



## **Current and emerging industrial-scale CO<sub>2</sub> capture**

### **A brief overview**

### **1<sup>st</sup> Report of the Thematic Working Group on:**

### **CO<sub>2</sub> capture and utilization**

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EU CCUS PROJECTS NETWORK (No ENER/C2/2017-65/SI2.793333)



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## About the CCUS Projects Network

The CCUS Projects Network comprises and supports major industrial projects under way across Europe in the field of carbon capture and storage (CCS) and carbon capture and utilisation (CCU). Our Network aims to speed up delivery of these technologies, which the European Commission recognises as crucial to achieving 2050 climate targets. By sharing knowledge and learning from each other, our project members will drive forward the delivery and deployment of CCS and CCU, enabling Europe's member states to reduce emissions from industry, electricity, transport and heat.

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## Executive summary

This report follows from discussions at the European CCUS Projects Network's second knowledge-sharing event for members, held in the Netherlands on 16<sup>th</sup> October 2019. The aim of the report is to illustrate that CO<sub>2</sub> capture is feasible and operating at an industrial scale today, largely with amine-based technologies. According to the GCCSI, 19 CO<sub>2</sub> capture facilities world-wide are currently operating. Six of these facilities (Sleipner, Snøhvit, Boundary Dam, Petra Nova, Quest CCS, Port Arthur) are presented in this report to exemplify the feasibility of industrial-scale CO<sub>2</sub> capture.

Several CO<sub>2</sub> capture projects are currently being developed across Europe, some of them are focusing on capture only, and others are developed in the context of a full-chain CCS project. The present report presents a non-exhaustive list of emerging CO<sub>2</sub> capture projects in Europe, as summarized in the table below.

| Project (country)                          | Type of CO <sub>2</sub> source               | CO <sub>2</sub> capture capacity                                                   | Capture technology                                                                   |
|--------------------------------------------|----------------------------------------------|------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Fortum Oslo Varme (NO)                     | Waste to Energy                              | 400 kt CO <sub>2</sub> /year                                                       | Amine (Shell)                                                                        |
| Norcem Brevik (NO)                         | Cement                                       | 400 kt CO <sub>2</sub> /year                                                       | Amine (Aker Solutions)                                                               |
| LEILAC/Lixhe (BE)                          | Cement                                       | 76 tonnes CO <sub>2</sub> /day (intermittent)                                      | Indirect calcination                                                                 |
| Drax Bioenergy and CCS (UK)                | Biofueled energy                             | 4 x 4 Mt CO <sub>2</sub> /year                                                     | Amine or non-amine chemical considered                                               |
| KVA Linth (CH)                             | Waste to Energy                              | 100 kt CO <sub>2</sub> /year                                                       | Amine                                                                                |
| ECRA CCS, Colleferro (IT) and Retznei (AT) | Cement                                       | 842 ton CO <sub>2</sub> /day (Colleferro); 1231 ton CO <sub>2</sub> /day (Retznei) | Oxyfuel                                                                              |
| Acorn (UK)                                 | Gas processing and H <sub>2</sub> production | Gas processing 340 kt/year, H <sub>2</sub> production 500 kt/year                  | Several proven commercial CO <sub>2</sub> capture technologies are being considered. |
| Ervia and Gas Networks Ireland (IE)        | Natural gas fired power and oil refinery     | Envisages to begin with 2.5 Mt CO <sub>2</sub> /year                               | Not yet decided/ disclosed                                                           |

The CO<sub>2</sub> capture technologies currently relevant for or developing towards commercial-scale applications are not limited to the ones listed above. In this report a brief overview of relevant technologies and suppliers is included for completeness. In this context, Technology Centre Mongstad (TCM) is presented with its abilities to verify and de-risk CO<sub>2</sub> capture technologies.



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# Current and emerging industrial-scale CO<sub>2</sub> capture: an overview

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## 1 Introduction

**A Clean Planet for All**, COM (2018) 733 [1], is the new European strategic vision for a prosperous, modern, competitive and climate neutral economy which states that Carbon Capture and Storage (CCS) deployment is necessary for tackling CO<sub>2</sub> emissions that cannot be cut through e.g. energy efficiency and renewables. Especially, CCS is required for abating emissions from energy-intensive industries and (in the transitional phase) for the production of carbon-free hydrogen. It is observed in A Clean Planet for All that CCS has not yet reached the commercialization stage, hampered by among other topics, the *lack of demonstration* of CCS technology<sup>1</sup>.

### 1.1 Objective and scope

The objective of this brief report is to illustrate that CO<sub>2</sub> capture, as the first stage in any CCS chain, is already operating at an industrial scale today, and that additional CO<sub>2</sub> capture projects and technologies are emerging. The realization of CO<sub>2</sub> capture projects in Europe will provide the above-mentioned lacking demonstrations of CO<sub>2</sub> capture installations. For completeness, an additional objective with the report is to provide a brief and more general overview of different CO<sub>2</sub> capture technologies, and of CO<sub>2</sub> capture technology suppliers on the market.

This report follows from discussions at the European CCUS Projects Network's second knowledge-sharing event for members, held in the Netherlands on 16<sup>th</sup> October 2019. Discussions in the thematic working group on CO<sub>2</sub> capture and utilization concluded that there is a necessity to convey the message about the feasibility of CO<sub>2</sub> capture to a broader audience. Also, it was concluded that that an assembly of information on existing and emerging CO<sub>2</sub> capture projects and technologies would be useful to the individual CCUS Projects Network members, as well as for the future work of the group.

### 1.2 Report structure

This report consists of three main sections. *The Current industrial-scale CO<sub>2</sub> capture for storage or enhanced oil recovery (EOR)* presents examples of current operating CO<sub>2</sub> capture plants at industrial scale. The section *Emerging CO<sub>2</sub> capture projects in Europe* presents some of the emerging industrial CO<sub>2</sub> capture projects in Europe, with focus largely on members of the CCUS Projects Network. The section *CO<sub>2</sub> capture technologies overview* is included to provide a broader picture on activities within the field of CO<sub>2</sub> capture, and is included to illustrate the broad CO<sub>2</sub> capture technology portfolio that is being developed and gradually becoming available for industrial applications through technology suppliers.

