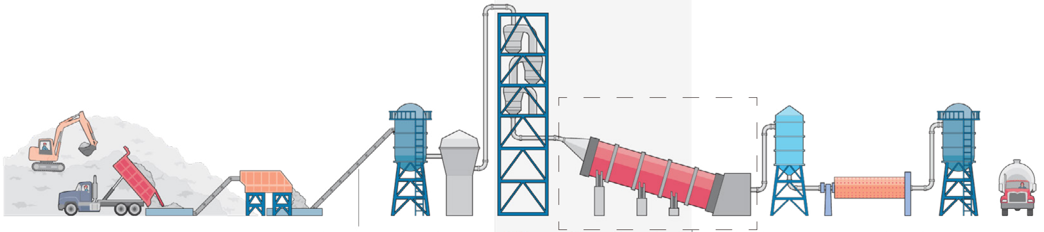
The cement manufacturing process starts with grinding raw materials, including limestone and clay to a fine powder, and heating the raw material to a very high temperature (1450) in a cement kiln. The output of this process is cement clinker, rounded lumps, that are then grinded and mixed with gypsum to create cement.

The cement industry, similar to any other energy intensive industry, contributes to two types of emissions: process-related and energy-related emissions. About 60% of these emissions are associated with process-related emissions from the chemical process of limestone calcination in the clinker kiln. Today, clinker kilns are mainly fuelled by coal, oil, petroleum coke, and natural gas.

Decarbonising processes will require the expansive deployment of emerging technology solutions which are not yet commercially available but require government support to boost R&D and attract financing into pilot and demonstration projects.

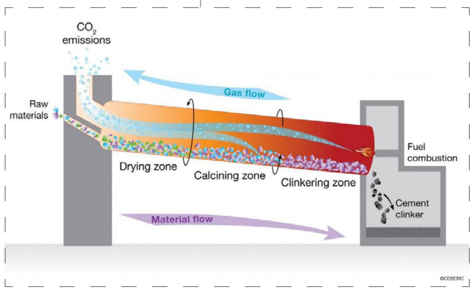
Figure 7 Cement Process

Raw materials, energy, and resources | **Clinker and cement manufacturing**



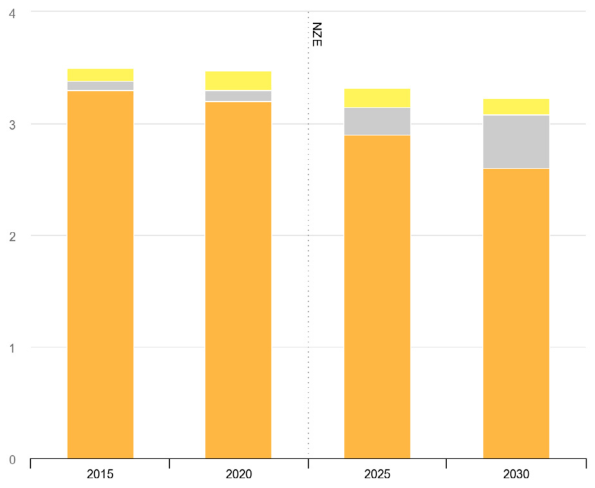
	Quarry	Crusher	Transport[1]	Raw mill	Kiln and preheater/ precalcinator[2]		Cooler[3]	Cement mill	Logistics[4]	**Total**
Energy, mega-joule/ton	40	5	40	100	3,150		160	285	115	3,895
CO_2, kilogram/ton	3	1	7	17	479 Calcination process	319 Fossil fuels	28	49	22	925

[1]Assumed with 1kWh/t/100m.
[2]Assumed global average, data from the Global Cement and Concrete Association, Getting the Numbers Right 2017.
[3]Assumed reciprocating grate cooler with 5kWh/t clinker.
[4]Assumed lorry transportation for average 200km.



Source: *McKinsey and Company, 2020*

Figure 8 Global thermal energy intensity and fuel consumption of clinker production in the Net Zero Scenario, 2015-2030



Source: IEA, Global thermal energy intensity and fuel consumption of clinker production in the Net Zero Scenario, 2015-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-thermal-energy-intensity-and-fuel-consumption-of-clinker-production-in-the-net-zero-scenario-2015-2030, IEA.

Technology solutions for the carbon neutral cement sector

Industrial energy efficiency: Energy efficiency of the cement sector can be improved through energy and waste heat recovery, and increasing the proportion of dry and semi-dry processes. Traditional plants would feed limestone to the kiln by producing a slurry using water, but the evaporation of this water is very energy intensive. Innovation and digitalisation of processes can help optimise the intensity of the kiln flame resulting in fuel savings.

Electrification: Switching from traditional fossil fuels to an electrified thermal energy supply that is based on zero-carbon technologies such as renewable energy and nuclear power can be a solution for decarbonisation of cement production in the long-run. Intermittency of variable renewable energy sources poses a risk to processes that require constant energy and heat flow. Nuclear power as baseload can play an important role in system balancing and substitution for lack of reliability of electric power sources. Electrified heating results in a high concentration of CO_2 in the flue gases compared to combustion heating, making it thus attractive for CO_2 capture and use.

Biomass: Biomass or biomass with carbon capture and storage (BECCS) can replace fossil fuels to generate heat and fuel chemical processes in the production of cement. However, increasing competing demand for the limited supply of biomass from other sectors does not make it a viable option to decarbonise cement production.

Carbon capture, use and storage (CCUS): CCUS has high potential in decarbonising the production of cement. CO_2 capture can be applied to both combustion- and process-related emissions. Currently a number of post-combustion carbon capture pilots on cement plants are under development. However, transport and storage of captured CO_2 that is critical to making the business case for CCUS technology to be applied in the cement sector remains a challenge. It is necessary to identify storage sites in the proximity of existing or future cement plants.

Hydrogen: Hydrogen as an energy vector can be a clean solution of thermal supply for the cement sector. Hydrogen can reach the high temperatures that are required in cement production. As properties of hydrogen differ from traditional fossil fuels currently used, it would require extensive modifications to existing cement kiln designs and supporting infrastructure.

New materials and circular economy: Materials intensity could be solved through circularity. About 30% of infrastructure materials could be substituted with alternative materials. Clinkers can be partially substituted by supplementary cementitious materials, such as fly ash and blast furnaces from steel production. Optimised and alternative design choices as well as cement and concrete recycling can play an important role.

Case study: Deployment of CCUS in Cement Sector

Location: Norway

Project type: Carbon capture and storage CCS

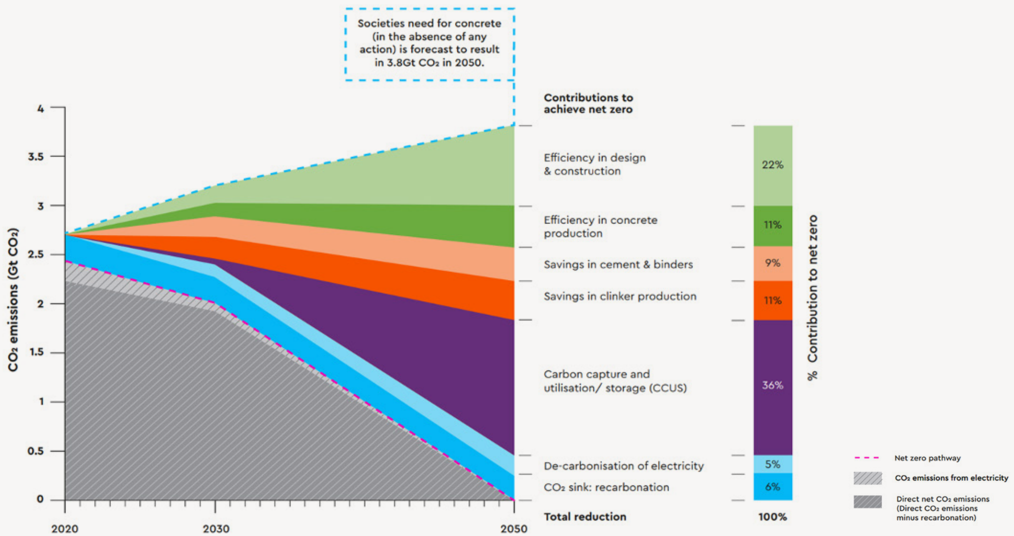
Background: HeidelbergCement's Norcem subsidiary in Norway is a prime example of the CCS value chain. The project is currently preparing to build its carbon capture and storage (CCS) unit at the Brevik cement plant. Aker Solutions was awarded the Euro 50 milion contract in late December 2020 to build the unit after the Norwegian government confirmed its investment in the project.

