GASSNOVA

Report

Technology status for CO_2 capture, transport and storage

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Hans Jørgen Vinje

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Abbreviations and definitions

bar	Unit of measure for pressure
Bcm	Billion cubic metres
BioCCS (BECCS)	Bioenergy with Carbon Capture and Storage
bn	Billions
$CaCO_3$	Calcium carbonate
CCS	CO_2 capture and storage
CCS chain	Whole value chain for removal of CO_2 from industrial waste gases, followed by transport and geological storage of CO_2
CCUS	Carbon capture, utilisation and storage
CFZ	Controlled Freeze Zone
CLC	Chemical looping combustion
CTS	Clean Technology Scenario
CO_2	Carbon dioxide
CO_2-eq	CO_2 equivalents
CO_2-EOR	Carbon Dioxide Enhanced Oil Recovery
CRI	Commercial Readiness Index
CSLF	Carbon Sequestration Leadership Forum
EIIs	Energy Intensive Industries
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
EU	European Union
FME	Norwegian Research centres for environmentally friendly energy
GCCSI	Global CCS Institute
H_2	Hydrogen
H_2S	Hydrogen sulphide
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
Km	kilometres
Kwh	Kilowatt-hours (one kilowatt-hour)
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
m^3	Cubic metres
mn	Millions
MPE	Norwegian Ministry of Petroleum and Energy
Mt	Megatonnes (= million tonnes)
MW	Megawatts
Mwh	Megawatt-hours
NCCS	Norwegian CCS Research Centre
NGO	Non-governmental organisation
NH_3	Ammonia
NTNU	Norwegian University of Science and Technology
OD	Norwegian Petroleum Directorate
OECD	Organisation for Economic Cooperation and Development
pct	Per cent
RTS	Reference Technology Scenario
SMR	Steam methane reforming
SSB	Statistics Norway

TCM	Technology Centre Mongstad
TRL	Technology readiness level
TWh	Terawatt-hours
UiO	University of Oslo
WEI	World Energy Investment
WEO	World Energy Outlook

1 INTRODUCTION

CO_2 capture, transport and storage (CCS) is a climate tool to reduce CO_2 emissions into the atmosphere. CCS can be used to reduce emissions in both the quota and non-quota sectors and within a wide range of different industries. CCS also comprises a chain of different technological solutions that have to be established in order to retain captured CO_2 from the emission point until it is stored. This report provides an overview of different sectors and describes how CCS as a climate tool can be used. The report also provides an overview of the technological maturity of various capture technologies, transport solutions and storage options. Finally, it describes the innovation cycle within CCS.

1.1 BACKGROUND

The purpose of this report is to present a technology status for the various elements within the CCS chain and a discussion of how CCS can be used in different sectors. The report has been updated with information since the 2015 concept selection report from the Norwegian Ministry of Petroleum and Energy's (MPE) and is appended to the updated socio-economic analysis for the Norwegian CCS full-scale project.

1.2 SUMMARY

The IEA's World Energy Outlook (IEA WEO 2019) estimates that CCS will contribute 9% of the energy-related emission-reduction measures needed to achieve their sustainable development scenario. In this scenario, CCS is equally divided between measures in the power sector and in manufacturing. The IEA's WEO emphasises that CCS will have to play a significant role in managing emissions from coal and gas power plants currently being built because of the long life of these plants and the limited room for emissions in a 2050 perspective. New power plants in Asia and the USA are particularly highlighted in this context.

The manufacturing sector accounts for 21% of global emissions. The sector expects an increase in production volume to meet a general increase in demand. In Norway, industrial emissions in the quota sector account for 23% of the country's emissions. In 2016, Norwegian Process Industries presented "The Norwegian Process Industries Roadmap - 2016". Their mapping of types of emission reduction measures in manufacturing highlights CCS and BioCCS as key tools. Two-thirds of the measures needed to become climate-neutral in 2050 are related to CCS. Some industries have few alternatives to CCS for complete decarbonisation, as CO_2 is generated as a by-product from the raw materials. Norwegian industry is broadly representative of global manufacturing. There are two exceptions; the production of steel is less than the global average while the proportion of ferroalloys produced is greater. Learning effects from the implementation of CCS on Norwegian industry will therefore have great potential for sharing internationally.

Hydrogen (H_2) is the raw material and energy carrier for a variety of industrial processes and can become an alternative to carbon-rich input substances in a number of sectors e.g. manufacturing, transport, power generation, heating of buildings and household use. The IEA's WEO points to hydrogen and biomethane as important energy carriers with a low carbon content. They also point to the potential of leveraging the world's gas distribution network, which has double the capacity for energy distribution relative to the world's electricity grid. H_2 with a low carbon footprint can be produced, for example, from renewable energy by electrolysis of water, or reforming natural gas with CCS. Both production methods can have similar energy consumption levels and CO_2 footprints when used.

Processing industry is often co-located with other industries in business parks or linked together in other types of cluster. When CCS is implemented, positive synergies can be triggered by the exchange of product and energy flows suitable for various capture technologies and shared post-processing facilities for CO_2.

In other words, the analyses show that CCS can be an important tool in many different sectors and industries if CO_2 emissions are to be significantly reduced or removed altogether.

From a technological perspective, all parts of the CCS chain – capture, transport and storage – are sufficiently mature to be realised at full scale. As early as the 1930s, a process for capturing CO_2 using amines was patented in the United States. In Norway, Yara has been capturing and transporting CO_2 by ship and tanker truck for several years, for delivery to the food industry. Equinor also has several decades of experience in capturing, transporting and storing CO_2 offshore. Nevertheless, the underlying solutions in the CCS chain have significant development potential.

For CO_2 capture, there are five main types of technology: CO_2 capture with liquids, solids and membranes, combustion with pure oxygen, and precipitation of solid CO_2 at low temperatures. There is constant development within these technology groups. The development focuses on reducing costs, understanding and improving knowledge of health, environmental and safety aspects, and reducing technological risk.

The different types of capture technology can initially be used in all industries that produce CO_2 emissions. The choice of technology will be governed by the specific features of the different industries with respect to CO_2 concentration at the emission point, the available energy to power the capture plant and other site-specific conditions. Whether the CO_2 capture facility is to be retrofitted or integrated into the original design of an industrial process will also determine the choice of technology.

Transport of CO_2 is happening on a large scale and has a high degree of technological and commercial maturity. CO_2 is currently used as a raw material in various industries such as enhanced oil recovery (CO_2-EOR), in the food industry and for other industrial purposes. CO_2 is transported to consumers in pipelines, on ships, by tanker truck and by rail. The biggest market for CO_2 is for CO_2-EOR in North America, where the CO_2 is mainly transported in onshore pipelines. Transport of CO_2 by ship to ports and onward by tanker truck is common in the food industry in Europe. Developments in CO_2 transport focus on developing more cost-effective solutions at larger volumes, better modelling and simulation tools and improvements in material technology.

CO_2 can be stored deep underground in porous rocks such as sandstone. CO_2 storage uses natural reservoirs such as oil and gas fields or saltwater aquifers that have natural geological barriers to "seal" the porous injection zone. CO_2 used for enhanced oil recovery (CO_2-EOR) can be regarded as permanently stored because most of the CO_2 will remain in the reservoir when hydrocarbon production ceases. A large part of the research and development work is aimed at developing technology elements to be used in several of these types of storage, such as monitoring technology and simulation models for CO_2 distribution in the reservoir formation, material technology, well components and safety measures in case of leakage.

Although the solutions chosen in the Norwegian full-scale project are technologically mature, a full-scale demonstration is considered very important because it can facilitate further commercialisation and maturation of new solutions.

Norway has more than 20 years of experience in CO_2 handling and Europe's only two operational CO_2 storage sites are Norwegian. Over time, the Norwegian authorities have focused on capturing, transporting and storing CO_2 and have built up solid expertise covering the whole the research and development chain, as well as funding major research infrastructure for CCS.

The industrial use of the solutions is in many ways the "fuel" that drives an innovation system. Without further commercial maturation, technology development will miss out on the potentially large cost reductions triggered by further commercial projects.

This cost reduction often starts with feedback loops in the innovation system that provide for more targeted research and development to optimise the technology. The Norwegian demonstration project will provide a basis for various industries and players, and so stimulate technological development. This could help to trigger further maturation for existing and next-generation technology.

The players in the Norwegian innovation system for CO_2 handling are supporting the implementation of the Norwegian full-scale project. The project will be a useful learning platform for further development of CCS.

2 Potential for CCS as a climate tool in various economic sectors

According to the IEA WEO (2019), global emissions of CO_2 are steadily increasing. In 2018, emissions related to energy production came to 34 billion tonnes of CO_2 and the emission rate increased by 2.3% after a temporary levelling off in 2014-16. There are many ways to reduce CO_2 emissions and multiple solutions may be used for different emission sources. According to the IEA WEO, CCS will account for 9% of the measures needed to realise their scenario for sustainable development in energy production. In this scenario, CCS is equally divided between measures in the power sector and in manufacturing.

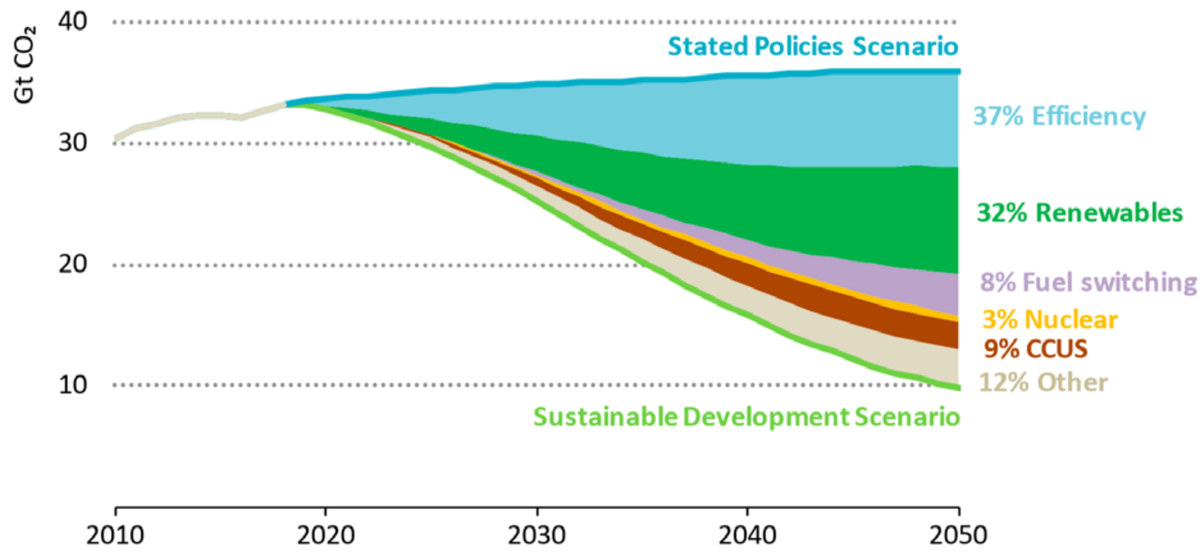


Figure 1: Energy-related CO_2 emissions and emission reduction measures against the Sustainable Development Scenario. Source IEA WEO 2019

In addition to emissions related to energy production, there are significant emissions from other sectors. The figure below shows the breakdown of greenhouse gases from different economic sectors.