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<sup>1</sup> Additionally, economic viability, regulatory barriers in some Member States and limited public acceptance are mentioned as factors preventing CCS commercialisation





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## 2 Current industrial-scale CO<sub>2</sub> capture for storage or enhanced oil recovery (EOR)

This section presents some of the operating, industrial-scale CO<sub>2</sub> capture facilities as of today. Only installations with capture for permanent storage or enhanced oil recovery, at a scale relevant for CO<sub>2</sub> capture or use (CCUS) are described. As of November 2019, the Global CCS Institute reports 19 operating industrial-scale CO<sub>2</sub> capture facilities worldwide [2]. Six of these installations are presented in sections 2.1-2.5. Sleipner and Snøhvit projects are, due to their similarities, presented in one joint section, and are included due to their connection to offshore CO<sub>2</sub> storage. Boundary Dam and Petra Nova are examples of CO<sub>2</sub> capture from power generation whereas Quest and Porth Arthur are examples of H<sub>2</sub> production with CO<sub>2</sub> capture. The other projects listed by the Global CCS institute are equally interesting, but are only briefly mentioned in section 2.6, since a complete overview of these facilities was deemed too lengthy for this report.

It should be noted that CO<sub>2</sub> capture for e.g. food industry is well known but is not covered in this report.

### 2.1 Sleipner and Snøhvit natural gas sweetening (Norway)[3]

**Project characteristics:** Currently, Sleipner and Snøhvit are the only industrial-scale operating CCS projects in Europe. In both facilities CO<sub>2</sub> is separated from natural gas and injected back into formations for storage. At Sleipner, CO<sub>2</sub> captured from natural gas from the Sleipner Vest and Gudrun fields is injected in the Utsira formation (North Sea). At Snøhvit, CO<sub>2</sub> was previously injected into the Tubåsen saline formation; now it is injected into the Stø formation (Barents Sea).

In 1996 Sleipner was the first site where CO<sub>2</sub> was injected into a dedicated storage site (opposed to EOR). Sleipner was the first industrial-scale CCS project worldwide.

**Location:** Norway. Natural gas from the Snøhvit offshore development is processed in Melkøya, an island very near Hammerfest (Northern Norway)[4], [5] and Sleipner is an offshore platform in the North Sea, about 250 km west of Stavanger.

**Operator/Owner:** Equinor operates both the CO<sub>2</sub> capture plants and the storage facilities. The licensees of Sleipner Øst (where the CO<sub>2</sub> capture plant is located) are Equinor Energy AS (59.6%), ExxonMobil Exploration and Production Norway AS (15.4%) LOTOS Exploration and Production Norge AS (15%) and KUFPEC Norway AS (10%)[6]. The licensees of the Snøhvit field are Equinor Energy AS (36.79%), Petoro AS (30%), Total E&P Norge AS (18.4%), Neptune Energy Norge AS (12%) and Wintershall Dea Norge AS (2.81%)

**Capture technology:** Amine. As a first of a kind plant, the CO<sub>2</sub> capture facility in Sleipner was developed for this application by Statoil (now Equinor); Aker Solutions was also involved in the development [7]. In Snøhvit, aMDEA is used for liquid absorption [8].

**CO<sub>2</sub> capture capacity:** Sleipner 1 Mt CO<sub>2</sub>/year; Snøhvit, 0.7M ton CO<sub>2</sub>/year

**CO<sub>2</sub> source stream:** Sleipner produces natural gas containing 9% CO<sub>2</sub>; Snøhvit produces natural gas with 5-8% CO<sub>2</sub>

**CO<sub>2</sub> captured and stored/used for EOR:** Stored, injected into saline aquifers.



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**Operating year:** Sleipner 1996; Snøhvit, 2008

**Additional comments:** Storage data from Sleipner will soon be released [9].



Figure 1. Processing plant of gas from Snøhvit in Melkøya<sup>2</sup>

## 2.2 Boundary Dam coal-fired power plant, BD3 (Canada)[10], [11]

**Project characteristics:** This is the world's first fully integrated and full-chain industrial-scale CO<sub>2</sub> capture and storage facility, with CO<sub>2</sub> capture retrofitted to a coal-fired power plant [12].

**Location:** Estevan, Saskatchewan, Canada

**Operator/Owner:** SaskPower

**Capture technology:** amine solvent; Shell (formerly Cansolv) combined SO<sub>2</sub> and CO<sub>2</sub> capture process.

**CO<sub>2</sub> capture capacity:** 1M ton CO<sub>2</sub>/year.

**CO<sub>2</sub> source stream:** exhaust flue gas from coal-fired power plant (115 MWe)

**CO<sub>2</sub> captured and stored/used for EOR:** part of the CO<sub>2</sub> is used for EOR in the Whitecap Resources oil reservoir and part is injected into the Deadwood formation (Aquistore project [13]).

**Operating year:** 2014

**Investment:** 1.467 billion CAD

**Lessons learned** [14]: Reasons for challenging undertaking were:

1. Power plant operators did not have experience in the amine absorption process (chemistry/chemical engineering).
2. The Shell process was not previously proven at commercial-scale at a coal-fired plant.
3. Process complications associated with fly ash and other contaminants.
4. Significant levels of amine degradation complicated performance.

The public commitment to directly address stakeholder concerns regarding the level of investment and a central vision to reach a CO<sub>2</sub> capture goal was a successful tactic to overcome difficulties. Learning and understanding operational capacities of each process unit was important, also to make

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<sup>2</sup> Figure taken from [https://commons.wikimedia.org/wiki/File:Melk%C3%B8ya\\_2015.jpg](https://commons.wikimedia.org/wiki/File:Melk%C3%B8ya_2015.jpg) Licensed under the Creative Commons Attribution 2.0 Generic license.



better decisions regarding necessary enhancements. Temperature control and thermal reclamation was improved. Flexibility for maintenance was also improved. Monitoring (instrumentation) to prevent fouling was included in the control system.

Two key success factors were the ability to continue to realize value from a 1970 power unit and that the value of the retrofitted power plant also comes from three valuable by-products (CO<sub>2</sub>, sulphuric acid and fly ash). An IEAGHG [report](#) [11] gives more detail about this project.



Figure 2 Boundary Dam Power Station Saskatchewan<sup>3</sup>

## 2.3 Petra Nova coal-fired power plant (United States) [15]

**Project characteristics:** CO<sub>2</sub> capture retrofitted to a coal-fired power plant. Currently it is the world's largest post-combustion CO<sub>2</sub> capture system in operation.