Description: The project will use Aker's amine solvent scrubbing process to absorb CO_2 from the cement plant's flue gas. FLSmidth has also been contracted to conduct modification work at the cement plant by making adjustments to the production process and removing particles from the flue gas. The unit is scheduled to be commissioned in late 2024. At this time around 400,000t/yr of CO_2 will be captured from one of the cement plant's two production lines. The CO_2 from Brevik will be sequestered under the North Sea as part of the Norwegian government-backed Northern Lights project. Aker has also won a contract from energy company Equinor in December 2020 to deliver liquefied CO_2 from the cement plant by ship to a receiving terminal in Øygarden, outside Bergen. At this point the CO_2 will be stored intermittently before eventually being injected into subsea geological structures via a subsea pipeline.

Global Cement and Concrete Association Net Zero Map

The GCCA 2050 Cement and Concrete Industry Roadmap(GCCA Concrete Future Roadmap) for Net Zero Concrete is the collective commitment of the world's leading cement and concrete companies to fully contribute to building the sustainable world of tomorrow.

- The roadmap sets out a net zero pathway to help limit global warming to 1.5°C
- The sector is committed to producing net zero concrete by 2050 and is committed to acting now.
- Over the last three decades, the industry has already made progress with proportionate reduction of CO_2 emissions in cement production of 20%.
- This roadmap highlights a significant acceleration of decarbonisation measures achieving the same reduction in only a decade. It outlines a proportionate reduction in CO_2 emissions of 25% associated with concrete by 2030 from today(2020) as a key milestone on the way to achieving full decarbonisation by the mid-century
- The roadmap actions between now and 2030 will prevent almost 5 billion tonnes of CO_2 emissions from entering the atmosphere compared to a business-as-usual scenario.
- GCCA members pledge to achieve the roadmap aims, contributing in line with their position in the cement and concrete value chain.
- Enabling a transition of the sector and making full use of circular(economy) opportunities, as well as supporting the development and implementation of innovations and key infrastructure. The roadmap outlines this pathway to net zero:



Policy actions

Strategic and early policy planning can play an important part in preparing the sector for a full technology deployment and project scaling once they mature. **Policy actions include**:

- **Commit to R&D in new technologies** and support large-scale demonstration projects for breakthrough technologies to create evidence base
- **Encourage electrification of kilns** through low- and zero-carbon power supply
- **Encourage deployment of CCUS technologies** in the cement sector and make adjustments to the regulatory framework to facilitate uptake of CCUS technologies. Development of CO_2 storage and transport infrastructure is needed.
- **Promote green public procurement** and promote low-carbon building materials
- **Embrace just transition strategy** to create green jobs and support affected workers and communities

Steel Industry

The iron and steel industry produces one of the most important engineering and construction materials. It is also one of the largest industrial sources of CO_2. Globally, it accounts for about 7-9% of anthropogenic CO_2 emissions (approx. 3 Gt CO_2/year) (CCS institute, 2020). To put it into context, if the steel industry was a country, it would be the 5th largest contributor to global CO_2 emissions.

Overview

Fossil fuels are used as an energy source and as a feedstock in the production of steel. In integrated blast furnace and basic oxygen furnace (BF-BOF) and direct reduction iron electric arc furnace (DRI-EAF) steelmaking, fossil fuels (primarily coal) are used as reducing agents to convert iron ore into iron as well as for the generation of heat needed for industrial processes. Steel can be produced via three main processes:

Integrated blast furnace (BF)/basic oxygen furnace (BOF): Around 70% of global steel production today is using a coal-dependent BF/BOF process. The iron ore is reduced in the blast furnace before it is refined to crude steel using a basic oxygen furnace. This requires high temperatures in the range of 1100-1600 °C which is achieved mainly by burning fossil fuels. Emissions from this method are around 2 tCO_2 per ton of crude steel. This means that the mass of CO_2 emissions from manufacturing is double the mass of steel produced.

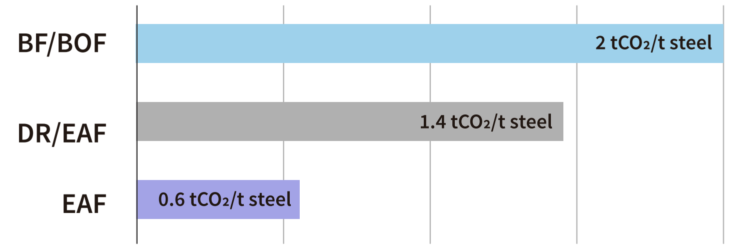
Electric arc furnace (EAF): This process uses scrap steel, direct reduced iron (DRI), or hot metal as a feed. Today this method accounts for 25% of global steel production. Its emissions are usually lower than the BF/BOF process. However, it depends on the power source of the electricity used. On average, emissions are around 0.6 tCO_2 per ton of crude steel.

Direct Reduced Iron-Electric Arc Furnace (DRI-EAF): At present this process is applied to make around 5% of global steel production. No melting is needed for this process as it reduces iron ore using a blend of H_2 and CO. Carbon monoxide is usually derived from natural gas. The carbon emitted is around 1.4 tCO_2 per ton of crude steel.

Figure 11 Major steelmaking process routes

Source: *BHP website*

Figure 12 Typical carbon emissions intensity by process



Source: *McKinsey and Company, 2020*

Technology solutions for the carbon neutral cement sector

Industrial energy efficiency: : This includes primary strategies of reducing energy intensity through better plant utilisation, increasing equipment effectiveness, and recovering waste heat (a by-product of machines or processes that use energy). Other options include maximising the iron content in raw materials to decrease the usage of coal and increasing the use of fuel injection through natural gas, plastics, biomass or hydrogen.

Electrification: Electric heating could provide benefits of rapid heating, fast production ramping/process start up, and high thermal efficiency. In conjunction with energy efficiency, it can lead to minimising energy use and reducing heat loss.

Biomass: : Biomass can fuel blast furnaces or replace natural gas in DRI processes. This depends on the regional availability of sustainable sources of biomass material. Where available, biomass has the potential to reduce carbon intensity of steel production by as much as 50%. Biomass with CCS can also play a significant role in moving toward net negative carbon emissions in regions with excess of biomass.

Carbon capture, use and storage (CCUS): CCUS can make a significant contribution to steel production. Retrofitting blast furnaces and basic oxygen furnaces with CCS can be a mid-term solution until DRI production options with zero-carbon hydrogen become more cost-competitive. Recent IEA projections indicate that by 2060 CCS needs to be installed on about 21% of global crude steel production capacity. This corresponds to 506 Mt of CO_2 captured annually.