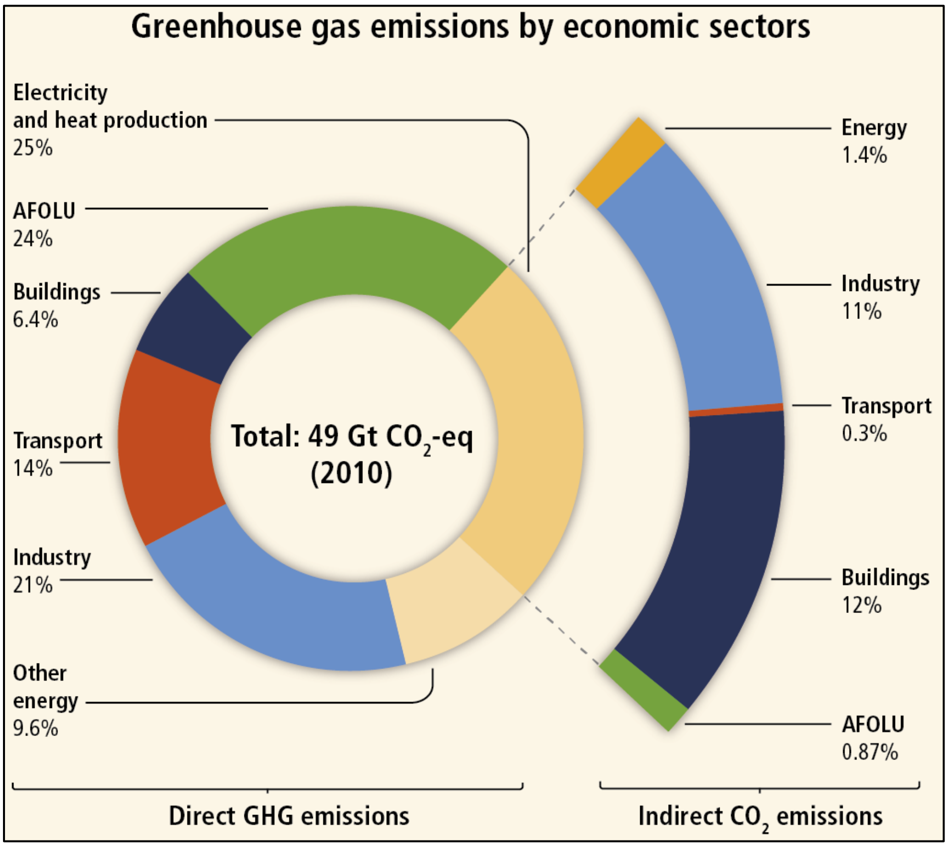


Figure 2: Global greenhouse gas emissions by economic sector. Source IPCC AR5 Climate Change 2014

CCS is a tool for CO_2 reduction which can be used by several economic sectors. This report focuses on CCS as a climate tool for various industries in the manufacturing sector, hydrogen and energy production. In the manufacturing sector, we focus on direct CO_2 emissions from production, not the indirect emissions from the source of their energy consumption, which are included in the analysis of the energy sector.

2.1 CO_2 emission sources in Norway

Norwegian greenhouse gas emissions amounted to 53.1 million tonnes of CO_2 equivalents in 2018 (source: SSB). This amounts to about 0.1 per cent of the world's greenhouse gas emissions. In 2018, 83.4% of greenhouse gas emissions in Norway were CO_2, and the ratio of CO_2 emissions to other greenhouse gases is steadily increasing as emissions of the latter have decreased.

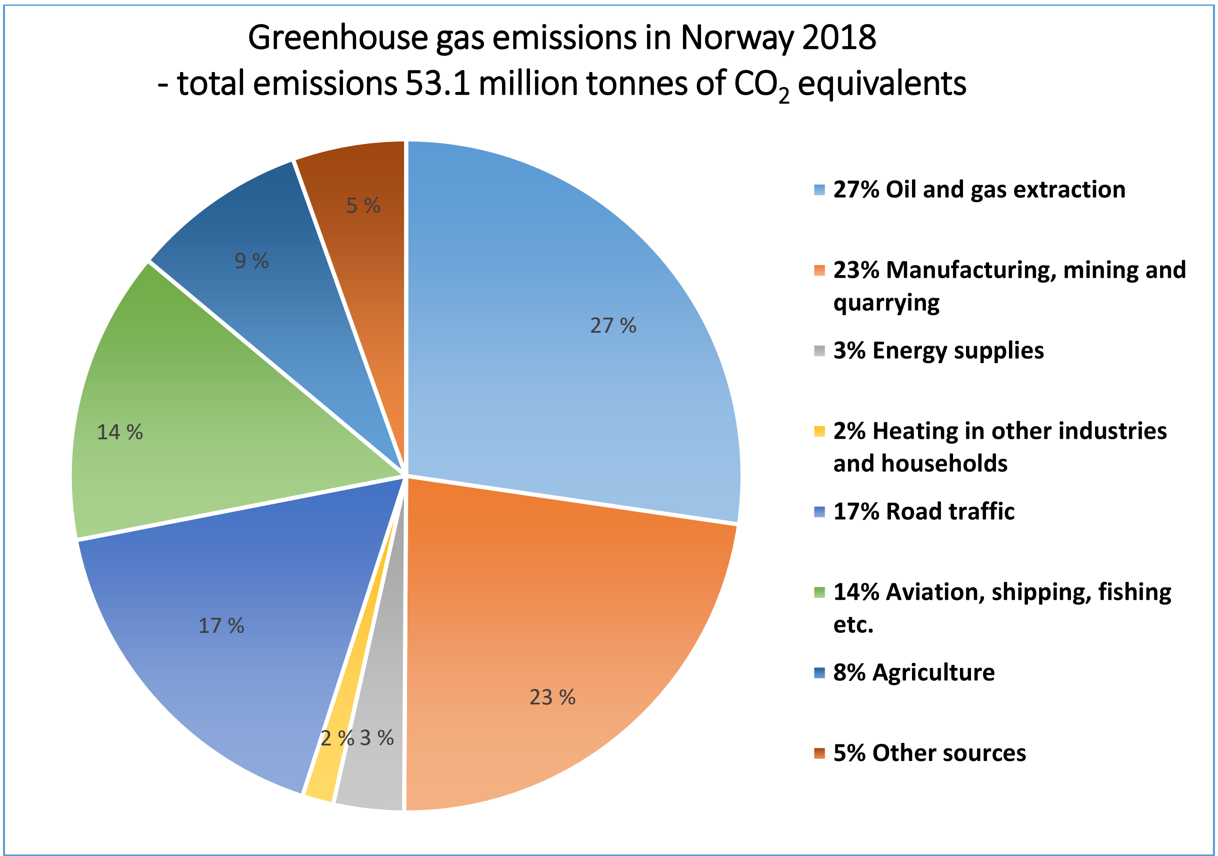


Figure 3 Greenhouse gas emissions in Norway in 2018. Source: SSB (https://www.ssb.no/natur-og-miljo/statistikker/klimagassn/aar-endelige)

The breakdown of emission sources in Norway differs significantly from the global average in that Norway has very low CO_2 emissions from the energy sector because of the large proportion of hydropower. The share of emissions from manufacturing is relatively close to the EU average and the global breakdown, but the composition of the manufacturing sector is different. Norway has low emissions from iron and steel production compared to other countries, and relatively large emissions from production of other metals such as aluminium, silicon and ferroalloys.

Figure 4 shows the breakdown of emissions from different processing industries in Norway.

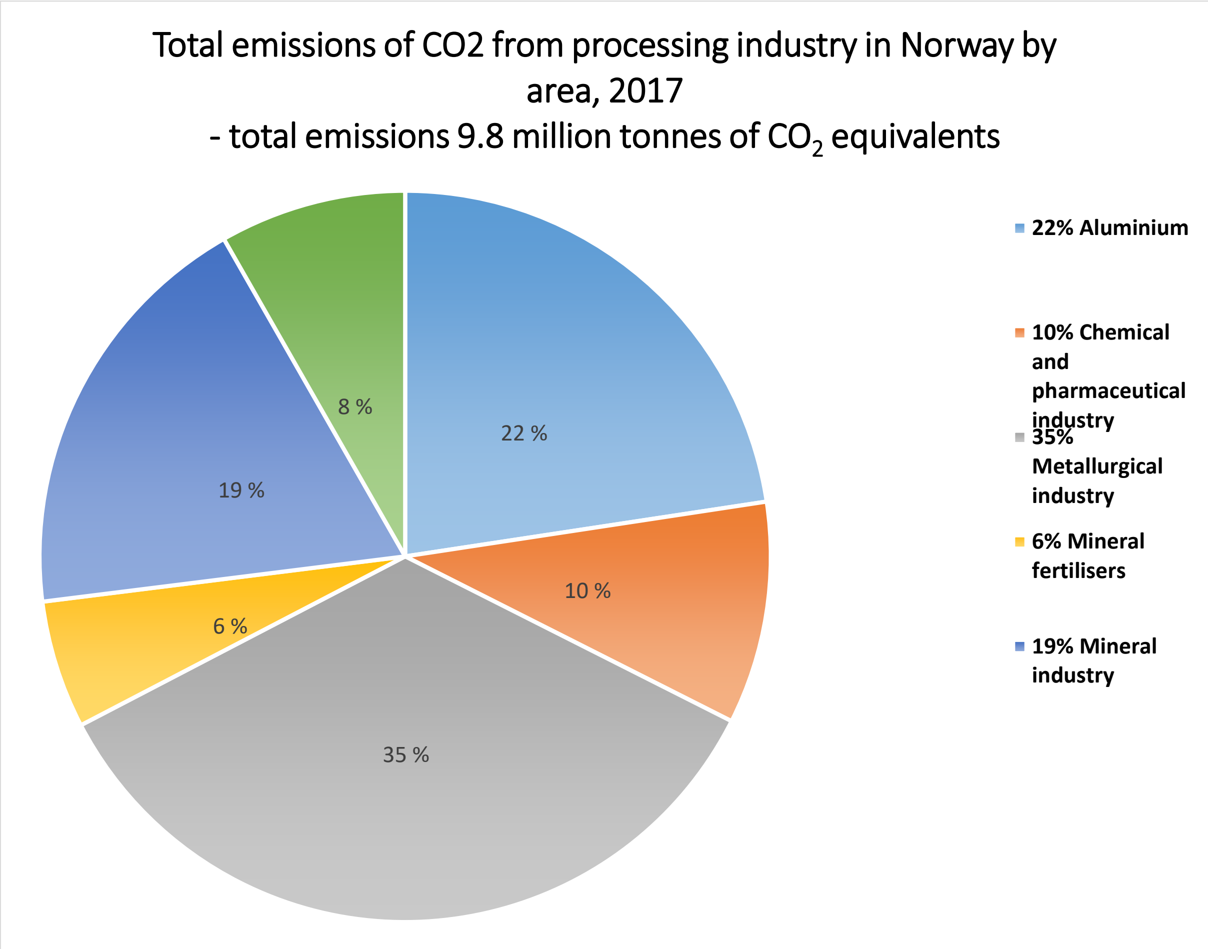


Figure 4: Breakdown of emissions from processing industry in 2017 (CO_2 from bio-based sources counts zero in the greenhouse gas accounts but is included here to show total emissions of CO_2). Source SSB (https://www.ssb.no/natur-og-miljo/statistikker/klimagassn/aar-endelige)

2.2 CO_2 capture as a climate tool for different sectors

The development of technologies for CO_2 capture has been based on well-known separation technology for gases. Since the 1970s, the technology has been adopted in USA from highly concentrated CO_2 sources for use in enhanced oil recovery. The technology is also used in gas processing around the world and in connection with LNG production. Further development of the technology for use as a climate tool has long focused on CO_2 from fossil power plants, especially using amine-based "post-combustion" processes. These technologies are now almost market-ready, although further technological improvement could reduce uncertainty and costs. CO_2 emissions from other types of industry, such as cement, steel mills and bioenergy, have received growing attention in recent years. This has brought specific factors related to the emission source to the fore in the development and selection of capture technology. There is also a focus on cost reductions from implementing CCS through synergies with nearby companies.