**Location:** WA Parish Generating Station, Thompsons, Texas, United States

**Operator/Owner:** Petra Nova Parish Holdings, LLC, a joint venture between NRG Energy (50%) and JX Nippon Oil & Gas Exploration (50%). NRG owns the power plant.

**Capture technology:** amine-based (post-combustion), KM CDR Process and KS-1 Solvent

**CO<sub>2</sub> capture capacity:** 1.6 Mt CO<sub>2</sub>/year (4.7 ton/day); 33% of total emissions of a 654 MW coal-fired power plant, corresponding to 90% of a 240 MW slipstream of flue gas.

**CO<sub>2</sub> source stream:** slipstream of exhaust flue gas from coal-fired power plant.

**CO<sub>2</sub> captured and stored/used for EOR:** CO<sub>2</sub> is used for EOR in oil field (West Ranch oil field); 130 km pipeline.

**Operating year:** 2017 (January). Construction started in July 2014, and was completed on budget and on schedule.

**Investment:** 1 billion USD (retrofit costs), of which 190 million USD from DOE (US).

**Lessons learned** [16]: Monitoring, verification and accounting (MVA) plan was developed by the University of Texas Bureau of Economic Geology to sync with oilfield operations and manages the plan

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<sup>3</sup> Figure taken from [https://commons.wikimedia.org/wiki/File:Boundary\\_Dam\\_Power\\_Station\\_Saskatchewan.jpg](https://commons.wikimedia.org/wiki/File:Boundary_Dam_Power_Station_Saskatchewan.jpg) Licensed under the Creative Commons Attribution-Share Alike 4.0 International license.





during a 3-year demonstration period. The plan includes reservoir modelling, CO<sub>2</sub> mass balance accounting, pressure monitoring, fluid sampling, groundwater monitoring, soil gas monitoring.

Lessons learned for CCS projects:

1. On-time/on-budget possible due to up-front planning, turn-key contracting and strong partners.
2. "First of a kind" projects require more time for commissioning and start-up than conventional projects.
3. Successful advanced energy projects will bring together a range of partners with diverse core competencies that collectively span all aspects of the venture [17].
4. Considering economics, minimize single points of failure and include spare part program for long-lead spares.



Figure 3 W.A. Parish Power Plant, Thompsons, TX<sup>4</sup>

## 2.4 Quest CCS (Canada) [18]

**Project characteristics:** The Scotford Upgrader is designed to process and convert 255 000 barrels of oil equivalent per day of diluted bitumen into synthetic crude oil. Producing the hydrogen required for the bitumen upgrading generates CO<sub>2</sub>, which can be captured.

**Location:** Scotford Upgrader, Northern Alberta, Canada

**Operator:** Shell

**Owners:** Shell Canada (60%), Chevron Canada Limited (20%), Marathon Canadian Oil Sands Holding Limited (20%)

**CO<sub>2</sub> capture capacity:** 1.2Mt CO<sub>2</sub>/year (one-third of the emissions from the Scotford Upgrader)

**Capture technology:** ADIP-X, regenerative-amine process with three absorbers and one amine stripper [19].

**CO<sub>2</sub> source stream:** process gas streams of three hydrogen-manufacturing units

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<sup>4</sup> Figure taken from <https://www.flickr.com/photos/royluck/5518927574> with a Attribution 2.0 Generic (CC BY 2.0) license.



**CO<sub>2</sub> captured and stored/used for EOR:** CO<sub>2</sub> is compressed to ~12 MPa and stored in the (deep saline) Basal Cambrian Sands (BCS) formation (65 km pipeline).

**Operating year:** 2015: regeneration unit in May; compression, dehydration and piping in August. Design capacity reached in September 2016.

**Investment:** 1 310 million CAD. Shell estimates that a similar project would cost 20-30% less with earned experiences [20]. Quest was awarded 120 million CAD from the Clean Energy Fund in Canada (CEF) and 745 million CAD from the Province of Alberta. Constructions started in second quarter of 2012.

**Lessons learned:** The measurement, monitoring and verification (MMV) plan (technologies and systems) is important for stakeholder acceptance and to ensure that the capture and pipeline facilities, as well as the storage site perform as expected. The governments of Alberta and Canada have been important support. Capacity milestones have been reached ahead of time. Joint transportation and storage facilities reduce costs. A recent IEAGHG [report](#) [21] gives more detail about these lessons.

## 2.5 H<sub>2</sub> production in Valero Refinery, Port Arthur (United States) [22], [23]

**Project characteristics:** This was the first commercial-scale, steam methane reformer hydrogen production facility incorporating vacuum-swing adsorption CO<sub>2</sub> capture. This was implemented as a retrofit project in two hydrogen production plants (steam-methane reformers) located in the Valero Refinery.

**Location:** Valero Refinery in Port Arthur, Texas, USA

**Operator/Owner:** Air Products. Denbury was subcontracted to undertake monitoring, verification and accounting (MVA) activities, and the Texas Bureau of Economic Geology (UT Austin) and UT Dallas were subcontracted for portions of MVA.

**CO<sub>2</sub> capture capacity:** Nameplate capacity is 0.95 Mt CO<sub>2</sub>/year, but during tests the equivalent of 1.045 Mt CO<sub>2</sub>/year were captured in both plants.

**Capture technology:** Vacuum-swing adsorption; capturing 90% of the CO<sub>2</sub>

**CO<sub>2</sub> source stream:** process gas stream from steam-methane reformers, with 10-20% CO<sub>2</sub>

**CO<sub>2</sub> captured and stored/used for EOR:** CO<sub>2</sub> is used for EOR in West Hastings Oil Field.

**Construction:** Engineering (FEED) study completed in 2010; investment decision in May 2011.

**Operating year:** First plant started capturing in December 2012 and the second in March 2013; full scale capture in May 2013

**Investment:** 431 million USD of which DOE provided 284 million USD (2009-2017).

**Lessons learned:** The key success factors were related to coordination and partnership between the technical team, site host, consultants, contractors; as well as deep financial commitment by the US DOE and regulatory incentives. A monitoring, verification and accounting (MVA) plan was also important. A publicly available [IEAGHG report](#) [23] gives more details about lessons learned.