Hydrogen : The most promising technology to decarbonize the steel sector. Hydrogen can be used as a fuel to generate heat as well as a reduction agent replacing coking coal to remove oxygen from iron ore, leaving water as a by-product instead of CO_2. Also, green hydrogen can be used instead of natural gas to make direct reduced iron (DRI) or for direct iron electrolysis. DRI and EAF using hydrogen represents a technically proven production method that enables nearly emission-free steel production.

New materials and circular economy: By using scraps in electric arc furnaces or fossil carbon replacements like waste wood that has been treated to become bio-coal. This substitution of fossil coal by circular carbon aids the transition towards a circular carbon economy CCE.

Case study: Deployment of Hydrogen in the Steel Sector

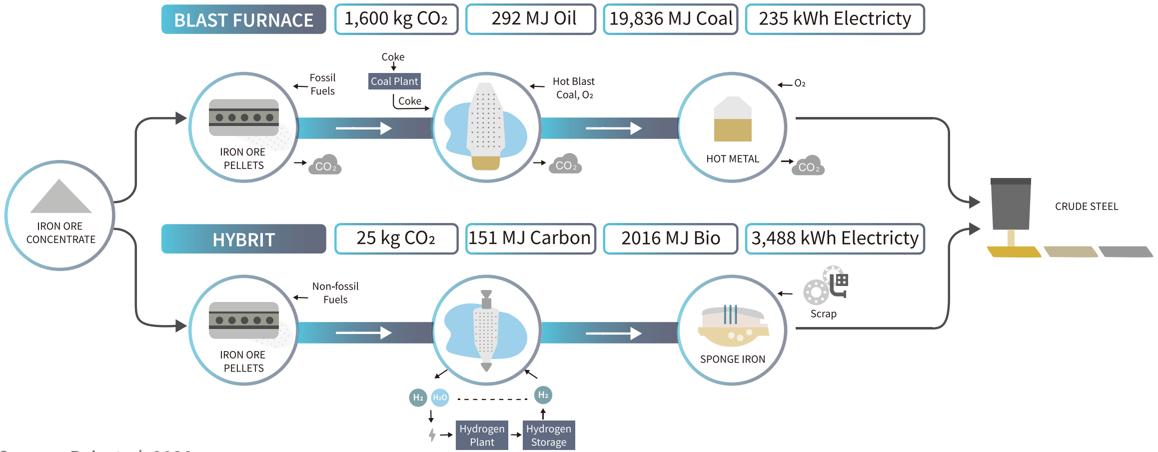
Location: Svartöberget in Luleå, Sweden

Type of project: Steel Production using Hydrogen

Background: HYBRIT is the world's first fossil-free steel-making technology with virtually no carbon footprint. In 2016, the HYBRIT project was launched as a joint venture between LKAB, SSAB and Vattenfall. The project is aiming to replace coking coal, traditionally needed for ore-based steel making, with hydrogen.

Description: Sweden has unique conditions for initiatives like HYBRIT with good access to fossil free electricity, Europe's highest quality iron ore, and a specialized and innovative steel industry. With the political backing and de-risking of the early stage of the HYBRIT project, it can be argued that HYBRIT is the outcome of a long-standing political intent to ensure a competitive basic industry sector in Sweden. The process that HYBRIT is currently piloting is the use of hydrogen instead of coal as a "reduction agent" to remove the oxygen from the iron in iron ore. This enables the most critical step in the steel value chain to become virtually free of carbon emissions. These steel plants can replace polluting blast furnaces with a process that emits water vapor instead of CO_2. So, its emissions will be basically water.

Figure 13 Alternative steel production pathways



Source: *Pei, et al. 2020*

The reason why HYBRIT stands out is because it has the most aggressive timeline to address the root cause of the CO_2 emissions. Its pre-feasibility study started in 2016 followed by the second phase of pilot trials in just 2 years 2018-2024. The third phase is planned to take place from 2025 to 2035, and will be focused on trials at a demonstration plant.

Despite early successes, some identified challenges remain. It is still unclear how to develop an efficient process of industrial scale that would be fully powered by hydrogen and remain economically viable.

Steel manufacturing is an essential industry that will play a pivotal role in the transition as it is a component of electric vehicles, wind turbines, infrastructure and manufacturing processes. Countries worldwide are taking different approaches towards decarbonising steel industry:

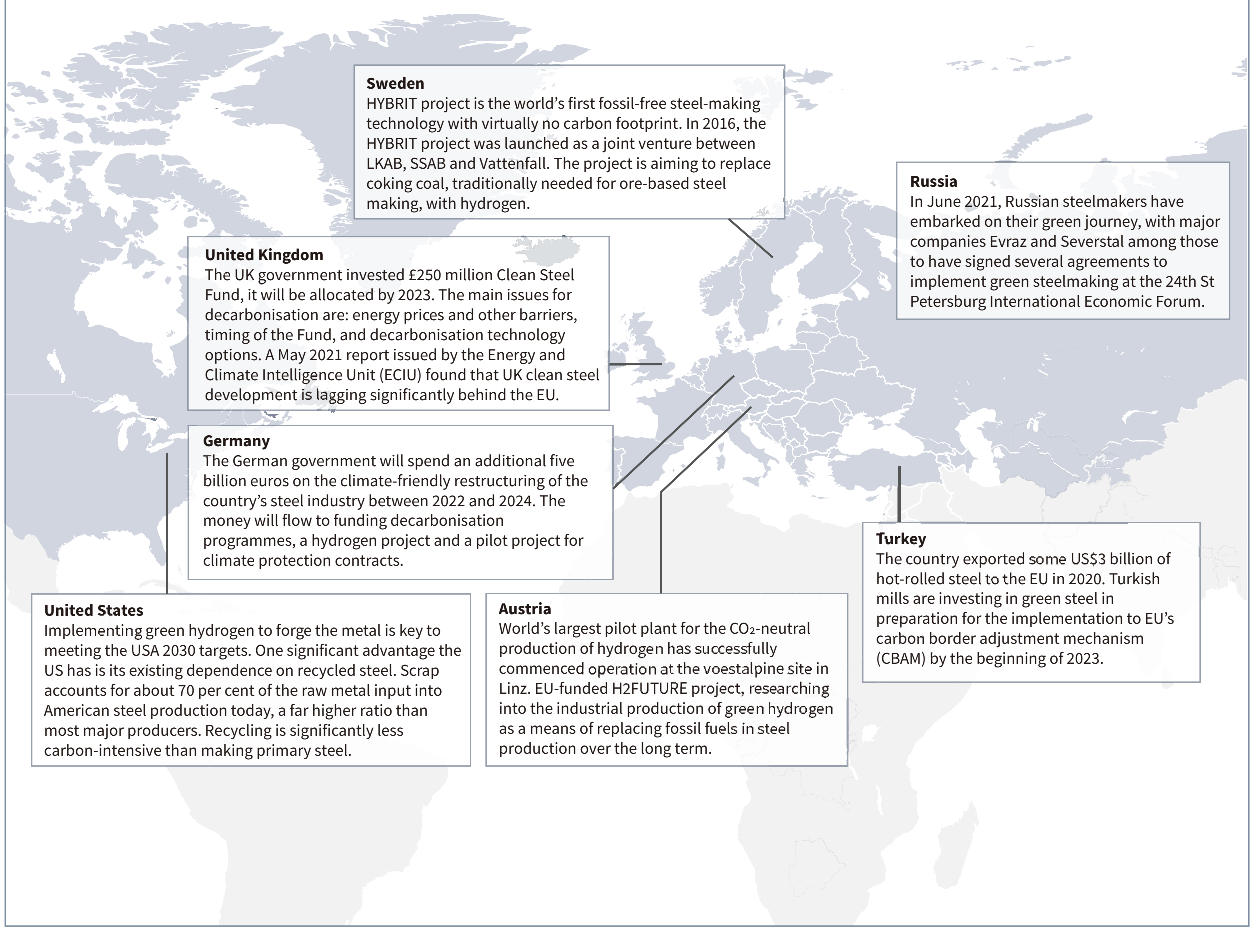
- UK has set up a £250 million Clean Steel Fund as long-term signal of support to the steel sector and its decarbonisation efforts.
- In Europe, according to Energy and Climate Intelligence unit, 23 hydrogen steel projects are either planned or under way across Europe, including plans to produce hundreds of thousands of tonnes of green steel by as early as next year. The region's steel industry has said it aims to reduce its emissions by 30 per cent by 2030 and by as much as 95 per cent by 2050.
- Major Russian companies such as Evraz and Severstal have signed several agreements to implement green steelmaking
- In the US, implementing green hydrogen to forge the metal is key to meeting its 2030 targets. The US is already on the path as it has a high dependence on recycled steel. Scrap accounts for about 70 per cent of the raw metal input into steel production today in America.