The sub-sections below discuss aspects of CO_2 capture in processing industry, hydrogen production and power generation.

2.2.1 CO_2 capture in processing industry

For several industries, CO_2 handling will be an important alternative to reducing CO_2 emissions. This is because their CO_2 emissions are based on the actual raw material used in their end product. For example, 60% of emissions from the cement industry come from turning limestone into cement. 50% of emissions from steel production come from oxide reduction using carbon, and 70% of emissions from the production of mineral fertilisers come from the process itself. The IPCC (2014b) estimates that around 21% of the necessary cuts in greenhouse gas emissions in manufacturing need to be made by CO_2 handling if the two-degree target is to be achieved.

Several types of processing industry can also reduce their CO_2 emissions by using hydrogen in their industrial processes. This hydrogen must be produced with a low CO_2 footprint to get the desired climate effect. The next section specifically discusses the production of emission-free hydrogen.

In May 2019, the IEA presented its report on “Transforming Industry through CCUS” (IEA CCUS 2019), highlighting CCUS as one of the most cost-effective means of reducing emissions. They predict that CCUS will account for 24% of cumulative emission reductions in their “Clean Technology Scenario (CTS)” up to 2060, against their “Reference Technology Scenario (RTS)”.

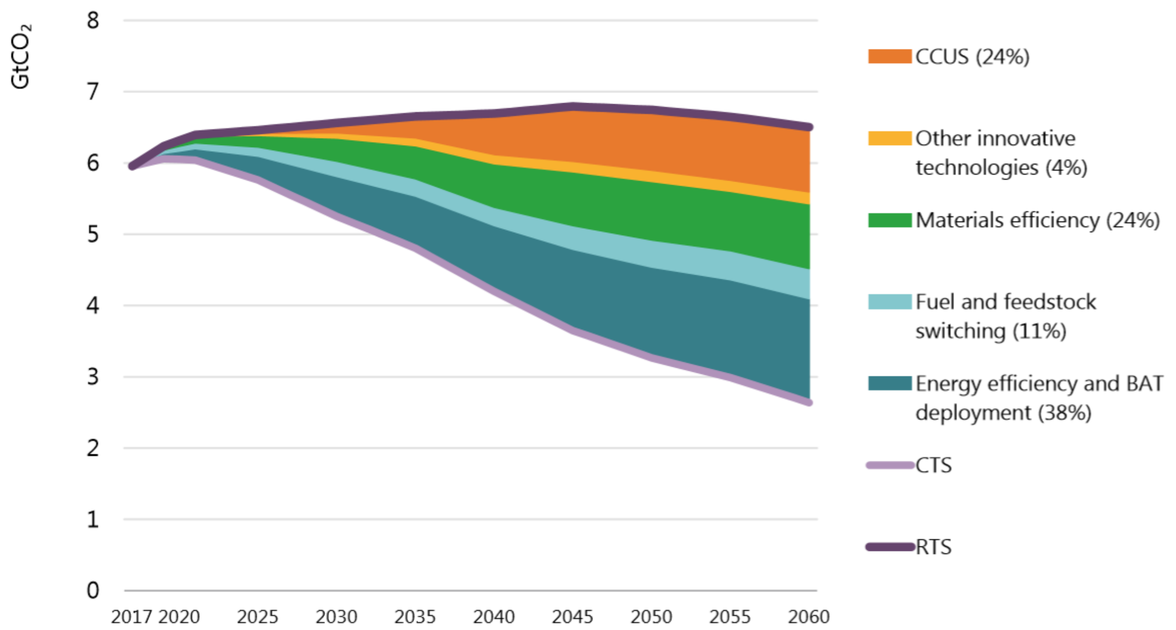
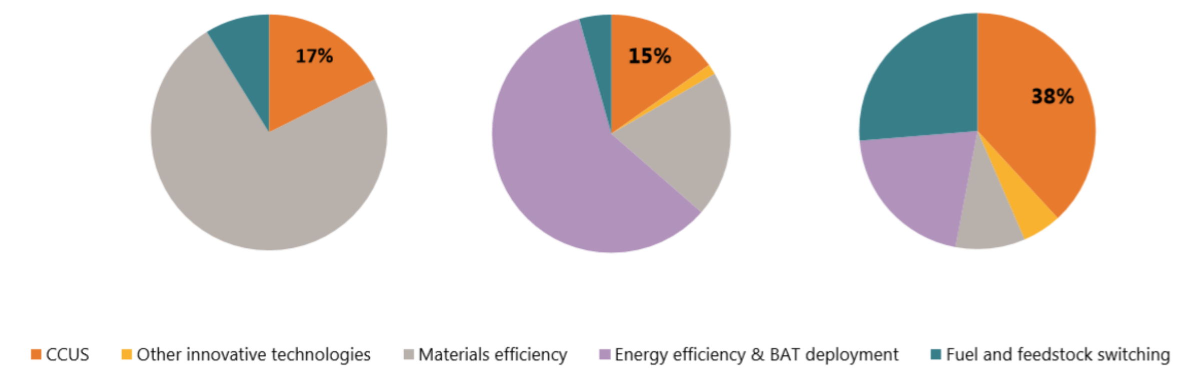


Figure 5: Emission reductions for “key” industry segments (cement, iron/steel and chemical industries) with different emission reduction measures. Source: IEA CCUS 2019

The different sectors will have different degrees of CCUS implementation, where CCUS in the chemical industry could account for as much as 38% of cumulative emission reductions in the IEA CCUS 2019 “Clean Technology Scenario (CTS)”.



Notes: Materials efficiency includes opportunities that exist throughout value chains, such as designing for long life, lightweighting, reducing material losses during manufacturing and construction, lifetime extension, more intensive use, reuse and recycling, and in the case of cement, it notably includes reduction in the clinker-to-cement ratio; BAT = best available technology.

Figure 6: Global CO_2 reductions in the cement, iron/steel and chemical industries by emission reduction measures in the "Clean Technology Scenario (CTS)". Source: IEA CCUS 2019

In the spring of 2016, Norsk Industri presented its "Roadmap for processing industry 2016" for CO_2 reductions in Norwegian processing industry as input to the government-appointed expert committee for green competitiveness. Among other things, the roadmap made a survey of various measures industry could take to reduce CO_2 emissions from manufacturing and create products with a lower CO_2 footprint, in order to enhance the competitiveness of Norwegian industry in a future low-carbon society. About 2/3 of the measures for CO_2 reduction are CCS or BioCCS (BECCS). See figure.

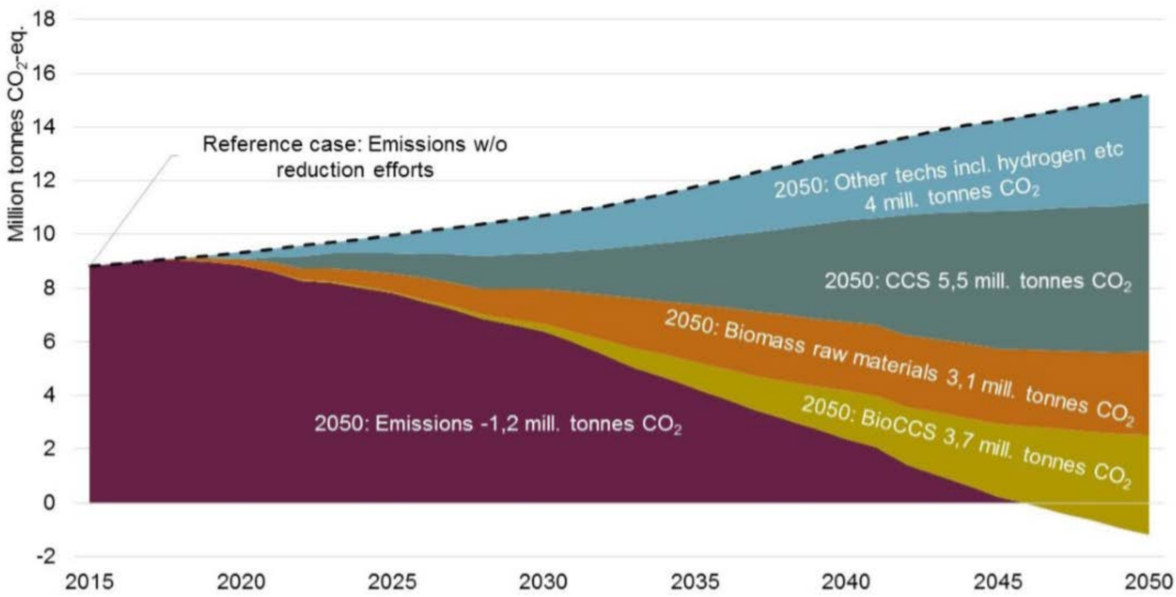


Figure 7: Emissions and emission reductions by type compared to reference path without any measures. Source: Norsk Industri - Roadmap for processing industry 2016

Note on figure: The terms CCS and BioCCS differ only in the source of the CO_2. CCS is used if the CO_2 comes from fossil or mineral sources, and BioCSS where it comes from biogenic sources. There are no fundamental technological differences on the solutions included in CCS and BioCCS.

Following this roadmap, Process 21 (https://www.prosess21.no/) has been established to provide strategic advice and recommendations on how Norway can best make the move towards minimal emissions from processing industry up to 2050 while also facilitating sustainable growth in processing industry during this period. A CCS expert group has been established as part of this work.

Support has been provided through the CLIMIT programme for several industry clusters in recent years. These have received grants to evaluate which capture technologies could be suitable for their emissions and identify possible synergies from implementing common components for CO_2 handling (e.g. shared compression equipment and stores for shipping out CO_2). These industry clusters represent the biggest industrial emission points in Norway.

Information about the projects will be posted on climit.no.

Over the past two years, there have been several reports on how industrial emissions can be reduced, and the role of CCS in this perspective.

McKinsey & Company:

- Decarbonization of industrial sectors: the next frontier. June 2018.

Carbon Sequestration Leadership Forum (CSLF):

- Carbon Capture, Utilisation and Storage (CCUS) and Energy-Intensive Industries (EIIs). September 2019

The factors discussed in these reports include:

The most affordable sources for early CCS chains are industrial processes that produce exhaust gas with a high CO_2 concentration, lowering the cost of CO_2 capture. According to the IEA WEO, more than 500 million tonnes of CO_2 are released globally from such sources. Methanol and ammonia production are examples of CO_2 emissions with high concentrations from parts of the processes. The production of bio-based fuels has emissions of almost 100% pure CO_2. In the metal industry, the exhaust gas may be mixed with air, which leads to low CO_2 concentrations in the emissions. This industry is considering different solutions to increase the CO_2 concentration in its emissions. In general, CO_2 capture from exhaust gases under atmospheric conditions and at low concentrations (particularly at <3% CO_2 by volume) will be more expensive than with higher concentrations or where CO_2 can be captured in pressurised processes.

The share of CO_2 per product unit is another factor that varies between different industries. It can vary between <1 tonne CO_2/tonne product to >10 tonnes CO_2/tonne product in Norwegian industry. This is just the difference related to emissions from the industrial process itself, and the figures may be even higher where fossil fuels are the main source of energy. This factor, and the cost per tonne of product, mean that different industries have different exposures to the CO_2 quota price in the European Emissions Trading System (ETS), or other CO_2 taxes.

There are major learning effects between industries where different types of CO_2 capture technology can be applied to the different industrial sources. The choice of capture technology for each industry will be partly based on the natural conditions in the individual industry (e.g. available residual heat from industrial processes). Local conditions in the factories will also affect this (e.g. available area, and synergies with other nearby industries).