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Figure 4 Valero Energy Corporation Refinery in Port Arthur, Texas<sup>5</sup>

## 2.6 Other large-scale projects with CO<sub>2</sub> capture

The Gorgon project in Australia is the most recent to start operations (August 2019). The Gorgon LNG facility with CO<sub>2</sub> injection in Australia will, when fully operational, be the largest geological storage facility in the world, with up to 4 M ton CO<sub>2</sub>/year [24]. The only large-scale offshore EOR operation is in Brazil's Petrobras Santos Basin, separating CO<sub>2</sub> from associated gas aboard anchored, floating production, storage, and offloading (FPSO) vessels, using membranes [25].

Other large-scale facilities are CNPC Jilin Oil Field (amine, 0.6 M ton CO<sub>2</sub>/year, EOR) in China and Abu Dhabi CCS (amine, 0.8 M ton CO<sub>2</sub>/year, EOR) in the UAE. Projects in the U.S. include Illinois Industrial CCS (1 M ton CO<sub>2</sub>/year, Injection), Lost Cabin gas plant (0.9 M ton CO<sub>2</sub>/year, EOR), Great Plains Synfuels Plant (3 M ton CO<sub>2</sub>/year, EOR), Enid Fertilizer (0.7 M ton CO<sub>2</sub>/year, EOR) [2].

## 3 Emerging CO<sub>2</sub> capture projects in Europe

The CO<sub>2</sub> capture projects described in section 1.2 provide evidence that CO<sub>2</sub> capture is feasible on industrial scale and is being done today. But the story does not end there – CO<sub>2</sub> capture projects are emerging world-wide, [2], [26]. To illustrate this development, some of the planned CO<sub>2</sub> capture projects and technologies that are being brought towards industrial-scale implementation in Europe are presented below. It must be noted that this is a non-exhaustive list.

### 3.1 Fortum Oslo Varme (Norway)[27]

**Project characteristics:** CO<sub>2</sub> capture from Norway's largest waste-to-energy plant, one of two candidates for CO<sub>2</sub> capture in the Norwegian Full-Scale CCS project. The Waste-to-Energy (WtE) plant incinerates more than 400 kt/y waste to generate power, district heating and cooling for Oslo. The excess heating from the capture process will be utilized in the district heating system.

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<sup>5</sup> This figure is taken from [https://en.m.wikipedia.org/wiki/File:Industrial-720706\\_640.jpg](https://en.m.wikipedia.org/wiki/File:Industrial-720706_640.jpg) and has been released into the public domain by its author, Carol M. Highsmith.



**Location:** Klemetsrud, Oslo, Norway

**Operator/owner:** Fortum Oslo Varme (FOV) and the municipality of Oslo (50% each)

**Capture capacity/potential:** 400 kt/y CO<sub>2</sub>, approximately 50% of the CO<sub>2</sub> is of biological origin (biomass)

**Capture technology:** Post-combustion capture by amine technology (Shell technology)

**CO<sub>2</sub> destination:** After capture CO<sub>2</sub> will be liquefied and stored in intermediate storage tanks. Transport from the capture plant to Port of Oslo by emission free trucks (transport distance about 10 km). Ships will load CO<sub>2</sub> every 4 days for transport to Kollsnes on the Norwegian West coast. Thereafter, the CO<sub>2</sub> will be transported with pipeline (~100 km) for permanent offshore storage. CO<sub>2</sub> transport and storage is managed by the Northern Lights project.

**Project timeline:** Feed study for the CO<sub>2</sub> capture plant was delivered to the Norwegian government on October 31<sup>st</sup>, 2019. Investment decisions for the Norwegian Full-Scale CCS project are expected by end 2020/beginning 2021 [28]. CO<sub>2</sub> delivery for transport and storage is expected in 2024 if investment decisions are positive.



Figure 5 Klemetsrud Waste to Energy plant<sup>6</sup>

### 3.2 Norcem (Norway)[29], [30]

**Project characteristics:** CO<sub>2</sub> capture from a cement plant, one of two candidates for CO<sub>2</sub> capture in the Norwegian Full-Scale CCS project. Norcem declare that they have a vision of zero CO<sub>2</sub> emissions from concrete products, from a life cycle perspective, by 2030.

**Location:** Brevik, south-east Norway (coastal area)

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<sup>6</sup> Figure taken from [https://no.wikipedia.org/wiki/Fil:Klemetsrud\\_energigjenvinningsanlegg\\_02.JPG](https://no.wikipedia.org/wiki/Fil:Klemetsrud_energigjenvinningsanlegg_02.JPG) under Creative Commons license



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**Operator/Owner:** Norcem, part of HeidelbergCement Northern Europe

**Capture capacity/potential:** 400 kt CO<sub>2</sub>/year

**Capture technology:** Post-combustion capture by amine technology (Aker Solutions technology)

**CO<sub>2</sub> source stream:** combination of CO<sub>2</sub> released from calcination of limestone, combustion of coal, waste derived fuels and biomass.

**CO<sub>2</sub> destination:** After capture, CO<sub>2</sub> will be liquefied and stored in intermediate storage tanks. Ships will load CO<sub>2</sub> every 4 days for transport to Kollsnes on the Norwegian west coast. Thereafter, the CO<sub>2</sub> will be transported with pipeline (~100 km) for permanent offshore storage. CO<sub>2</sub> transport and storage is managed by the Northern Lights project.

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Figure 6 Norcem Brevik Cement plant<sup>7</sup>

### 3.3 Indirect calcination in cement kiln LEILAC [31], [32] (Belgium)

**Project characteristics:** LEILAC (Low Emissions Intensity Lime And Cement) is a EU Horizon 2020 (H2020) research and innovation project (2016-2020) that pilots a CO<sub>2</sub> capture technology for unavoidable emissions in the cement and lime industries. LEILAC is an example of branch-specific CO<sub>2</sub> capture technology.

**Location:** the pilot plant is hosted in a Heidelberg Cement plant in Lixhe, Belgium

**Operator/owner:** HeidelbergCement Group owns the plant where the technology is tested, the technology is proprietary of Calix. Calix is the core technology provider and project leader [33].

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<sup>7</sup> Picture taken from [https://no.wikipedia.org/wiki/Fil:Norcem\\_Brevik\\_fra\\_sj%C3%B8en.JPG](https://no.wikipedia.org/wiki/Fil:Norcem_Brevik_fra_sj%C3%B8en.JPG) under Creative Commons license.