Policy actions

Policy planning and early actions can position the steelmaking sector as one of the leading sectors in decarbonisation. Policy actions include

- **Commit to R&D in new technologies** and support large-scale demonstration projects for breakthrough technologies to create evidence base
- **Create a regulatory framework to de-risk investments** in low- and zero-carbon technologies, such as zero-carbon electricity, hydrogen and CCUS, required for green steel production.
- **Promote green public procurement** and develop a market for low- and zero-carbon steel.
- **Encourage steel reuse strategies** that promote steel reuse and scrap recovery in electric arc furnaces as the technology is available at a competitive cost.
- **Embrace just transition strategy** to create green jobs and support affected workers and communities

Figure 14 Green steel initiatives around the world



Chemical Industry

The chemical industry is also classified as a hard-to-abate industry. This industry is the largest industrial consumer of both oil and gas, as well as the largest industrial energy consumer overall. This consumption and production results in just under 1 $GtCO_2$/yr of emissions from the sector, as reported by the IEA. This is because it uses fossil fuel as feedstock not only as a source of energy. Similarly, to the cement and steel sector, the chemical industry is also one of the backbones of developed economies. The chemical industry in Europe and the US contributes to $1.1 trillion to GDP and employs over 1.7 million people.

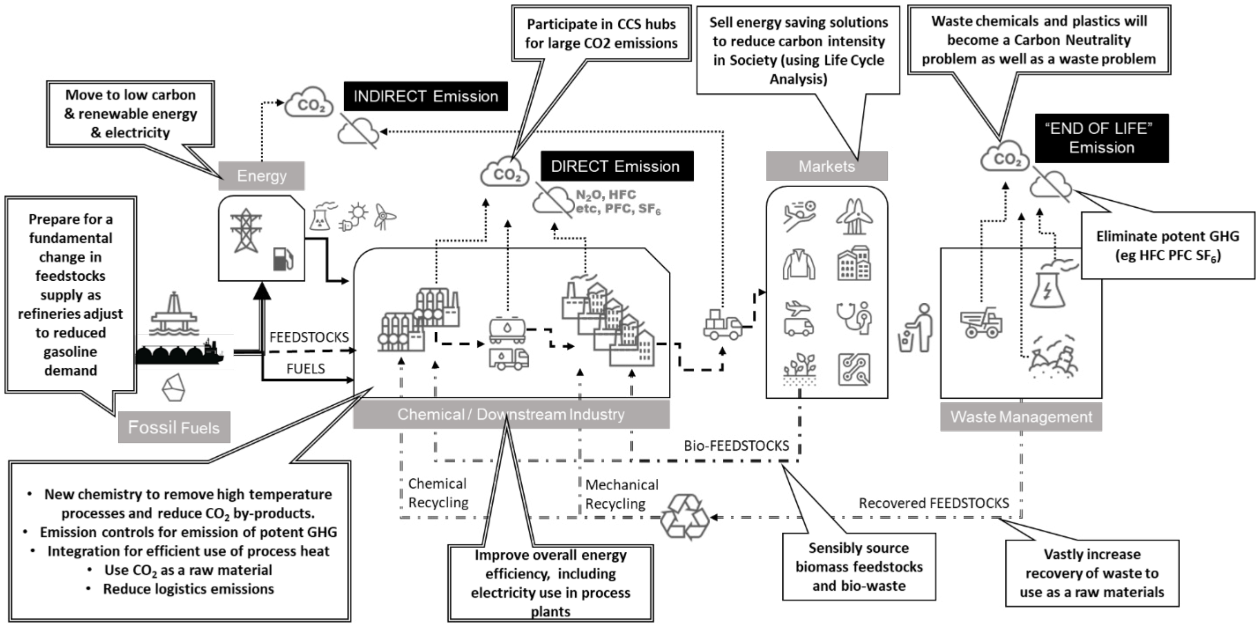
Overview

“Chemical industry” is a generic term that includes high value chemicals such as methanol and ammonia, amongst others. The industry emissions are divided into two types:

Indirect Emissions: result from energy products used in process heat and electricity to run operations as well as from the transport emissions from the logistics of moving chemicals and supplying the market.

Direct Emissions: result from the process of chemical production itself in the factories. (On large chemical sites operating their own electricity plants and steam boilers, some ‘indirect’ emissions become ‘direct emissions’).

Figure 15 Chemical Industry: Circular Economy & Carbon Neutrality. Callouts with thicker lines are most relevant to Carbon Neutrality. Other Call Outs relate to Circular Economy



Source: Decarbonising Chemical Industry, Denis Hicks, 2021

Technology solutions for the carbon neutral cement sector

Industrial energy efficiency: Can be improved by improving existing processes, commercializing new processes, and recycling waste heat. Efficiency also can be improved by the use of digital tools, such as predictive analytics, advanced visualisation, and energy management applications powered by artificial intelligence (AI).

Electrification: Methanol and ethylene can be produced by reacting carbon dioxide and water in an electrochemical reactor, leading to decarbonisation of the production of a much wider range of commodity chemicals. Producing ammonia electrochemically is an example of replacing fossil fuel inputs in the chemical manufacturing process as well, while production of methanol from carbon dioxide provides an opportunity for closing the carbon loop.

Biomass: Chemical conversion processes allow the production of solid, liquid and gaseous biofuels, which can substitute almost any kind of fossil fuel and reduce the associated greenhouse gas emissions.

Carbon capture, use and storage (CCUS): CCUS is the most important contributor to chemical sector decarbonisation, accounting for 38% of overall emissions reductions. CO_2 capture in chemicals is also the highest (14 $GtCO_2$ per annum) owing to several production processes that yield relatively pure streams of CO_2 that are relatively inexpensive to capture.

Hydrogen: Replacing the combustion of fossil fuels with the conversion of CO_2 into synthetic gas using a mixture of hydrogen and carbon monoxide, which could then be used to synthesize methanol, aromatic compounds or other base chemicals such as ethylene, propylene or benzene.