2.2.2 Hydrogen production from natural gas with CCS

Hydrogen is a raw material and energy carrier for a number of different industrial processes today, and has the potential to replace carbon-rich input materials in a number of sectors including manufacturing, transport, power generation and the country's heating needs in the form of gas.

In the IEA World Energy Outlook 2019, hydrogen (together with biomethane) is identified as an important energy carrier with a low CO_2 footprint, which can be added to the current gas mix to help reduce the CO_2 footprint. They also point to the potential for energy distribution using the world's natural gas networks, which have twice the capacity for transporting energy compared to the world's electricity grids.

Today's hydrogen production is primarily from fossil sources and half is used to make ammonia for fertiliser production, followed by equal amounts for refining and methanol production.

Hydrogen is produced mainly from fossil fuels, with a small percentage from electrolysis of water.

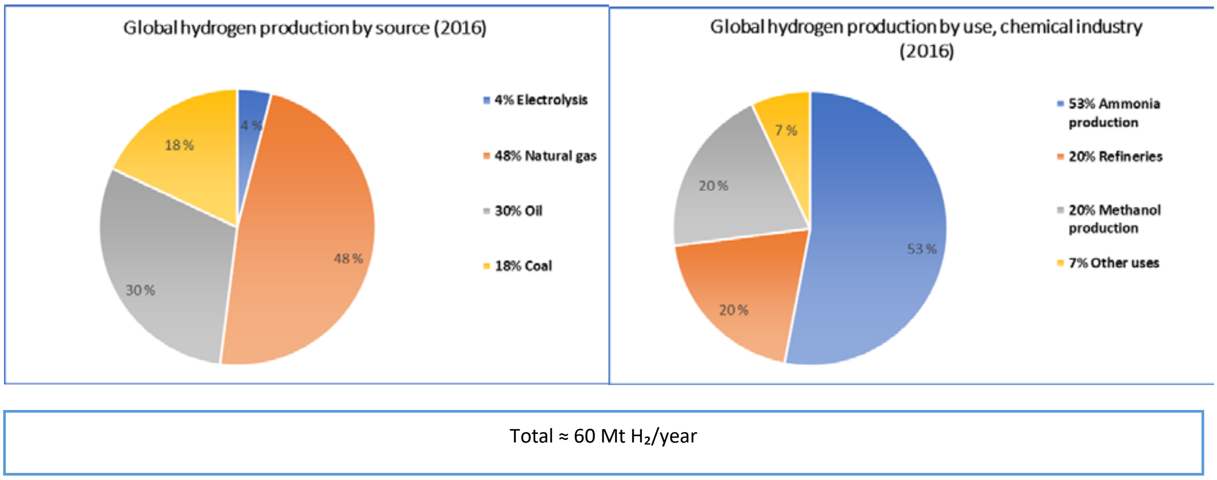


Figure 8: Global hydrogen production by source, and hydrogen production related to use in the chemical industry. Source CSLF (2019): CCUS and Energy Intensive Industry report

The figure above shows global hydrogen production by source (left panel; based on several sources including Evers, 2008) and use (right panel; from Essential Chemical Industry - online, last updated July 2016).

There is a high level of activity in the development of a "hydrogen economy" and the Hydrogen Council 2017 expects a tenfold increase in global hydrogen production and use up to 2050. There have also been high hopes for a widespread "hydrogen economy" in the past, and there is still some uncertainty as to the scale of this development in the future, but an important difference from the past is that, if hydrogen is to be used, it must be produced with a low CO_2 footprint.

Examples of emerging projects for reuse of hydrogen as an energy carrier are:

- Hydrogen as an energy export to Japan from reforming brown coal in Australia (ref: https://hydrogenenergysupplychain.com/). The project is looking at converting brown coal in Australia into hydrogen, removing CO_2 from production with CCS, and storing CO_2 in geological deposits off the southeast coast of Australia. Refrigerated and pressurised liquid hydrogen will be exported by ship to Japan where it be used, among other things, as an energy source for power generation and for fuel in hydrogen-powered cars.

- Hydrogen for use in heat production (ref: https://www.h21.green/). The H21 project in northern England is looking at converting natural gas from the North Sea into hydrogen using CCS. CO_2 will be captured and stored back in the North Sea. Hydrogen will be fed into existing/modified gas infrastructure as the primary source of heat for both domestic and industrial use.

Production of hydrogen

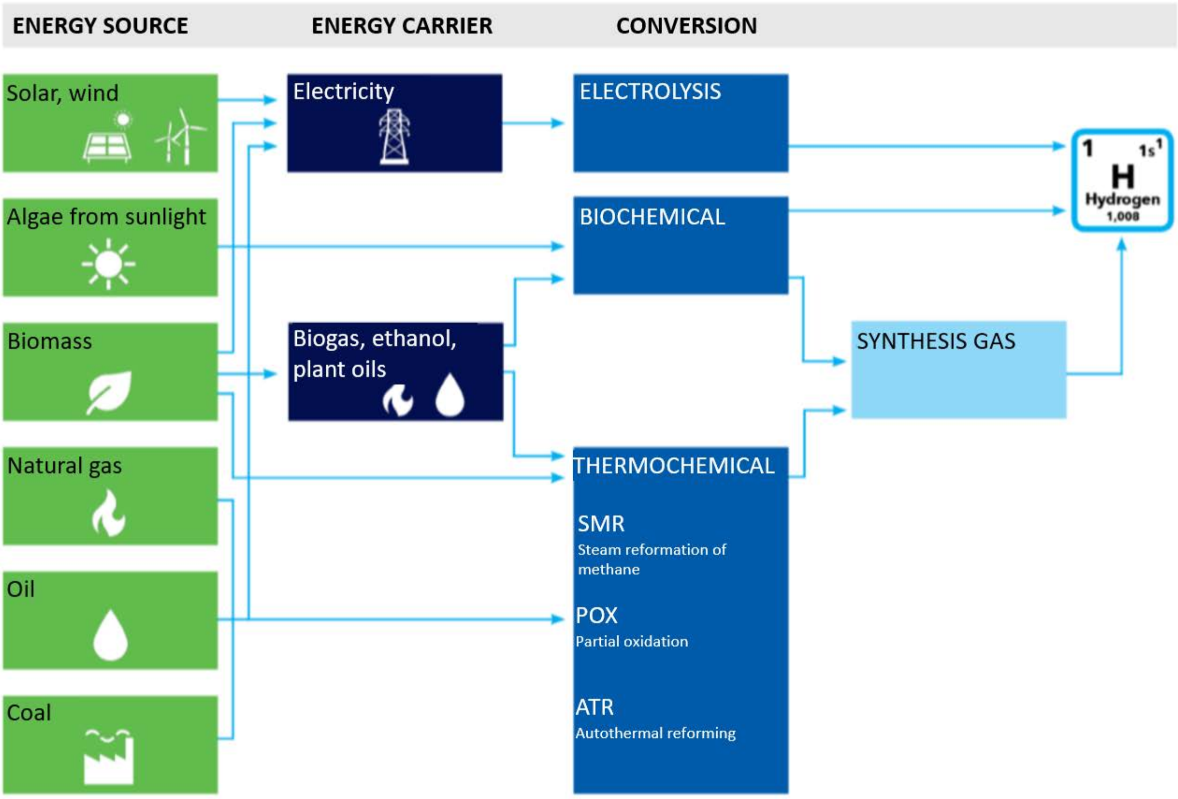


Figure 9: Production methods for hydrogen (source: DNV GL – Report no. 2019-0039, Rev. 1)

The figure shows different production routes for hydrogen. The source of electrical energy and the way in which CO_2 is handled from carbon-based sources determines the CO_2 footprint of hydrogen.

Hydrogen produced by electrolysis of water and reforming fossil sources with CCS is often referred to as green and blue hydrogen respectively. This is an imprecise conceptual apparatus, as green hydrogen may not necessarily be using renewable energy from the electricity grid, and the efficiency of CO_2 capture in the production of blue hydrogen cannot be guaranteed. Both technology paths have basically the same potential for producing hydrogen with a low CO_2 footprint. Green and blue hydrogen can be broadly complementary methods of producing hydrogen. Smaller volumes and access to renewable electricity favour green hydrogen, while larger volumes and access to large gas resources and CO_2 stocks favour blue hydrogen. The next section considers access to energy to be converted into hydrogen, energy loss from conversion, and energy required to liquefy hydrogen for transport.

There is a great need for energy in the production of hydrogen. Approx. 55 kWh of electric power is needed to produce 1 kg of hydrogen by electrolysis. In Norway, 225,000 tonnes of H_2/year are produced (2018), primarily from natural gas (without CCS). If this volume were to be replaced with hydrogen from electrolysis, it would equate to the use of 11.25 TWh, or about 8% of Norway's electricity production. By way of comparison, using natural gas with CCS would consume <1% of Norway's gas production (Norway exported 117.4 billion m^3 of gas in 2017). This is enough to produce around 25 million tonnes of hydrogen (DNVGL 2019). This shows that, if hydrogen production is to be increased, the production of hydrogen from natural gas with CCS will be key to having sufficient sources for the energy needed, based on current access to renewable electricity.

In converting from one energy carrier to another, there are losses in energy based on physical and chemical laws. This is an important consideration when deciding what the original energy source should be used for. For hydrogen production, there will be losses from the use of renewable energy, biomass or fossil sources compared to alternative uses of the energy source. The energy loss from producing hydrogen by electrolysis is around 35-40%, against 20-30% from reforming natural gas including CCS.

Hydrogen production by electrolysis of water is based on small modular units and requires only access to energy and water. This makes it suitable for local production of hydrogen. Transporting and storing hydrogen requires the hydrogen gas to be compressed or converted to liquid form. Conversion to liquid form requires energy equivalent to at least 20% of the energy in the hydrogen being transported.

Current production of hydrogen includes CO_2 capture.

Globally, 48% of current hydrogen production is from natural gas, and steam methane reforming (SMR) is the most widely used method. SMR is discussed below as an example of how this process uses CO_2 capture in today's production and how CO_2 emissions can be further reduced with CCS.

The process splits natural gas into hydrogen and CO_2. This process takes place under pressure and CO_2 is currently removed from the product stream primarily with solvent-based capture technology. This makes up approx. 2/3 of CO_2 emissions. Most of this captured CO_2 is now released into the atmosphere. Where there is a commercial market, some of this CO_2 is used for fertiliser production (urea), for enhanced oil recovery (EOR), or as CO_2 for the food industry. The SMR technology also burns gas to provide energy for the reforming process (approx. 1/3 of the CO_2 emissions). CO_2 from this combustion is currently released from these plants, but it can be captured in the same way as flue gases from other combustion processes with CO_2 capture technologies.

2.3 Greenhouse gas emissions in the energy sector

The IEA WEO 2019 estimates that global demand for energy will increase by 25% to 2040 with an average growth of 1% per year. In 2018 there was an increase of 2.3%. The WEO deals with three different scenarios with different trends in power generation and associated CO_2 emissions. Only the "Sustainable Development" scenario meets the CO_2 reduction target in the Paris Agreement and limits global warming to below 2°C. The three scenarios are shown in the figures below.