This project is financed by the European Commission under service contract No ENER/C2/2017-65/SI2.793333.



**Capture capacity/potential:** The pilot plant has a capacity of 240 ton/day of raw meal for cement production and 200 ton/day ground limestone, respectively. This corresponds to 76 tonnes CO<sub>2</sub>/day. In July 2019, it was announced that the technology concept was operating successfully [33], [34]. Currently capturing around 5% of a typical cement plant's process emission, LEILAC is developing a modularised scale up approach (capable of capturing at least 20% of a typical cement plant's process emissions) with a retrofit capability, that will ultimately enable all of the cement plant calciner CO<sub>2</sub> emissions to be efficiently captured [35].

**Capture technology:** Direct Separation (Calix)[36], aims to enable the cement and lime industries to capture their unavoidable CO<sub>2</sub> process emissions for minimal cost. By using indirect heating, the highly concentrated CO<sub>2</sub> released by processing raw materials is not mixed with combustion air, and can be separated without the need for additional processes or chemicals.

**CO<sub>2</sub> destination:** within the current LEILAC project it is not planned to compress or liquefy the CO<sub>2</sub> separated, due to the intermittent nature of the pilot test runs [35]. The participants of LEILAC are nevertheless interested in the development of the complete CCUS chain.

**Project timeline:** The H2020 project lasts 2016-2020.

### 3.4 Drax Bioenergy and CCS (UK)[37]

**Project characteristics:** CO<sub>2</sub> capture from Drax's Biomass Generation Facility in North Yorkshire, England. The facility has four 100% Biomass Fired generators each of 670MW, providing 12% of the UK's renewable electricity in 2018.

**Owner/operator:** Drax Group PLC

**Location:** Drax Power Station, Selby, North Yorkshire, England.

**Project timeline:** The project is currently in feasibility stage. Pre-FEED studies on one or more technology are to begin next year, with Full FEED expected on the capture plant in 2021. Investment decisions will be taken in 2023/2024 in line with the development of UK CCUS Policy and the Onshore and Offshore Transport & Storage Infrastructure, being developed by project partners National Grid Ventures and Equinor. Project delivery of the 1st BECCS unit is expected in 2027.

**Capture technology:** Post combustion capture technology, amine and non-amine-based chemistries currently being assessed.

**Capture capacity/potential:** 4Mt/year CO<sub>2</sub> per unit, 16Mt/year CO<sub>2</sub> in total. Unit 2 is targeting deployment in 2027, deployment for Units 1, 3 & 4 planned to follow.

**CO<sub>2</sub> destination:** After capture, CO<sub>2</sub> will be transported into the Southern North Sea, with the Endurance field the initial storage location, the project is expected to act as the anchor project within the Zero Carbon Humber, and Project collaboration between Drax, National Grid Ventures and Equinor.

### 3.5 KVA Linth WtE plant (CH) [38]

**Project characteristics:** CO<sub>2</sub> capture from a waste to energy plant. It is the first candidate for CO<sub>2</sub> capture in Switzerland. The Waste to Energy (WtE) plant incinerates about 112 ktons of waste annually



This project is financed by the European Commission under service contract No ENER/C2/2017-65/SI2.793333.

to generate electrical power, district heating, and recycle ferrous and non-ferrous metals from the bottom ash.

**Owner/Operator:** 28 local communities from the Cantons of Glarus, Schwyz and St. Gallen, forming an association for waste disposal and recycling in the Linth area in Switzerland.

**Location:** Niederurnen (Canton of Glarus, Switzerland)

**Project timeline:** Preliminary study for full CO<sub>2</sub> capture from 2 incineration lines, including the decision for a suitable process concept, basis engineering including the implementation, mass and energy flows, and CAPEX/OPEX estimation. Realization can be independent from the time schedule for the renewal of one incineration line, depending on the political commitment and financial support from the government.

**Capture technology:** Amine capture; however, the applied amine still has to be evaluated.

**Capture capacity/potential:** 100 kt CO<sub>2</sub>/year, approximately 50% of the CO<sub>2</sub> is of biological origin

**CO<sub>2</sub> destination:** After capture, CO<sub>2</sub> will be liquefied and stored in intermediate storage tanks. Possibly a pipeline will deliver the CO<sub>2</sub> to a railway station nearby for loading railway containers. Thereafter, the CO<sub>2</sub> will be transported by train and brought to the transport chains of the Northern Lights project.



Figure 7. KVA Linth Waste to Energy plant<sup>8</sup>

### 3.6 ECRA CCS project (Italy/Austria)

**Project characteristics:** The European Cement Research Academy (ECRA) is a platform for the European cement industry to support, organize and undertake research activities within the context of the production of cement and its application in concrete. Very few, if any, cement kilns are foreseen

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<sup>8</sup> Picture provided by Stefan Ringmann, KVA Linth.



to be built in the future, and focus is therefore on enabling retrofit of oxyfuel CO<sub>2</sub> capture in existing cement kilns in Europe. ECRA is member of the board for the Norcem CO<sub>2</sub> capture project, thus ensuring knowledge sharing on CO<sub>2</sub> capture in the cement industry.

Demonstration of the oxyfuel CO<sub>2</sub> capture technology is planned through the retrofit of two existing cement kilns. Elements of the oxyfuel technology have been tested previously (Burner, calciner and clinker cooler<sup>9</sup>) but not the full oxyfuel process.

**Owners/operators and Locations:** First demonstration is planned in Colleferro in Italy (owned by HeidelbergCement Group), and thereafter in Retznei in Austria (owned by LafargeHolcim Group). The Colleferro kiln is currently in stand-by and uses only petcoke as fuels and has been identified as a suitable candidate for the first implementation of oxyfuel retrofit. The Retznei plant has the goal of using 100% alternative fuels [39].

**Project timeline:** The project is currently awaiting financing, and the timeline is therefore uncertain.

**Capture technology:** Oxyfuel CO<sub>2</sub> capture, where fuel is burnt in an oxygen-rich atmosphere rather than in air. This yields a CO<sub>2</sub>/H<sub>2</sub>O-rich flue gas.