New Material with circular carbon economy: Using sustainable waste or bio-based feedstocks, such as plant or animal fats, sugar, lignin, hemicellulose, starch, corn or alga as a part of circular carbon economy concept can help tremendously in the carbon neutrality of chemical sector. The use of industrial clusters can facilitate a wider deployment of low-carbon technologies at a lower cost. Merging the two concepts of carbon neutrality and carbon circularity will help prevent any inconsistencies and support solving the long-standing problem of the chemical sector.

Case study: Deployment of CCUS in the Chemical Industry

Name: Antwerp@C

Location: Port of Antwerp, Belgium

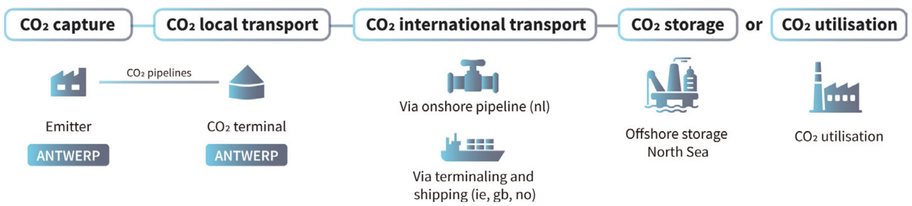
Type of Project: Chemical Cluster

Background: The project is a collaboration between Air Liquide, BASF, Borealis, ExxonMobil, INEOS, Fluxys, Port of Antwerp and TotalEnergies. The aforementioned companies joined forces at the end of 2019 under the name of Antwerp@C, to investigate the technical and economic feasibility of building CO_2 infrastructure to support future CCUS applications. The project has the potential to reduce the CO_2 emissions within the port (18.65 million tonnes greenhouse gas emissions in 2017) by half between now and 2030.

Description: Since Belgium does not have suitable geological strata, international collaboration will be necessary to transport the CO_2 across borders and store it permanently, for example in depleted offshore gas fields. For this purpose, Antwerp@C is investigating the possibilities of transport the CO_2 by pipeline to Rotterdam, Netherlands or by ship to receivers in Norway. Antwerp@C is pursuing two initiatives for cross-border CO_2 transport infrastructure, namely the CO_2 TransPorts project for a pipeline to Rotterdam and the Northern Lights project for transport to Norway by ship.

By the end of 2020, the Antwerp@C project had been awarded a €9m in Connecting Europe Facility (CEF) grant.

Figure 16 CCUS applications in the Port of Antwerp project



***Source**: Port of Antwerp, 2020*

Policy actions

- **Provide incentives for energy efficiency** and emissions reduction to improving catalytic processes by switching to renewable energy and alternative raw materials
- **Encourage electrification of processes** by implementing an energy tax or incentives for system improvement.
- **Move to low carbon** by purchasing renewable energy/low carbon energy.
- **Participate in CO_2 Hubs for CCS** to capture and store emissions especially in processes that yields pure streams of CO_2 that are relatively inexpensive to capture.
- **Develop new technology for the processes emitting the largest amounts of GHG** by using the proper technology to scrub out emissions in older units that are not already fitted with abatement technology and increasing the reliability of this equipment and ensure proper maintenance is critical to its efficiency.

Table 1 Summary of technology solutions for target industries

SECTOR	ENERGY EFFICIENCY	BIOMASS	CARBON CAPTURE, UTILIZATION AND STORAGE	HYDROGEN	ELECTRIFICATION	CIRCULARITY
CEMENT	• Improve energy and waste heat recovery. • Increase the proportion of dry and semi-dry processes. • Innovate and digitalise the processes to optimise the intensity of the kiln flame.	Encourage fuel switching from fossil fuels to biomass with CCS to generate heat and fuel chemical processes.	Deploy CCS technologies to cut CO_2 emissions in both combustion- and process-related emissions. This technology has high potential to decarbonise production of cement.	Invest in the research of hydrogen as a solution of thermal supply. Applying hydrogen can reach high temperatures but it would require extensive modifications to the existing cement kilns design.	Switch to electrified thermal energy supply and ensure that the electricity is generated from low- and zero-carbon technologies, such as the renewable energy or nuclear power.	• Embrace circularity concepts to improve the carbon intensity of materials. • Substitute clinker by cementitious materials.
STEEL	Reduce energy intensity through better plant utilisation, increased equipment effectiveness and recovered waste heat.	Encourage fuel switching from fossil fuels to biomass. Biomass can fuel blast furnaces or replace natural gas in direct reduced iron (DRI) processes.	Deploy CCUS solutions and encourage retrofitting blast furnace and basic oxygen furnace with CCS.	Deploy hydrogen as a fuel to generate heat as well as a reduction agent replacing coking coal. Green hydrogen can be used instead of natural gas to make direct reduced iron (DRI).	Electrify heating to utilise the benefits of rapid heating, fast start up production and high thermal efficiency.	Encourage circularity solutions by using scraps in electric arc furnaces or fossil carbon replacements like waste wood.
CHEMICALS	• Improve existing processes and encourage technologies that allow recycling of waste heat. • Deploy digitalisation to improve energy efficiency across the processes.	Encourage chemical conversion processes that can substitute fossil fuels and reduce the carbon footprint.	Deploy CCS technologies to improve the carbon footprint of the chemical sector.	Encourage production of synthetic fuels through the deployment of hoyden and carbon monoxide.	Apply electrochemical reactors to produce methanol and ethylene.	Deploy sustainable waste or bio-based feedstocks in the chemical processes.

4. Circular Carbon Economy and Industrial Clusters

The circular carbon economy is an integrated and inclusive approach to transitioning toward a more comprehensive, resilient, sustainable, and climate-friendly industrial sector that supports and enables sustainable development. The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended.

Industrial clusters are groups of companies and industries, often representing supply (e.g. power generation) and demand (e.g. cement, steel, chemicals), physically located in the same area. Notable examples include Humber (UK), Rotterdam (Netherlands), and Chemelot Industrial Park (Netherlands). Another good example is the state-of- the-art Northern Lights (Norway), which provides the infrastructure for CCUS activities to the industrial clusters in Europe. While sector specific decarbonisation initiatives are extremely important, there is also an opportunity to leverage the benefits of co-location to reduce CO_2 and other emissions.

Industrial clusters have been around for over 100 years and act as economic growth engines for countries. They take advantage of co-location to enhance competitiveness through enhanced resource efficiency, shared logistics and shared knowledge. Now there is an opportunity to use that co-location to accelerate their path to carbon neutrality, while maintaining competitiveness.

Some Industrial clusters may build shared electrification infrastructure (e.g. microgrids) and take advantage of co-location to fully utilise opportunities for demand optimisation. For heavy industry clusters, it may become more economically viable to build shared CCS infrastructure and find uses for captured CO_2 within the cluster. The cluster approach also encourages the shared hydrogen infrastructure, leveraging of the internal supply and demand hydrogen markets and avoiding the need to invest in long-distance infrastructure.

While sector specific decarbonisation is essential and must continue, it is necessary to simultaneously accelerate the transition of industrial clusters towards net zero aided by the carbon circular economy. Taking a systemic approach to accelerating the transition of industrial to carbon neutrality will not only help reduce emissions, but also improve economic benefits in terms of job creation, higher wages, and increased competitiveness.

Embracing an industrial cluster approach enables collaboration between different stakeholders. The stakeholders include governments, industries and financers. The weight of policy support falls on the governments in terms of developing economical models to support the low-carbon infrastructure as well as support in R&D investment across industry and academia. A broad-based collaboration is needed across energy-intensive industries to develop commercial models and unlock private and public financing for development of the technologies and solutions to reach the net-zero targets by mid-century.