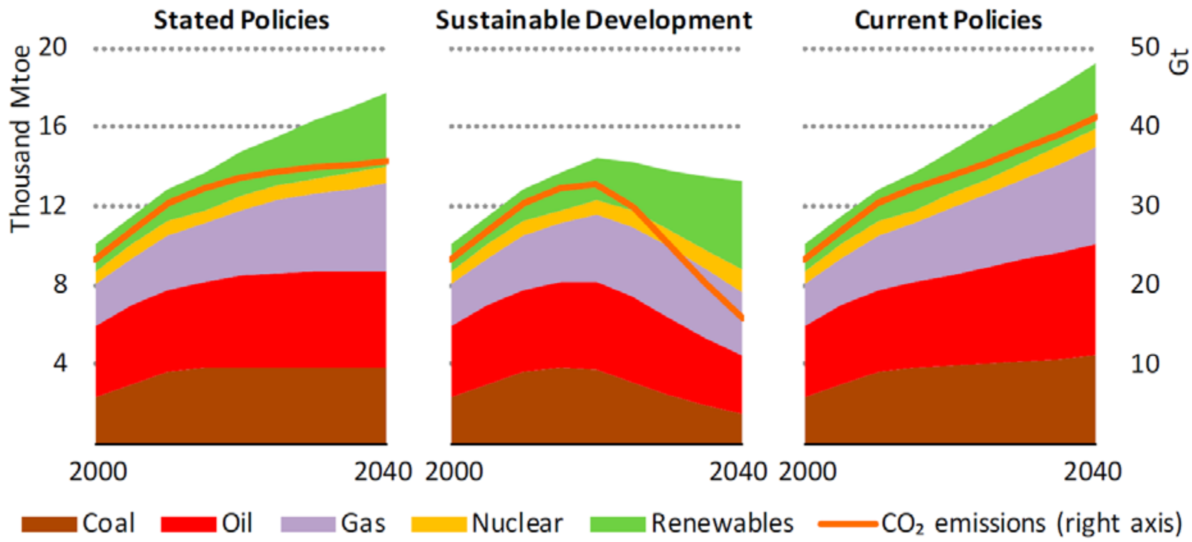


Figure 10: The world's expected energy production by source, with corresponding CO_2 emissions by scenario. Source IEA WEO 2019. (Mtoe = million tonnes of oil equivalents - left axis; Gt = gigatonnes of CO_2 - right axis)

Only the "Sustainable Development" scenario shows the demand for energy peaking at today's level and a sharp reduction in associated CO_2 emissions out to 2040. Gassnova expects to see an to increase to 2030 followed by a reduction to 2040. Energy from coal and oil is greatly reduced from current levels and is largely replaced by renewable energy sources. The reduction in CO_2 from fossil power generation using CCS is expected to account for 9% of this (see Figure 1). This reduction is in addition to the decrease in the proportion of fossil energy production.

In the "Stated Policies" scenario, there is continued growth in energy production from natural gas up to 2040 and a constant percentage of the world's energy production. For oil and coal, the volume will stabilise at current levels and take a smaller percentage share.

2.3.1 Coal power

Coal power accounted for 27% of global energy production in 2018 and, in the IEA's "Stated Policies" Scenario, it is expected to decrease to 21% in 2040. This decrease is offset by increased use of coal for industrial purposes and total consumption of coal up to 2040 remains around the current level of 5,400 million tonnes per year. There are huge variations between different parts of the world. Expected reductions in coal consumption in China (-9%), the USA (-40%) and the EU (-73%) are offset by increases in India (+97%) and South-East Asia (+90%)

In the IEA WEO "Sustainable Development" scenario, CCS systems equivalent to 160 gigawatts (GW) are expected to be implemented in coal-fired power plants, equivalent to 40% of the electricity from the world's coal-fired power plants. The IEA notes out that the "Stated Policies" scenario does not provide enough incentive to adopt CCS.

The IEA WEO stresses that CCS will be a key solution for decarbonising "young" coal-fired power plants which will be operational until well after 2050. The IEA points specifically to the power plants in Asian countries which are building many of these to meet the energy needs of a growing economy.

Examples of CCS installations at coal-fired power plants in recent years include:

In 2014, a CCS facility was completed at the Boundary Dam coal-fired power plant in Saskatchewan, Canada. As of December 2019, 3 million tonnes of CO_2 have been captured. CO_2 from the plant is used for enhanced oil recovery (EOR). In 2017, the Petro Nova CCS system at the W. A. Parish coal-fired power plant in Houston, USA, was put into operation. Designed to capture up to 1.45 Mt of CO_2 per year, the plant is the world's largest CO_2 capture facility now in operation. CO_2 from this plant is also used for EOR. Both facilities use liquid-based capture technology.

2.3.2 Gas power

Gas power currently accounts for 23% of total energy production. Natural gas saw extraordinary growth in 2018, with a 4.6% increase in volume, and accounted for about half of new energy production around the world. The world's gas consumption has undergone close to 80% growth since 2010. This is mainly due to three elements: the "shale gas revolution" in the United States, increased demand in China, and a higher ratio of gas to oil production in the Middle East. Production of liquefied natural gas (LNG) has seen a sharp increase in the same period to meet the demand for gas in markets without access to natural gas distribution by pipeline.

The IEA's "Stated Policies" scenario expects a global increase in natural gas volumes of 40% by 2040 compared to current levels. The share of world energy production from gas power increases to 25% in the same period. 50% of the global growth in gas volumes is due to increased consumption of natural gas as a raw material for the processing industry.

CCS at existing gas-fired power plants has received little attention globally in recent years. An interesting technology for CO_2 capture in a new type of gas-fired power plant is under development. The company Net Power is developing gas power technology where CO_2 capture is an integral part of the process itself. The technology is also known as the Allam process, after its British inventor Rodney Allam. The process is based on gas turbine technology where the combustion air is replaced with pure oxygen and recycled CO_2. The flue gas that drives the turbine will then consist mainly of CO_2 and water. The process has very efficient heat recovery which includes recycling of CO_2, and this means that it only needs the gas turbine stage. In comparison, traditional gas turbine gas power technology in a combined cycle power plant has both a gas turbine stage and a subsequent steam turbine stage, with the latter using the residual heat in the flue gas. Combustion with pure oxygen simplifies CO_2 capture in that pure CO_2 only needs the moisture removed before further transport and storage. The Allam process requires electricity to produce pure oxygen. Overall, however, the Allam process with integrated CO_2 capture has the potential for high efficiency and it is now being tested in La Porte, Texas, with a 50 MW (fuel) gas turbine. In their evaluation, the IEAGHG (2019) use an efficiency figure of 54% for the Allam process, but they also write that Net Power has referred to up to 59% efficiency with proprietary improvements to the process. In the same study, gas turbine combined cycle power plants with and without liquid-based CO_2 capture are rated at 49-51% and 59% efficiency respectively. The fact that the Allam process can reach an efficiency level between conventional gas power with and without CO_2 capture means that the process represents a very interesting and radical initiative for turbine-based gas power with CCS.

3 Status of CCS technology

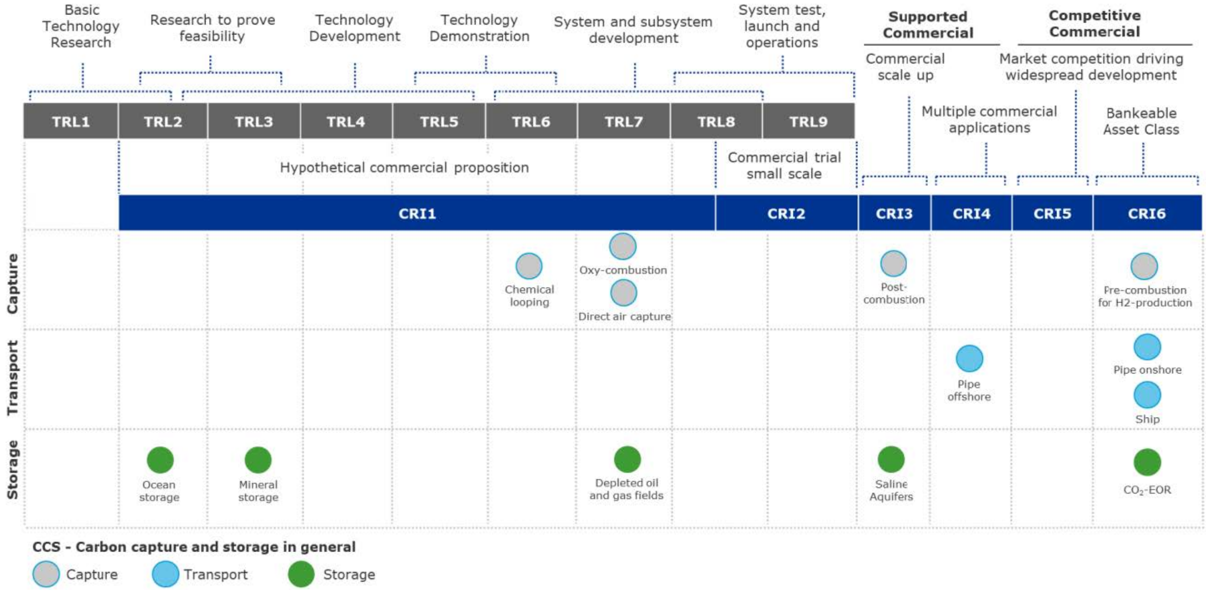


Figure 11: Technology maturity within CCS. Source DNV GL Report no.: 2019-1092

Technological maturity is often measured on a so-called TRL scale. This scale indicates how far a technology has come in the development process and what documentation exists for its performance, and on what scale. The methodology was developed by NASA in the United States and has become widely used. Among other things, it was consistently used in the EU Horizon 2020 programme. There are variants of the scale, but this report uses the same definition that DNV GL uses in its report on the cost curve for CCS from TRL 1-TRL 9 (Ref: DNV GL report no: 2019-1092).

Even when the technology has reached TRL 9, there is still huge development potential with associated cost reductions. This is often referred to as the extent to which the technology is commercially mature, expressed as a Commercial Readiness Index (CRI). The CRI methodology was developed by the Australian government to determine the kind of support renewable energy technologies need in order to be developed commercially to a level where the traditional investment and financial markets operate independently. The CRI is divided into six levels as shown in Figure 11. Source (ARENA 2014)

3.1 CO_2 capture technology

CO_2 capture is traditionally divided into three main categories based on whether CO_2 is captured before or after combustion, or from combustion with pure oxygen. These are often referred to as pre-combustion, post-combustion or oxy-combustion and have a clear reference to thermal power plants. They are based on hydrogen production with CO_2 handling, CO_2 capture in the flue gas from a power plant, and combustion with pure oxygen. However, the status of CO_2 capture technology will now be presented in terms of whether CO_2 is captured using liquids, membranes, combustion with pure oxygen or solids, or at low temperatures. This division into five groups does not cover all cases. Within cement production, for example, a technology is being developed in which calcination takes place separately and thus provides very pure CO_2.

The maturity of these capture methods, based on the three sources IEAGHG (2019), Wood (2018) and Bui et al. (2018), is presented in Figure 12. The TRL scale, which runs from 1 to 9, covers maturity from the concept stage (1) all the way up to full-scale construction under commercial conditions (9). The highest TRL level is shown within each of the five groups, and for some subgroups. We can see from Figure 12 that only liquid and solid-based CO_2 capture have a commercial maturity level (TRL 9) whereby solids apply only to hydrogen production. There is a constant development in these technology groups and various projects will be able to fill the scale all the way down to TRL 1. The sections below discuss these capture types and also comment on technologies that do not fit into these five groups. CO_2 capture will be discussed in connection with natural gas processing, hydrogen production and capture from flue gas/process gas, while Figure 12 simply shows the highest TRL for CO_2 removal in hydrogen production and CO_2 capture from flue gas.