**CO<sub>2</sub> capture capacity/potential** [40]: 842 ton CO<sub>2</sub>/d from the Colleferro plant and 1231 ton CO<sub>2</sub>/day from the Retznei plant (with 90% capture rate)

### 3.7 ACORN CCS and H<sub>2</sub> production (Scotland, UK) [41]

**Project characteristics:** The Acorn project is centred around the St Fergus Gas Terminal, in north east Scotland, where around 35% of natural gas in the UK comes onshore. Here, a hub for CCS will be established for CO<sub>2</sub> captured from existing industrial sources and from new hydrogen (H<sub>2</sub>) production facilities. Thus, there are two elements of the Acorn project, Acorn CCS and Acorn Hydrogen, with Acorn CCS leading first and being operational in 2024. The ERA-NET ACT Acorn [42] project was a collaboration between eight European partner organizations to progress the project's feasibility phase. The current industrial phase of work is running until late 2020.

**Owners/operators and Locations:** The project is owned and operated by Pale Blue Dot Energy Ltd, with industrial contributions from both Shell and Chrysaor. The location is St Fergus Gas Terminal.

**Project timeline** [43]: The detailed engineering for Phase 1 of Acorn CCS is ongoing. Several proven commercial CO<sub>2</sub> capture technologies are being considered for capture plant which will aggregate two emission points. In Acorn Hydrogen, North Sea natural gas will be reformed into hydrogen (via SMR)[44] and CO<sub>2</sub> emissions will be mitigated through the Acorn CCS infrastructure. Produced hydrogen can be used for transport applications or fed into and blended with natural gas in the national transmission the gas grid [45].CO<sub>2</sub> injection from hydrogen production may be starting in 2024.

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<sup>9</sup> Tests were done in the H2020 project CEMCAP: [www.sintef.no/projects/cemcap](http://www.sintef.no/projects/cemcap)





**Capture technology:** Several proven commercial CO<sub>2</sub> capture technologies are being considered. A single capture system will process emissions from two initial sources in the gas processing terminal, with initial capture volumes of 340kt CO<sub>2</sub>/y.

**CO<sub>2</sub> capture capacity/potential** [46]: The gas terminals collectively emit 600ktCO<sub>2</sub>/y [41]. The project will start by capturing 340ktCO<sub>2</sub>/y from 2024. Additional 500 kt CO<sub>2</sub>/y from hydrogen production will be added a year later. Further build out from local, regional and international CO<sub>2</sub> sources will be added subsequently.

**CO<sub>2</sub> destination:** Acorn CCS is designed to take advantage of the existing gas pipelines that can be repurposed for CO<sub>2</sub> transportation, and storage in the Acorn CO<sub>2</sub> Storage Site which has been already licensed from the regulator. The project has built out plans for a more extensive CO<sub>2</sub> transport and storage system to deliver a service to local regional and international emitters. The plan is to use an existing onshore pipeline (Feeder 10, 280 km, 36") to bring CO<sub>2</sub> captured in the Grangemouth cluster to St Fergus. In addition, CO<sub>2</sub> from other sites in the UK and Europe can be imported through Peterhead Port. The transportation infrastructure element of Acorn CCS is a European Project of Common Interest (PCI).



Figure 8 St Fergus Terminal<sup>10</sup>

### 3.8 ERVIA, Gas Networks Ireland (Ireland)

**Project characteristics:** Ervia, distributes natural gas through Gas Networks Ireland. The company has a 2050 vision of a net zero carbon gas network [47]. The project foresees CO<sub>2</sub> injection in Ireland and the possible export of CO<sub>2</sub> to other countries for injection in fields in the North Sea [48].

The Cork CCS Feasibility study analysed the possibility of establishing a CCS industry cluster in the Cork area, in southern Ireland, capturing CO<sub>2</sub> from two natural gas power plants and Irving oil refinery. The project foresees using the existing offshore gas pipeline to the depleted offshore Kinsale gas field, off the coast of Cork (decommissioning due to start in 2020). In September 2019 Ervia signed a Memorandum of Understanding (MOU) with Equinor on assessing the potential for Ireland to benefit from Carbon Capture and Storage (CCS) [49].

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<sup>10</sup> Picture taken from [www.geograph.org.uk/photo/1695742](http://www.geograph.org.uk/photo/1695742) Licensed under the Creative Commons License



**Owners/operators and Locations:** Ervia and Gas Networks Ireland, in Ireland

**Project timeline:** The two natural gas power plants and refinery in Cork emit 2.5 Mt CO<sub>2</sub> /year [48]. In the 2050 vision, CCS will commence in 2028, capturing 2.8 Mt CO<sub>2</sub>/year in the Cork area. In 2030-2035 will add 0.6 Mt CO<sub>2</sub>/year from process emissions and 0.3 Mt CO<sub>2</sub>/year from the Whitegate Oil Refinery. Then, in 2038 additional 2.5 Mt CO<sub>2</sub> /year will be captured from two other power plants.

**Capture technology:** Not yet decided/disclosed.

**CO<sub>2</sub> capture capacity/potential:** The current vision is to start with 2.5 Mt CO<sub>2</sub> /year in Cork in 2028, to reach 18.7 Mt CO<sub>2</sub> /year in Ireland by 2050.



Figure 9 Whitegate Refinery and Power Station in Cork<sup>11</sup>

### 3.9 Emerging CO<sub>2</sub> capture research consortium of cement companies [50], [51]

In November 2019, a new research consortium of four European cement manufacturers was announced. The companies are Buzzi Unicem/ Dyckerhoff (Wiesbaden, Germany), Heidelberg Cement (Germany), Schwenk (Ulm, Germany) and Vicat (Paris, France). The consortium will set up a research facility to test CO<sub>2</sub> capture technologies for the cement industry at a semi-industrial scale. The testing facility will be in southern Germany, but the exact location is still undisclosed.

## 4 CO<sub>2</sub> capture technologies overview

This section briefly introduces CO<sub>2</sub> capture technologies currently relevant for or developing towards commercial-scale applications. It is important to note that the choice of technology will be influenced not only by technology maturity but by factors such as the source of CO<sub>2</sub> (e.g. concentration, pressure, flowrate) and type of industrial CO<sub>2</sub>-emitting facility being considered for capture, where the availability of waste heat is an important parameter. The list of described technologies is not exhaustive, but it should reflect relevant technologies for large-scale applications. Examples of technologies not currently relevant for large-scale applications and therefore not described in this report are electrochemical separation, microbial and microalgae, and direct air capture [52].