5. Examples from the UNECE and ESCWA Regions

The Humber Project (United Kingdom)

Location: Humber, United Kingdom

Background: The Humberside Industrial Cluster is one of 4 priority industrial clusters in the UK. It is the UK's largest cluster by industrial emissions (approx. 12.4 million tonnes of CO_2 being released per annum) and is working towards being a net-zero cluster by 2040. Its primary industries include steel, chemicals, cement and refineries. There are 4 main projects in the Humberside Cluster accelerating its path to net zero: Zero Carbon Humber, Humber Zero, Gigastack, and Northern Endurance Partnership.

Project Description: Zero Carbon Humber is a coalition of 12 entities (including supply side and demand side companies) collaborating on the mission to achieve net zero in Humber by 2040. The Zero Carbon Humber project is planning on the development of shared carbon capture infrastructure connecting emitters to an offshore CO_2 storage site (being developed through the Northern Endurance initiative). In addition, the project partners will produce low carbon hydrogen and transport to users within the cluster using shared hydrogen infrastructure. In the longer term, the project will also produce green hydrogen using offshore wind and electrolysers to be transported through this infrastructure. Simultaneously, opportunities for enhanced energy efficiency and circularity opportunities are being explored between the partners.

Solutions for carbon-neutral industries

Energy efficiency

Biomass

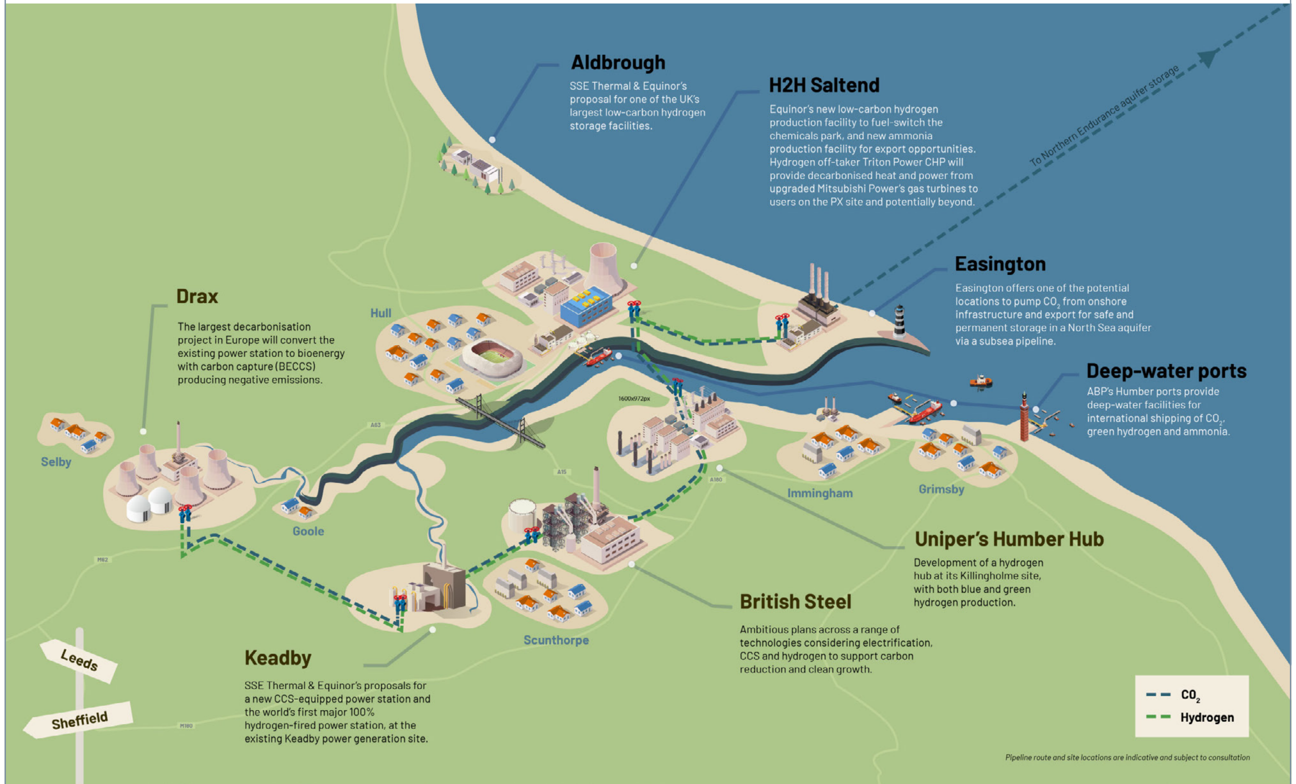
CCUS

Hydrogen

Electricification

Circularity

Figure 14 Schematic of Humber Group



Source: Zerocarbonhumber, 2021

The Port Rotterdam Port (The Netherlands)

Location: Rotterdam Port, South, Holland, Netherlands

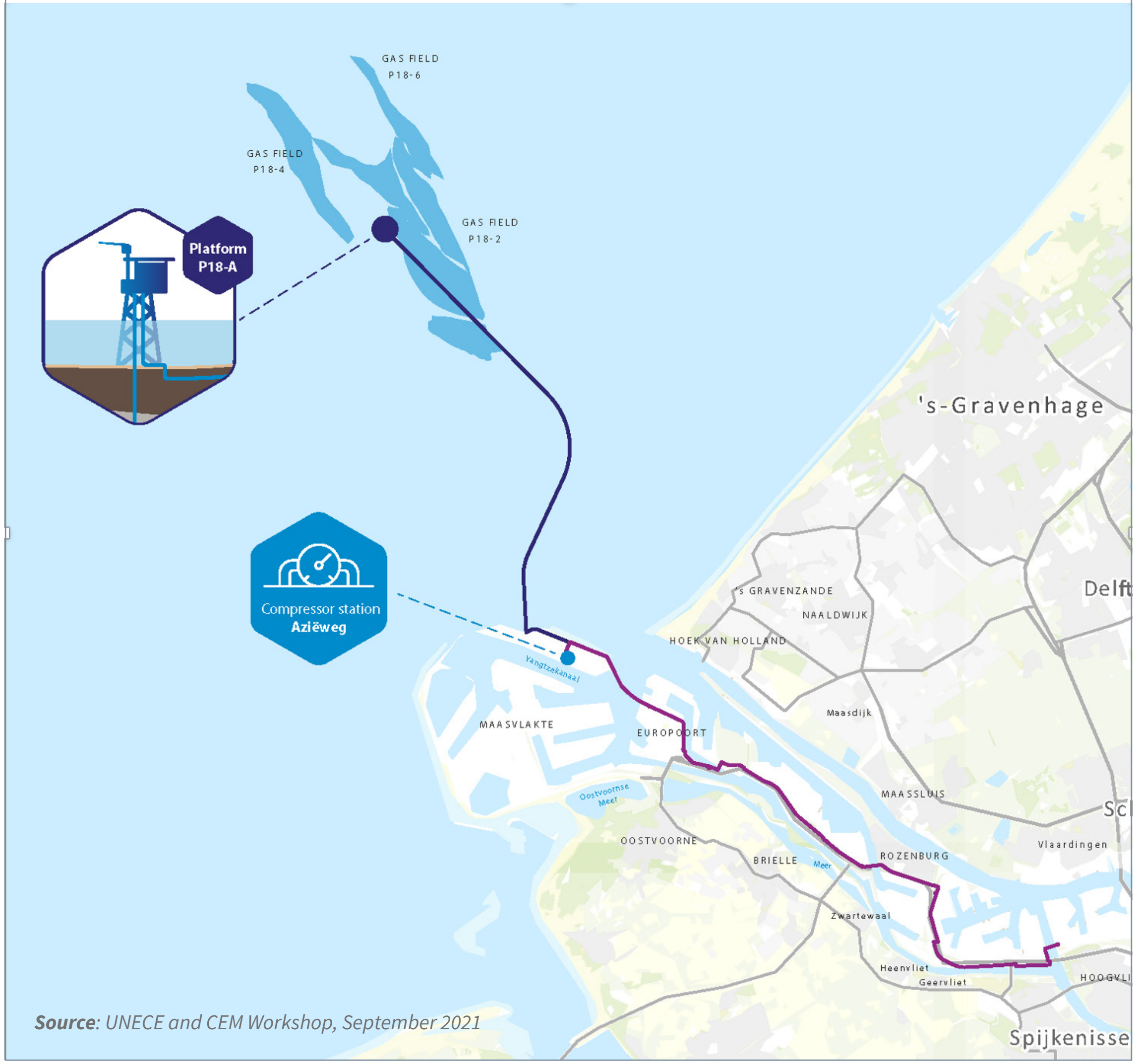
Background: The Port of Rotterdam CO_2 transport hub and offshore storage (Porthos) project is an innovative carbon capture utilisation and storage (CCUS) project being prepared near port Rotterdam in South Holland, Netherlands. It is proposed to be developed as an open-access project to capture, transport, and store the CO_2 produced from refineries, chemical, and hydrogen plants in the Port of Rotterdam area in a depleted gas fields in the North Sea. Expected to commence operations in 2023, the Porthos CCUS project will be capable of storing approximately 2.5 million tonnes (Mt) of CO_2 a year.