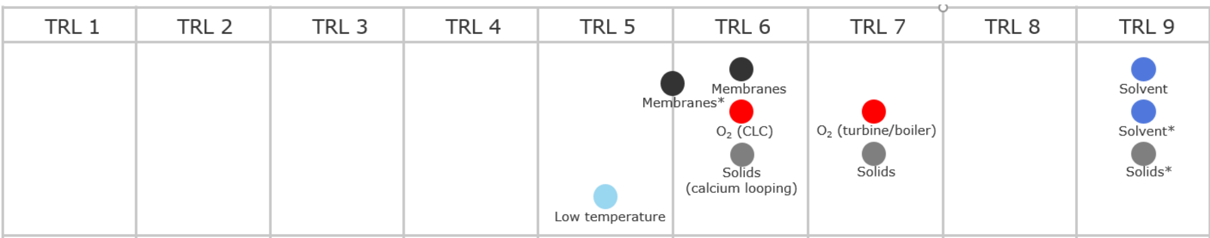


*Figure 12. Highest maturity level reached for CO_2 capture with liquids (blue dots), membranes (black dots), combustion with pure oxygen (red dots), solids (grey dots) and low temperatures (light blue dots). Technologies marked * are used in hydrogen production. The table is based on: IEAGHG (2019), Wood (2018) and Bui et al. (2018).*

3.1.1 Solvent

In the case of solvent-based CO_2 capture, the gas containing the CO_2 comes into contact with a liquid solvent and is captured by being dissolved or undergoing a chemical reaction with the solvent. The liquid solvent is then transferred to another unit/column where CO_2 is released by e.g. changing the pressure or temperature. The solvent is now regenerated and will circulate between these two units/columns. Solvent-based capture of CO_2 from natural gas is a mature technology that has been used for decades (Bui, 2018) to get natural gas with an excessively high natural CO_2 content ready for sale. Hydrogen production from natural gas e.g. in connection with ammonia production, is also commercially available. CO_2 capture from coal power is deployed on a large scale at Boundary Dam (Canada) and Petra Nova (USA), both designed to capture 1 million tons of CO_2 or more per year. Liquid-based CO_2 capture is therefore placed at TRL 9 in Figure 12 for both CO_2 capture and hydrogen production.

3.1.2 Membranes

Membranes exploit the fact that some gases in a mixture, e.g. hydrogen or CO_2, pass through materials more easily. This allows the hydrogen or CO_2 to be concentrated. Membranes can also be used in conjunction with other technologies, perhaps by having a membrane-based concentrating stage for CO_2 or with the chemical reactions (e.g. hydrogen production from natural gas) taking place inside the membrane unit itself. Membranes are in commercial use for natural gas handling and Wood (2018) mentions Santos Basin, which separates around 1 million tonnes of CO_2 per year from natural gas with excessively high natural CO_2 levels. In terms of hydrogen production, the IEAGHG (2019) finds that this is demonstrated with membranes at TRL 5-6. For CO_2 capture, the use of polymer-based membranes is set at TRL 6. In this context, we would refer to MTR in the USA, and the membrane development at NTNU was to be carried on by Air Products.

3.1.3 Combustion with pure oxygen

In the case of combustion with pure oxygen, the combustion air, which is approx. 80% nitrogen, is replaced with oxygen mixed with CO_2 or water vapour. The flue gas will then consist mainly of CO_2 and water. Water and smaller components are removed afterwards, and the result is almost pure CO_2. The technology requires some sort of production unit for oxygen. In the case of thermal power using a boiler (coal and gas), this technology has been developed to TRL 7 at Callide in Australia. Other major oxy fuel projects are Lacq (Total), Schwarze Pumpe (Vattenfall) and Cuiden. There is also ongoing development within gas turbines, and the Allam process from Net Power is a particularly promising technology which reached TRL 7 in 2019 with a test turbine in La Porte, Texas. This process is an example of a radical shift in technological development for gas power with CO_2 handling.

A particular strand within combustion with oxygen is chemical looping combustion (CLC). This sort of unit has an integrated oxygen generator where particles pick up oxygen in an air reactor before being transferred to the fuel reactor where the oxygen is released. The particles circulate between these two reactors. Processes like this are often called high-temperature looping processes with solids. Calcium looping (see below) is included in this category. Looping combustion is the subject of the Horizon 2020 project CHEERS (Chinese-European Emission-Reducing Solutions, 2017-2022), which aims to raise the CLC technology to TRL 7.

3.1.4 Solids

Gas can bind to the surface of a solid and can then be used to remove e.g. CO_2 from a gas flow. The solid matter can then be regenerated, i.e. release CO_2, typically by changing the pressure or temperature. This is a very mature technology which has been in use for 50 years for hydrogen production (Wood, 2018). The maturity for hydrogen production is therefore set at TRL 9. Solid-based CO_2 capture from flue gas has not been developed to the same level and, based on the three sources cited above, the maturity level is TRL 6 to 7. Both Wood (2018) and Bui et al. (2018) place it at TRL 7, so this is used in Table 1 as the highest TRL level achieved.

High temperature processes such as calcium looping are based on the circulation of solids. Here CO_2 is captured by reacting with burnt lime in particle form which is then heated in another reactor to regenerate the particles and collect CO_2. This last part of the process resembles the calcination process in a cement factory. The technology is set at TRL 6 based on the existence of several test facilities in excess of 1 MW (heat output). The technology is under development and the CLEANKER project (CLEAN clinKER production by Calcium Looping Process, 2017-2021) under Horizon 2020 aims to get calcium looping used in cement production up to TRL 7.

3.1.5 Low temperature

In low-temperature CO_2 capture, the flue gas is cooled so CO_2 can be separated out as a liquid or in solid form. This technology is under development and the maturity level is set at TRL 5. This is based on Sustainable Energy Solutions (IEAGHG, 2019) which extracts CO_2 in solid form. There are hybrid solutions where a membrane step first concentrates CO_2 before the flue gas is cooled. This category, which could also be called physical separation of CO_2 or cryogenic CO_2 capture, also includes techniques based on supersonic flow rates. The processes in this category do not use chemicals.

Low-temperature processes have also been developed within gas processing, and Exxon has developed the Controlled Freeze Zone (CFZ) to extract CO_2 and H_2S from natural gas. This process is rated at TRL 7 (Wood, 2018).

3.1.6 Others

There are technologies that operate under special conditions or fall outside the five types of CO_2 capture based on liquids, membranes, combustion with pure oxygen, solids or low temperatures. Two examples of this are relevant to Norway.

Equinor has been working on process intensification for amine-based CO_2 capture with a concept that uses rotation and hence higher G-forces. Replacing the main components (absorber and desorber) with rotating components significantly reduces the size of the capture plant. This technology is now being pursued by Fjell Technology Group, which reports that this reduces the physical size of both absorber and desorber by 90%, and the technology is placed at TRL 4. The CLIMIT program has supported the development of this technology.

The calcination part accounts for approx. 60% of CO_2 emissions from cement production. This gas flow is directly integrated and is mixed with flue gas from combustion downstream in the cement production process, so the final CO_2 concentration will be around 20%. With indirect heating and separate calcination, however, almost pure CO_2 gas can be obtained. The Horizon 2020 project LEILAC (Low Emissions Intensity Lime & Cement), which runs from 2016-2020, is working on separate calcination. According to Hill et al. (2016), the LEILAC project will be able to raise this technology from TRL 4 to 7.

3.1.7 Technology suppliers for CO_2 capture from flue gas

Some post-combustion CO_2 capture facilities using flue gas have been and are being built on an industrial scale. Around 5-10 technology providers can deliver process design based on either open (MEA) or proprietary solvents. They have designed industrial-scale facilities that have been or are being built. Around half of these have experience of delivering whole EPC (Engineering, Procurement & Construction) projects to processing industry.

There are 3-5 other large EPC companies which do not themselves possess the core expertise in capture technology, but have built tens or hundreds of processing plants. These also have experience of building amine-based post-combustion capture facilities using flue gas. About the same number of similar companies have progressed capture projects, including FEED studies. These large EPC providers will typically carry out EPC projects in collaboration with technology providers who do not have sufficient size or expertise to do so themselves.

	Have built or are building
Technology supplier with EPC capability	3-5
Technology supplier without EPC capability	3-5
EPC supplier	3-5

Table 1: Technology suppliers of amine-based post-combustion technology for capture from flue gas.

The table below shows a selection of different technology developers that Gassnova is or has been in discussions with through its recent work within all types of CO_2 capture technology. There is great variation in the TRL level of these technologies.

Technology developers for CO_2 capture	
Company	**Technology name/description (Eng.)**
Liquid-based	
Shell (formerly Cansolv)	Aqueous amine solution
Siemens	Second generation PostCapTM amino acid salt process
Mitsubishi Hitachi Power Systems	Amine-based H3-1 solvent.
Mitsubishi Heavy Industries (MHI)	Amine-based MHI KM-CDR process
GE Power with Dow Chemical	Advanced amine process (AAP)
GE Power	Chilled ammonia process (CAP)
Aker Solutions	ACC (advanced carbon capture) Amine-based technology
Linde AG	Both pre-combustion, oxyfuel and post-combustion (with BASF)
Fluoride	Fluor Econamine FG PlusTM and other MEA processes
Fjell Technology Group Compact Carbon Capture	3C - rotating compact absorber/desorber
ION Clean Energy	Water lean solvent
Gas Technology Institute	Hybrid solvent / membranes
SRI	Mixed salt solvent system
Carbon Clean Solution	Amine-based solvent
Tecno Project Industriale	Open source amine-based solvent
Membranes	
Air Liquide	Membrane separation including methane
Air Products	Ion transport ceramic membrane to electrochemically separate O_2
Eltron (US)	Membrane separation of H_2
MTR	Membrane separation of H_2 and/or CO_2
Reinertsen	Paladium membranes
Solids and combustion with pure oxygen	
GE	Chemical Looping Combustion, boilers and gas cleaning units
Linde AG	Boilers
NetPower	CO_2-based cycle - Allam cycle
Svante	Rotating bed adsorbents
TDA Research	Alkalised alumina sorbent
Low temperature	
Air Liquide	CO_2 cryogenic purification units
Clean Energy System	CO_2 cryogenic units

Table 2: Technology developers/suppliers

3.2 Status of CO_2 transport technology

CO_2 is currently used as a raw material in various industries; e.g. for enhanced oil recovery (CO_2-EOR), in the food industry, and for other industrial purposes. CO_2 is transported to consumers in pipelines, by ship, truck or rail. The biggest market for CO_2 is for CO_2-EOR in North America, where CO_2 transport is mainly in pipes. Yara in Porsgrunn produces CO_2 which is transported by ship to ports in Europe. Although there is already a mature commercial market for transporting CO_2, there are still several factors driving R&D within transport for CCS:

- The volumes of CO_2 associated with CCS are very large, and more cost-effective solutions are needed than are available in today's market.
- Future transport networks and hubs where CO_2 from various sources can be mixed.
- New players with high standards of technical expertise and HSE (e.g. possible operators of future CO_2 stores such as Equinor, Shell, Total, etc.).
- Subsea pipeline transport generally has higher costs and operational risk than the equivalent onshore.

The primary focal areas for R&D in transport technology are:

- Analysing how different impurities and combinations of impurities in CO_2 affect phase behaviour and how corrosive compounds/conditions may arise.
- Improvement of simulation models and tools, related to flow modelling, sizing of pipelines and dispersion of CO_2 in case of leaks, for example.
- Development of more efficient ship designs.
- Development of new polymer materials that can withstand direct contact with liquid/supercritical CO_2 (for gaskets and seals in pipe and process systems).

These are areas that cut across the transport methods and raise fundamental choices underlying the structure of all value chains within CO_2 handling. For large quantities of CO_2, transport by ship or in pipeline systems is considered feasible. These transport solutions are discussed in the following sub-sections.

3.2.1 Transport by ship

Today's transport of CO_2 by ship is done with CO_2 in liquid form at pressures from 15 to 20 bar and temperatures between -30°C and -20°C. Technical solutions and guidelines for managing CO_2 under these conditions have been established, including: "*Safe transfer of liquefied carbon dioxide in insulated cargo tanks, tank cars, and portable containers*", published by the Compressed Gas Association (CGA).