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<sup>11</sup> Picture taken from [www.geograph.ie/photo/3476334](http://www.geograph.ie/photo/3476334); licensed for reuse under Creative Commons License.



Before outlining these technologies, an introduction is given to Technology Centre Mongstad (TCM), a member of CCUS Knowledge Sharing Network, and the abilities of TCM to verify and de-risk CO<sub>2</sub> capture.

#### 4.1 TCM – testing, verifying and improving CO<sub>2</sub> capture [53]–[56]

The Technology Centre Mongstad (TCM), in southwest Norway, is the world's largest facility for testing, verifying and improving CO<sub>2</sub> capture technologies. The aim of TCM is to help reduce CO<sub>2</sub> capture technology costs and risks before full-scale implementation. Two solvent-based post-combustion capture test facilities (~12MWe each [57], combined capacity 100kt CO<sub>2</sub> /year [58]) are available, namely, amine technology from Aker Clean Carbon (ACC, now Aker Solutions) [59] and a chilled ammonia process from Alstom (now GE). In addition, there is space and utilities on a third lot to test different plug-in technologies or equipment (e.g. some novel solvent, sorbent, and membrane systems). Flue gas from a gas turbine power plant (~3.5% CO<sub>2</sub>) and from a refinery catalytic cracker (~13% CO<sub>2</sub>), and mixtures thereof, are available for test campaigns. At TCM there are hundreds of sample points and 4000 measuring instruments connected to the control room, making possible to test advanced process control strategies. Test campaigns can be done to obtain, for example, information about solvent management, in-line process variations, environmental performance and the effect of process modifications.



Figure 10 Air view of Mongstad area, where TCM is located<sup>12</sup>

Since 2012, TCM has tested out technologies from Norwegian, American, Canadian, Indian, and Chinese companies, including Aker Solutions (former Aker Clean Carbon), GE (former Alstom Carbon Capture), Shell (former Cansolv), Carbon Clean Solutions, ION Engineering and Fluor. Examples of international collaboration are a contract with the U.S. Department of Energy (DOE) to test advanced capture technologies in TCM, a collaboration with the U.S. Department of Energy's Carbon Capture Simulation for Industry Impact (CCSI<sup>2</sup>), and a long-term collaboration with ENGIE Laborelec (Belgium). Open results from test campaigns at TCM using monoethanolamine (MEA) can be found [here](#) [60] and other research publications can be found [here](#) [61].

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<sup>12</sup> Figure taken from [https://no.wikipedia.org/wiki/Fil:Mongstad\\_oktober\\_2013.jpg](https://no.wikipedia.org/wiki/Fil:Mongstad_oktober_2013.jpg) under Creative commons license.



## 4.2 Amine capture (liquid absorption)

Post-combustion CO<sub>2</sub> capture with amine solvents is currently the most mature CO<sub>2</sub> capture technology, and it has been demonstrated at full scale [62], reaching a Technology Readiness Level (TRL)<sup>13</sup> 9 as evidenced in the large scale projects in Chapter 2, compared to the lower TRLs of other technologies<sup>27</sup>. It can be implemented as a retrofit option, so it can be installed in operating plants.

CO<sub>2</sub> is removed from the flue gases when it reacts with a (generally amine-based) solvent to form an intermediate compound (chemical bond). In a second vessel, the solvent is regenerated with the application of heat (energy from condensing steam) producing the original solvent and a CO<sub>2</sub> stream [63], see Figure 11. The absorption capacity of chemical solvents such as amines is higher compared with capacities of physical solvents (described below).

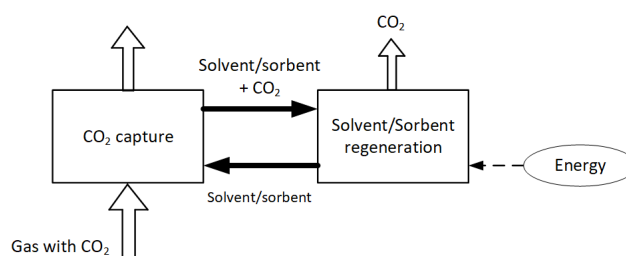


Figure 11 Separation with solvents or sorbents<sup>14</sup>

There are different commercial solvents, with different types of amine. There are also variations of the basic configuration, depending on proprietary technologies. Examples of amine-based technologies are BASF's aMDEA, Shell (used in [Boundary Dam](#) and to be used by Fortum), Shell ADIP-X (used in [Quest](#)), Aker Solutions (to be used by Norcem) and KM-CDR Process by MHI and KEPCO (used in [Petra Nova](#)).

The benchmark for chemical absorption has been 30 %weight MEA (monoethanolamine). However, in a recent technical report, the IEAGHG proposed a PZ+AMP (piperazine+ 2-amino-2methil-1-propanol, 1:2 molar ratio) as a new benchmark [52].

## 4.3 Liquid absorbents other than amines

Besides amines, there are other liquid absorbents, both physical and chemical, that can be used for CO<sub>2</sub> capture, with a similar process configuration as in Figure 11. With physical absorbents no chemical bonds are formed (as with amines) and CO<sub>2</sub> is simply dissolved physically; therefore, thermal requirements for regeneration are lower than for chemical solvents. Physical absorbents are relevant because some of them have been tested at a commercial scale and provide good results at high partial pressures [62]. Examples of physical solvents are DEPG (Dimethyl Ether of Polyethylene Glycol), MeOH (Methanol), NMP (N-Methyl-2-Pyrrolidone) and PC (Propylene Carbonate).

<sup>13</sup> TRL is a method to estimate the maturity of technologies, where TRL 1 is basic research technology (basic principles observed) and TRL 9 corresponds to normal commercial service. A description of each level can be found in [78].

<sup>14</sup> Figure made by Rahul Anantharaman, SINTEF Energy Research; modified by Adriana Reyes Lúa, SINTEF Energy Research.



Examples of technologies used at commercial scale are Selexol, in the Coffeyville Gasification Plant and the Enid Fertilizer Plant, and Rectisol in the Great Plains Synfuels Plant. Selexol uses dimethyl ethers of polyethylene glycol as solvent and Rectisol uses methanol. Other technologies are Purisol, Morphysorb. These processes are not specific for CO<sub>2</sub> and are considered to be for acid-gas removal.