Project Description: The port's industrial cluster is made up to a great extent of companies operating in the energy and CO_2-intensive sectors of oil refining, petrochemical manufacturing, and power and steam generation. The capital expenditure for this project is around 450-500 million Euros. The CO_2 captured in this cluster is 16% of the national emissions, this CO_2 will be stored in a depleted offshore gas field. The total capacity of the field is 37 Mt and the storage rate target is decided to be 2.5 Mt/year. CO_2 is captured by the customers of port Rotterdam including Air Liquide, Air Products, ExxonMobil, Shell. The captured CO_2 is transported via pipeline infrastructure provided by: Port of Rotterdam, EBN, and Gasunie. The planning for the project started in 2017 and it is planned to be operational by mid-2024.

Solutions for carbon-neutral industries

Energy efficiency | Biomass | CCUS
Hydrogen | Electricification | Circularity

Figure 15 Schematic of Port Rotterdam



Source: *UNECE and CEM Workshop, September 2021*

Westküste 100 project (Germany)

Location: Schleswig-Holstein, Germany

Background: The Westküste 100 project is focused on making the industrial processes, aviation, construction and heating more sustainable in the future. The 'Westküste 100' project models a regional hydrogen economy on an industrial scale. The conditions on Northern Germany's west coast are ideal for this: A strong wind energy region meets innovative companies that want to contribute to reaching the crucial climate targets. The project has a total budget of 105 million dollars (89 million euros).

Project Description: The consortium of the Westküste 100 project includes Holcim Germany, OGE, Stadtwerke Heide, Thüga and thyssenkrupp Industrial Solutions. These companies will work with the Region Heide Development Agency and the Fachhochschule Westküste (West Coast University of Applied Sciences). Within the five-year project period, an electrolysis plant with a capacity of 30 megawatts is to be installed initially. It will provide insights into the operation, maintenance, control and grid serviceability of the plants in order to transfer them to the next scaling step. This could, for example, be an electrolysis plant in the order of 700 MW, for which the electricity is generated by an offshore wind farm.

Solutions for carbon-neutral industries

Energy efficiency

Biomass

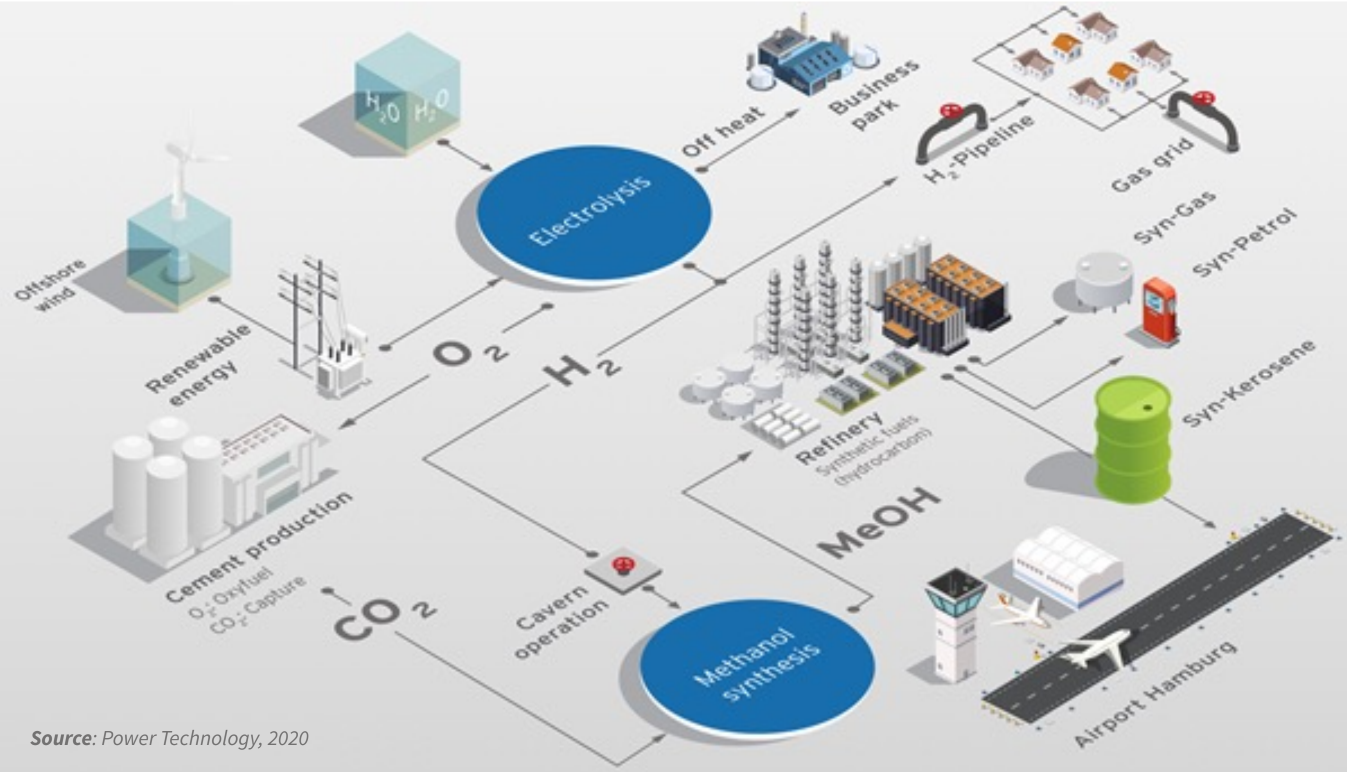
CCUS

Hydrogen

Electricification

Circularity

Figure 16 Schematic of Westküste 100



Source: *Power Technology, 2020*

Al Reyadah Project

Location: Abu Dhabi, UAE

Background: Al Reyadah is the world's first fully commercial carbon dioxide (CO_2) facility for the iron and steel industry, and the first commercial-scale carbon capture, utilization, and storage (CCUS) facility in the Middle East. The project was initiated in 2009, launched as a joint venture between Abu Dhabi National Oil Company (ADNOC) and Masdar in 2016 and full ownership was transferred to ADNOC in 2018.