The density of CO_2 is much higher in liquid form than as a gas, and this allows more CO_2 to be transported with a given size of ship. To transport CO_2 in connection with CCS, we need to view the pressure and temperature conditions in a wider context. Depending on the characteristics of the CO_2 source and the location and structure of the store, different ship designs and different pressure and temperature conditions will be best. Liquefaction will generally be more complicated at low pressures and temperatures. The CO_2 will have to meet stricter standards for the level of impurities such as water. At low pressures and temperatures, the storage tanks will require more insulation, but they could also be built with lower design pressure and wall thickness, which is expected to be cheaper.

Three main concepts for ship transport of CO_2 with different injection and storage solutions are shown in figure 13.

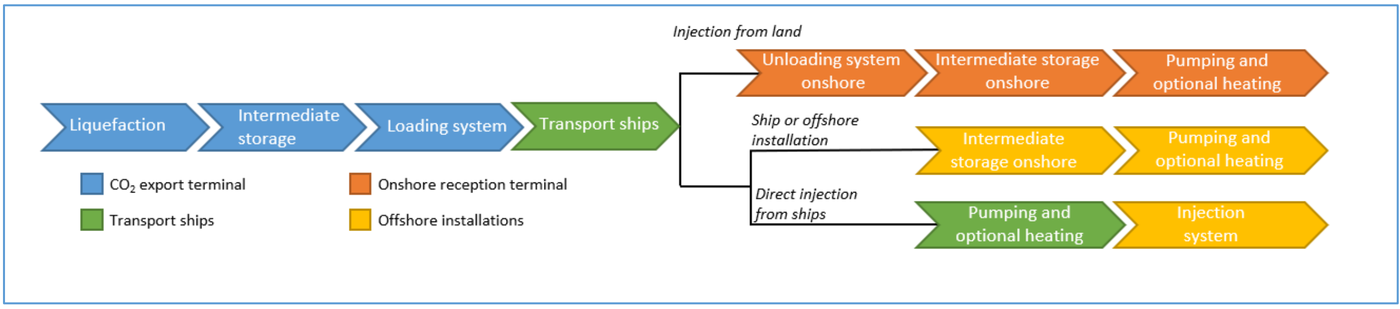


Figure 13: Three main concepts for injecting CO_2 for transport by ship, based on storing CO_2 from a facility onshore or an offshore installation/ship (source: Gassnova)

As shown in the figure above, CO_2 can be injected from a facility onshore, via an offshore installation/injection vessel, or directly from the transport ship. The Norwegian full-scale project is based on the solution with injection from an onshore facility. The two solutions based on offshore injection have only been considered in studies and have less technological maturity.

The established transport conditions between 15 and 20 bar are only suitable for quantities up to approx. 10,000 tonnes of CO_2 per ship if the voyages are limited to e.g. Northern Europe. In the Norwegian demonstration project, the distance between capture and storage facilities is around 400 nautical miles, and a ship with a cargo capacity of 7,500 tonnes will be able to transport around 600,000 tonnes of CO_2 per year over such a distance. For this ship, doubling the sailing distance will reduce the amount of CO_2 that can be transported each year by around 40%. So in order to achieve more efficient transport over long distances, the cargo volume needs to be increased.

To increase efficiency when transporting large quantities of CO_2, R&D is aimed at developing ship designs based on lower pressures and temperatures than are used in today's tankers. It may be possible in theory to approach the triple point of CO_2, which is 4.5 bar and -56.4°C, but in practice 5 to 10 bar and -55°C to -40°C will be used to ensure that dry ice is not formed when the CO_2 is handled in the systems for liquefaction, intermediate storage, and loading. The main advantage of transport at lower pressure is that the cargo tanks can be built with a larger diameter/cross-section, which generally means that the ships themselves can be bigger.

Multi-purpose ships, i.e. ships that are certified for use to meet other transport needs (e.g. LPG) in addition to CO_2, are also worth considering when choosing transport conditions and ship design.

3.2.2 Onshore pipe transport

There are currently 6,400 km of pipeline system for transporting CO_2 onshore, with a total capacity of 44.2 million tonnes of CO_2 per year (IEAGHG 2013-18). A large part of this pipeline system is in the USA, where it is used to carry CO_2 for enhanced oil recovery (EOR). This area of technology can thus be said to be mature for most applications.

With pipelines, it is most economical to transport CO_2 in a supercritical state, where the pressure is so high that the properties of the CO_2 become a mixture of those of CO_2 in the gas and liquid phases. A pressure slightly over 103 bar has become an industrial preference. In the USA, natural gas pipelines have been converted to transport CO_2.

Components in a CO_2 pipeline system typically comprise the following:

- CO_2 compressor/pumping stations
- Metering stations for purchase/sale of CO_2
- CO_2 conditioning (heat exchangers, filters, drying plants)
- Pipelines

Technological development is largely concerned with cost reduction in the design of parts of the transport system and reducing health and safety and environmental risks.

R&D efforts are directed, among other things, at developing models and tools to be able to size pipelines without expensive margins while still avoiding longitudinal breaks (i.e. damage to the pipe causing it to rupture lengthwise). Improved flow models are also key to further development as it is important for the design and operation of the pipe systems that the CO_2 flow should be in the right phase in the right place at all times. Precipitation of dry ice or hydrate in the wrong place can have serious adverse consequences, and two-phase flow can present challenges in maintaining the necessary capacity in the pipe system.

3.2.3 Offshore pipe transport

There is less experience with pipeline systems for CO_2 offshore than onshore in terms of the number of km and pipe systems in use. In Norway, Equinor has experience from its CO_2 pipeline at the LNG plant on Melkøya where 700,000 tonnes of CO_2/year are transported in a 110 km offshore pipeline before being injected into a geological formation in the Barents Sea.

The same components are used in an offshore pipeline transport system as onshore, and experience and technological development are broadly the same. One of the main differences is that components are placed on land at the start of the pipeline, which ends at the injection well on the seabed. The pressure is higher in the offshore pipe system than in onshore systems as the injection pressure comes from the onshore pumping station at the start of the pipeline. In a land-based system, on the other hand, this will usually be done at the injection well itself. Among other things, this makes it hard to produce good flow modelling tools to design the system for phase transitions and possible multi-phase flows to maintain control of the flow rate to the injection well. The CLIMIT-sponsored CO2FACT project is developing and validating software to simulate the flow of CO_2 through the pipeline and injection well for this type of system.

3.3 Status of CO_2 storage technology

CO_2 can be stored deep underground in porous rocks such as sandstone. In Norway, such sandstones are found mainly on the Norwegian continental shelf, and to a very small extent on land. Sandstones and shale are classed as sedimentary rock types. Sedimentary rocks are formed when sand and clay particles are pressed together and cemented into rock. This process takes place at high pressure and temperature. For sandstones, some of the spaces between the grains are preserved. These spaces, which are known as pores, can account for up to 20-30% of the volume of the rock, and it is in these pores that we find oil, gas and water. Shale, on the other hand, is formed of clay and does not have these pores as the clay forms small, flat grains. Shale is therefore a dense sedimentary rock which is often referred to as a caprock or seal. Layers of sandstone filled with oil and gas and naturally occurring CO_2, which have been stored for millions of years, show that anthropogenic CO_2 can also be permanently stored in sandstones, with the shale layer as an impermeable seal above.

Geological storage of CO_2 can occur either onshore or offshore in areas where the sole purpose is CO_2 storage, or with the intention of improving oil or gas production from mature fields (Holloway et al, 2006).

There are several technological possibilities for storing CO_2 permanently, using either: mineral storage, CO_2-EOR offshore, storage in depleted oil and gas fields, CO_2-EOR onshore, or storage in saline aquifers. Some are considered mature, while other types of technology are further down the maturity scale. See Figure 14 and subsequent sub-sections for a description of status.

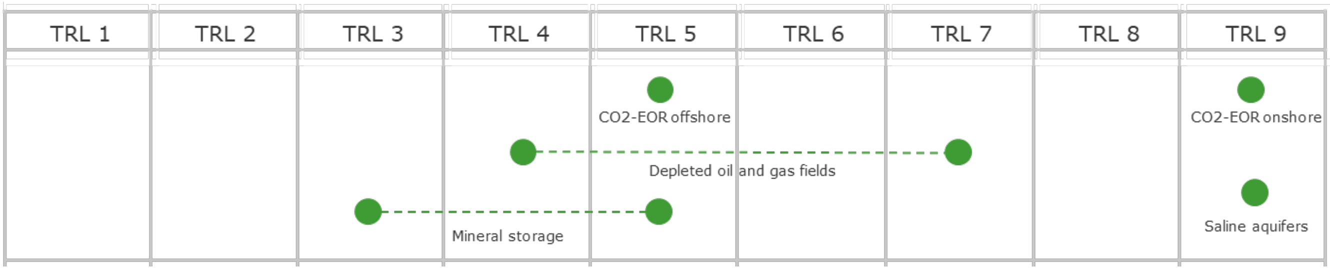


Figure 14: Overview of TRL status for CO_2 storage technology.

All the technologies shown in figure 14– with the exception of “mineral storage” – have several common system components for injecting CO_2 into geological formations underground. These components are listed here with a brief description of maturity and potential for future development:

- Pump, pipeline, wellhead, control systems: standard components from the oil and gas industry are used with possible minor modifications or qualification for use with CO_2.
- Seabed equipment: standard components from the oil and gas industry have been used, but there is a potential cost reduction in simplifying barrier designs for storage in saline aquifers. Further maturation of all-electric control systems for oil and gas production wells is also expected to lead to significant cost reductions.
- Well – There are five categories of well relevant to CO_2 storage:
  - Injection well for CO_2, drilled for the purpose.
  - Saltwater production well to relieve pressure build-up in the storage reservoir.
  - Monitoring well with instrumentation drilled only for this purpose.
  - Existing wells that are open and can be reused or closed.
  - Existing wells that have been closed. They cannot be reopened and represent a risk of CO_2 leakage into shallower formations or to the surface.

  All these categories must take account of corrosion of carbon steel pipes and degradation of cement for well integrity when exposed to CO_2. The use of corrosion-resistant steel is a mature solution, but it is limited to the most vulnerable parts of a well because of the cost. The use of special cement is constantly evolving, and several suppliers are offering such products on the market.
- Monitoring technologies are used to monitor the CO_2 being injected and possible changes in the well, reservoir and overlying sediments. There are currently several different technologies for CO_2 monitoring, and these are being further developed to increase accuracy and reduce costs.
- Simulation of CO_2 movement in the reservoir: Development of more precise simulation models to enable the operator to understand the CO2 distribution in the reservoir from measured data

3.3.1 CO_2-EOR onshore

TRL level 9 in Figure 12. Storage of CO_2 in oil and gas fields that are in production or nearing the end of their life has now been proven in a number of fields in several countries for enhanced oil recovery. For example, 13 of the 17 operational commercial-scale CCS projects already use CO_2-EOR (Bui et al., 2018).

Some of the key issues that have been resolved over the years have been concerned with the design of fields to handle reduced reservoir pressure, reuse of infrastructure and dealing with corrosion in existing wells (Sarah Hannis et al., 2017).

Along with its mature TRL status, CO_2-EOR can be assigned “bankable asset” status on the Commercial Readiness Index (CRI) scale described in section 3.

3.3.2 Offshore CO_2-EOR

TRL level 5 in Figure 14. Onshore CO_2-EOR relies on a large number of CO_2 injection wells and oil production wells placed from a few hundred metres to a few kilometres apart in order to utilise the reservoir efficiently. The wells are either equipped with material that can withstand the corrosive environment created by CO_2 and salt water or require regular maintenance.