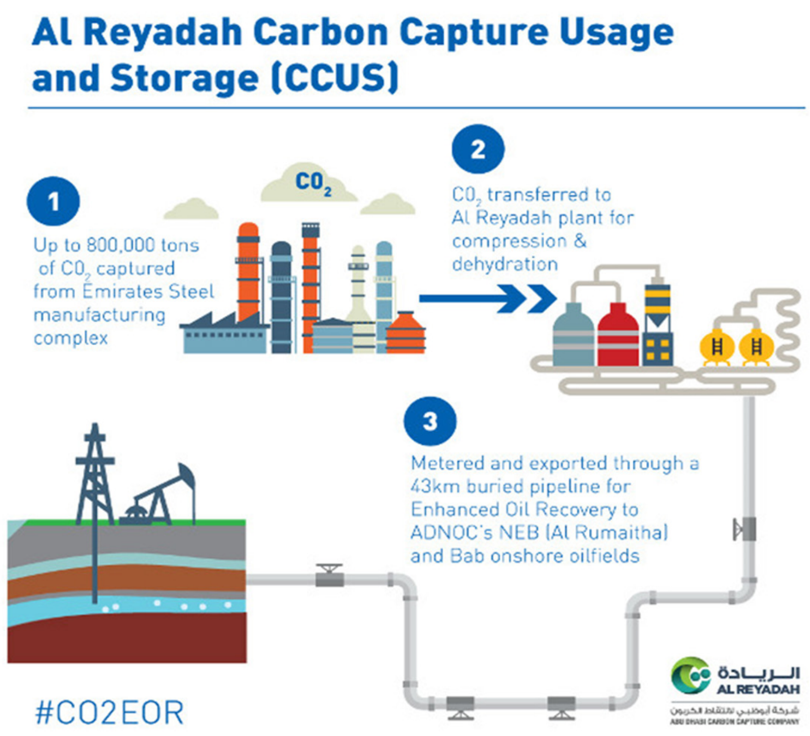
Project Description: The US$122 million project captures up to 800,000 tonnes of CO_2 from the Emirates Steel Industries (ESI) located in the Mussafah industrial area on the outskirts of Abu Dhabi city, UAE. CO_2 is captured from a Direct Reduced Iron (DRI) plant, using Aqueous monoethanolamine (MEA) absorption/recovery system leading to CO_2 rich (>99%) waste stream. Thereafter, CO_2 is compressed and dehydrated using the world's largest high-pressure compressor unit, which takes 41 million standard square feet per day of dry CO_2, it into a state where it acts like a liquid. It is then transported through a 43 km buried pipeline. CO_2 is then injected for enhanced oil recovery into Rumaitha and Bab onshore oil fields. The CO_2 is thereafter stored at a secure location several kilometers below the earth's surface.

Solutions for carbon-neutral industries

Energy efficiency | Biomass | **CCUS**

Hydrogen | Electricification | **Circularity**

Figure 17 Al Reyadah infographic



__Source__: Mena Herlad (https://www.menaherald.com/en/economy/energy/mena%E2%80%99s-first-carbon-capture-utilisation-storage-ccus-project-now-stream-abu-dhabi)

NEOM Hydrogen

Location: NEOM, Tabuk, Saudi Arabia

Background: The NEOM Green Hydrogen Project is the world's largest utility scale, commercially-based hydrogen facility powered entirely by renewable energy. A joint venture between NEOM, Air Products and ACWA Power, the project is based on proven, world-class technologies that will include the innovative integration of a combined capacity of over four gigawatts of renewable power from solar, wind and storage.

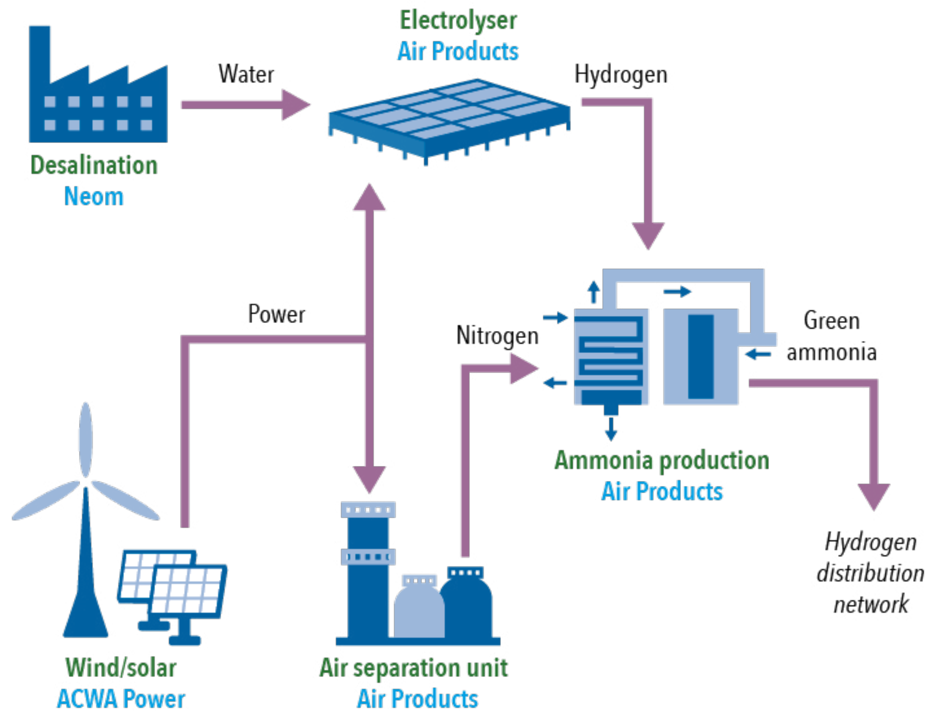
Project Description: When commissioned in 2026, it will produce 650 tons per day of hydrogen by electrolysis using thyssenkrupp technology; production of nitrogen by air separation using Air Products technology; and production of 1.2 million tons per year of green ammonia using HaldorTopsoe technology. When complete, the project will mitigate the impact of 3 million tons of carbon dioxide per year.

Solutions for carbon-neutral industries

Energy efficiency | Biomass | CCUS

Hydrogen | Electricification | Circularity

Figure 18 Schematic of NEOM Hydrogen



Source: https://www.globalwaterintel.com/global-water-intelligence-magazine/21/7generalneom-jumps-on-the-new-energy-train-with-5bn-hydrogen-from-desalination-project/

HeidelbergCement Morocco

Location: Safi, Morroco

Background: Morocco's second largest cement plant in Safi, HeidelbergCement's largest in the country,received an adjacent algae pond. Environmental innovator (Omega Green) has estimated the pond's rate of carbon dioxide removal at 80-100t/yr.

Project Description: In the microalgae project at HeidelbergCement's Safi cement plant in Morocco, the algae are produced by sunlight + CO_2 released from the kiln during cement production. One kg of algae uses two kg of CO_2 during photosynthesis. The microalgae meet the quality criteria for animal feed and aquaculture, which we had already verified in previous R&D projects in Sweden, Turkey and France.

Solutions for carbon-neutral industries

Energy efficiency

Biomass

CCUS

Hydrogen

Electricification

Circularity

Figure 19 **Schematic of HeidelbergCement**

Source: *HeidelbergCement Blog*

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