These factors related to efficient utilisation of the reservoir and corrosion have hindered the development of CO_2-EOR offshore (Sweatman et al, 2011) and there are no commercial projects running today, but some pilot trials are underway, including (US Department of Energy, 2014):

- the Lula Field in Brazil
- the Lower Zakum Field, Abu Dhabi
- Vietnam and Malaysia.

Based on these pilot trials which are underway, the TRL level has been set at 5.

3.3.3 Saline aquifer offshore

TRL level 9 in Figure 14. Saltwater formations have been used for CO_2 storage on a commercial scale for over 20 years on the Sleipner field in Norway. Other projects that have followed on an industrial scale include Snøhvit (Norway), Quest and Aquistore (Canada) and Gorgon (Australia) (Bui et al., 2018).

When the CO_2 liquid is injected into an aquifer, it displaces the salt water held in the pores in the rock around the injection site. Because CO_2 is lighter than water, it spreads outward in a cloud which creeps slowly upwards. It is therefore important to ensure that there are impermeable roof rocks above the saline aquifer.

In Norway, the Norwegian Petroleum Directorate (OD) has mapped the potential storage capacity of several saline aquifers, and the result is shown in Table 3 in gigatonnes of CO_2 (OD, 2014).

Aquifer	Capacity Gt	Injectivity	Seal	Maturity	Data quality
North Sea aquifers					
Utsira and Skade Formations	15,8	3	2		
Bryne and Sandnes Formations	13,6	2	2/3		
Sognefjord Delta East	4,1	3	2/3		
Statfjord Group East	3,6	2	3		
Gassum Formation	2,9	3	2/3		
Farsund Basin	2,3	2	2/3		
Johansen and Cook Formations	1,8	2	3		
Fiskebank Formation	1	3	3		
Norwegian Sea aquifers					
Garn and Ile Formations	0,4	3	3		
Tilje and Åre Formations	4	2	2/3		
Barents Sea aquifers					
Realgrunnen Subgroup, Bjarmeland Platform	4,8	3	2		
Realgrunnen Subgroup, Hammerfest Basin	2,5	3	2		
Evaluated prospects					
North Sea	0,44				
Norwegian Sea	0,17				
Barents Sea	0,52				
Abandoned fields					
North Sea	3				
Producing Fields_2050					
North Sea 2050	10				
North Sea_Troll aquifer	14				
Norwegian Sea	1,1				
Barents Sea	0,2				

Table 3: CO_2 storage capacity in saltwater formations on the Norwegian continental shelf (OD, 2014).

3.3.4 Depleted oil and gas fields

TRL level 4-7 in Figure 14. Storage of CO_2 in oil and gas fields that have ceased production is similar to CO_2-EOR, but the production wells are plugged and are not accessible for monitoring or maintenance. Despite its similarity to CO_2-EOR, large-scale storage has not so far been tried by this method, and the TRL level is set to between 4 and 7. To mature further, the industry will need better and more cost-effective technology to simulate the impact of CO_2 on existing wells, monitor the impact during operation and carry out ongoing maintenance over decades.

3.3.5 Mineral storage

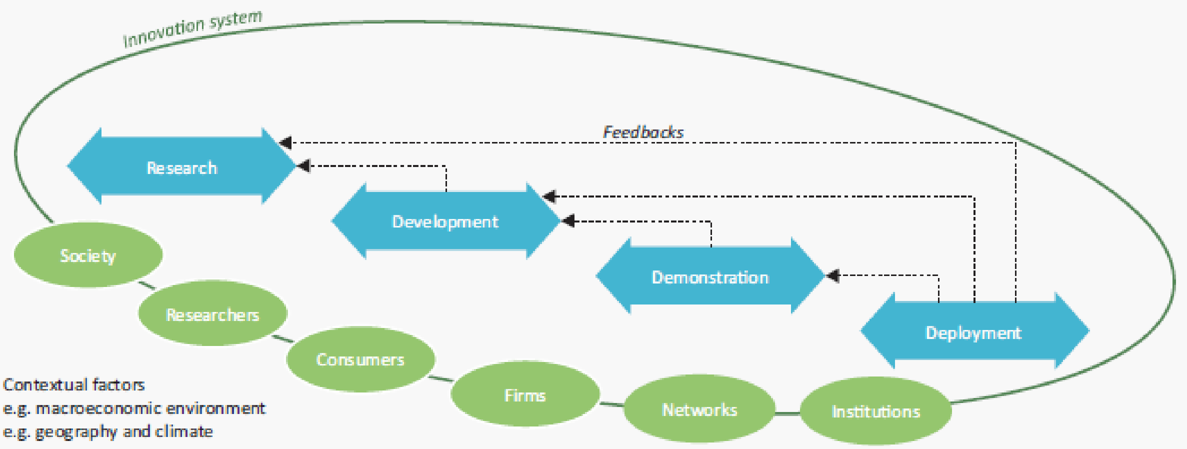
TRL level 3-5 in Figure 12. In this method, CO_2 reacts with rocks and minerals to form solid and stable carbonate rock types. New pilot projects and laboratory-based kinetic experiments have shown that this method, both *in situ* and *ex situ,* could be a viable option for long-term storage. Storage *in situ* focuses on minerals on the surface or underground. *Ex situ* storage is directed at industrial by-products on the surface, e.g. from mining.

Environmental risks include induced seismicity for *in situ* methods if the pressure is not properly controlled, as well as potential water and land use effects. However, there are fewer long-term concerns about CO_2 leakage with mineralisation methods compared to saline storage methods and so potentially lower long-term monitoring costs. The costs and benefits of CO_2 mineralisation have been compared to the cost of CO_2 storage in saltwater reservoirs (U.S. Geological Survey, 2018) and are still too high for industrial-scale deployment.

4 Innovation system

Norway has more than 20 years of experience in CO_2 handling, and the only two operational projects in Europe are Norwegian. Over time, the Norwegian authorities have focused on capturing and storing CO_2 and have built up solid professional expertise covering the whole research and development chain, as well as funding major research infrastructure. Norwegian investment was initially directed at the fossil fuel industry, gas extraction (offshore CO_2 tax) and gas-fired power plants with a low CO_2 footprint, but it has turned more towards capture from industrial sources and the development of storage from multiple sources. Norway also has strong NGOs which are drivers for both national and international efforts on CO_2 handling, and the initiatives have had strong support from interest groups and labour organisations across the political spectrum.

The players in the Norwegian "innovation system" for CO_2 handling and the dynamics between them will benefit from the full-scale project, and the full-scale project will benefit from their contribution to further development of CO_2 handling. See Figure 15 for the IEA's illustration of the elements and relationships within an innovation system for developing new (IEA, 2015) technologies.



Sources: GEA (2012), *Global Energy Assessment: Toward a Sustainable Future*, Cambridge University Press, Cambridge, United Kingdom and New York; the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Key point *Interactions across the entire innovation system will enable actors to develop necessary incremental improvements and breakthroughs in technologies needed to meet climate goals.*

Figure 15 Innovation System - IEA Energy Technology Roadmap (IEA, 2015)

A description of some selected parts of the innovation system in Norway which Gassnova is responsible for or otherwise engaged in is given below.

The CLIMIT research programme is split into two parts, with the Research Council of Norway covering the research base and Gassnova the pilot/demo phase. The aim of CLIMIT is to contribute to developing technology and solutions for capture, transport and storage of CO_2. In the programme plan for the period 2017-2022, the "early full-scale CO_2 value chain in Europe" is defined as a separate focus area. The CLIMIT programme can support research, development and demonstration projects based on experience from the full-scale project. The programme plan also includes *large-scale storage of CO_2* on the Norwegian continental shelf in the North Sea. CLIMIT can therefore help to develop solutions for enhanced oil recovery and hydrogen production with CO_2 storage, for example, as well as supporting technology suppliers and industry players in developing new solutions for CO_2 capture.

The Technology Centre at Mongstad (TCM) is the world's largest testing centre for CO_2 capture technology. Several suppliers have tested their capture technologies there since the centre opened in 2012. The current partnership agreement runs until autumn 2020. There are ongoing discussions within the partnership on continuing operations. Leveraging synergies with the Norwegian full-scale project will be an explicit part of TCM's strategy going forward.

Norway has a research centre for environmentally friendly energy (FME) dedicated to capturing and storing CO_2. The Norwegian CCS Research Centre (NCCS) started up in 2016 and is intended to run for eight years. NCCS has around 30 research and industry partners and a budget of more than NOK 400 million. SINTEF Energy is heading the programme in close cooperation with NTNU and UiO. NCCS has clear targets that support the full-scale project. Among other things, it states that *"NCCS should ensure that we bring about CO_2 storage in the North Sea"* and *"NCCS should contribute to the Government's ambition to implement a full-scale CCS chain by 2020".* Several of the industry players in the full-scale project are user partners in the programme. Gassnova has also agreed roles which allow experience from the full-scale project to be input.

A large number of CCS development projects in Norway have been supported over the last 20 years. A wide range of players have been involved, from university/research institutes, technology companies, service providers and potential end-users of CCS technology. One example of a specific technology/company is Aker Solution (formerly Aker Clean Carbon), whose liquid-based CO_2 capture technology has been developed from basic research to full-scale implementation-readiness.

CLIMIT R&D and Demo: “Solvit” is a development project led by Aker Solution to develop their environmentally friendly and cost-effective amine technology (2008 – 2016). The work was carried out in close cooperation with e.g. NTNU and Sintef. The project used Sintef’s testing facilities at Tiller. Aker developed a mobile testing unit (MTU) which was used to qualify their technology on a large number of different CO_2 sources in Norway and other countries.

TCM: Aker was chosen as contractor to build the generic plant to test liquid-based capture technology at TCM (2010–2012). Aker Solution’s technology was the first to be tested at this facility (2012–2014).

CLIMIT Demo: Norcem Test Centre (2015–2017). Aker Solution was chosen as a representative of liquid-based capture technology along with three other technology companies. This was part of Norcem’s programme for mapping suitable capture technologies at cement factories.

Full-scale demonstration project: Aker was chosen as a capture supplier to Norcem and delivered the front-end engineering design (FEED) study (DG3) to Norcem based on their corporate expertise and technology developed with support from the innovation system.

Figure 16: Illustrations from Aker Solution’s development phases

Effect of full-scale demonstration in the innovation system.

Basic research is supported by up to 100% of the innovation players, but the proportion of support decreases as technology matures further through the development phase, demonstration and realisation. The cost of development also increases significantly through these phases. In order for commercial players to justify the use of funds in development programmes, there has to be a potential market for the technology. In many ways, a full-scale demonstration and support for further commercialisation are the “fuel” driving an innovation system. Without further commercial maturation as described by the CRI (Commercial Readiness Index), the feedback loops in the innovation system will stop, and technological development will miss out on the potentially large cost reductions triggered by commercial projects. This cost reduction is often initiated by constant looping back in the innovation system with targeted research and development to optimise the technology. In a technology area such as CCS with a high degree of market failure, the players in the innovation system will pay even more attention to the positive signal given by a full-scale demonstration.

There are a number of international networks, applications and forums where CO_2 capture and storage work are being worked on. The Ministry of Petroleum and Energy, Gassnova and/or the Research Council of Norway are represented in a number of these. These bodies are playing an important role in maintaining an international focus and coordinating research, development and demonstration of CCS:

- EraNET-ACT
- Zero Emission Platform (ZEP)
- Strategic Energy Technologies Implementation Plans (EU SET planning)
- Carbon Sequestration Leadership Forum (CSLF)
- CEM
- Mission innovation
- Global CCS Institute (GCCSI)
- IEA Greenhouse Gas R&D Programme (IEAGHG)
- Cooperation agreement (MoU) on CO_2 handling with the USA
- North Sea Basin Task Force
- Carbon Capture & Storage Association (CCSA)
- CO_2 Geological Storage Europe (CO_2 GeoNet)

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