## 4.4 Adsorption

With solid sorbents the CO<sub>2</sub> adsorbs (not absorbs) into the surface of highly porous solids. Once the solid is saturated, the solid adsorbent can be regenerated via temperature (TSA), pressure (PSA) or electrical swings. The binding of CO<sub>2</sub> with the solid can be physical (physisorption) or chemical (chemisorption) [52].

To implement adsorption, a series of vessels (e.g. three) are required. One is in operation mode while the others are in regeneration mode. CO<sub>2</sub>-rich gas (e.g. syngas) is sent to the operating vessel (high pressure, low temperature), in which CO<sub>2</sub> is adsorbed and hydrogen-rich gas exits the vessel. Once that the adsorbent of the operating vessel is saturated, a new vessel becomes the operating vessel and the saturated vessel undergoes regeneration at a different temperature or pressure (low pressure, high temperature).

Pressure swing adsorption (PSA) is generally used with physical sorbents and is suitable for CO<sub>2</sub> capture at higher partial pressure [64], [65]. Low pressure can reach vacuum (vacuum-swing adsorption, VSA). In VSA, the adsorbents remove CO<sub>2</sub> under pressure and regeneration requires a series of pressure equalizations to reduce pressure before CO<sub>2</sub> is removed by a vacuum pump. This is the technology used in the [Air Products project at the Port Arthur hydrogen production facility](#). [23]. Temperature swing absorption (TSA) is usually required with chemisorption, because the bond is stronger. In general, solid sorbents require less energy than liquid absorbents, but can exhibit challenges like regeneration time or space requirements [52].

## 4.5 Membranes

Membranes are a thin barrier over which one species is more mobile than others present in the gas mixture, and the partial pressure difference across the membrane is the driving force for separation (Figure 12). CO<sub>2</sub> selective membranes typically produce a CO<sub>2</sub> enriched stream at low pressure and a CO<sub>2</sub> depleted stream at high pressure [66]. The required compression equipment can be limiting for scaling up. In some cases, low CO<sub>2</sub> partial pressure and presence of water vapor are also challenges, whereas their modular nature is an advantage. The requirements (and TRL) for the membrane will depend on the stream<sup>39</sup>. Membranes are used in the FPSO vessels in the Petrobras Santos Basin in Brazil to separate CO<sub>2</sub> from natural gas, but in general, membranes have a TRL of 6, and the process itself has a lower TRL [52].





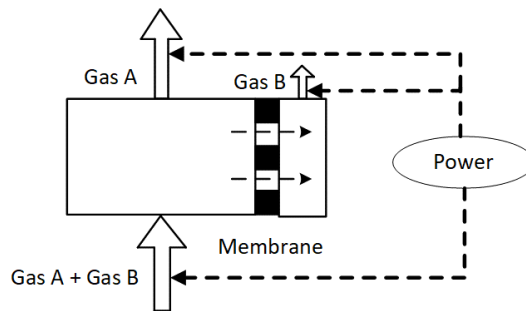


Figure 12. Separation with membranes<sup>15</sup>

## 4.6 Oxyfuel combustion

In oxyfuel processes, nitrogen is removed from air via an air separation process (typically cryogenic), producing nearly pure oxygen, which is used to burn the fuel, producing a flue gas of mainly CO<sub>2</sub> and water (steam). Water can be separated via cooling and a CPU (CO<sub>2</sub> compression and purification unit)<sup>37</sup>. In order to meet specifications for CO<sub>2</sub> transport and storage, other impurities such as SO<sub>x</sub>, NO<sub>x</sub> and Hg may also be necessary to remove from the flue gas. Oxyfuel technology was first developed for power plants. A 30 MW lignite-fired oxyfuel boiler pilot plant was built and tested at the Schwarze Pumpe power plant in Germany om 2009-2014 [67]. The Unity Power Alliance IsoTherm oxyfuel process has achieved a TRL-5 with a 5-MW<sub>th</sub> facility in Italy and a 15-MW<sub>th</sub> facility in Singapore. For gas turbines, Allam Cycle [68] development is led by Net Power (Texas). A TRL-5 of such technology would be achieved in its 25-MWe prototype startup [69]. A 30 MW lignite-fired oxyfuel boiler pilot plant was built and tested at the Schwarze Pumpe power plant in Germany om 2009-2014 [67]. This allowed testing the oxyfuel technology together with the other integrated units (Air Separation Unit and CO<sub>2</sub>-plant), reaching TRL-7. The largest oxy-PFBC (Pressurized Fluidized Bed Combustor) plant is a collaboration between Gas Technology Institute (GTI) and Linde has reached TRL-6 with a 1 MW<sub>th</sub> pilot in Canada [52], [70]. Oxycoal power plant technologies are reported to be under trials to establish TRL-8 during the period from 2016 to 2020 [71]. Oxyfuel technology is pursued for cement in the ECRA CCS project (refer to section 3.6).

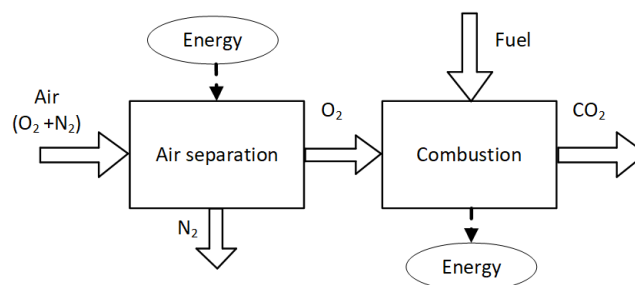


Figure 13 Oxyfuel combustion<sup>16</sup>

<sup>15</sup> Figure made by Rahul Anantharaman, modified by Adriana Reyes Lúa, SINTEF Energy Research

<sup>16</sup> Figure made by Adriana Reyes Lúa, SINTEF Energy Research.



## 4.7 High-temperature solids looping

The principle of this type of technology is a reacting solid circulating in a system of two interconnected beds.

In *chemical looping combustion*, the solid is a metal-metal oxide system used to transport oxygen from the air to the fuel, avoiding direct contact of air and fuel. The metal is oxidized in an air reactor, and the oxide is circulated the fuel reactor, where it reacts with the fuel. This way, the exhaust from the combustion contains mainly CO<sub>2</sub> and water, which are easily separated. This technology is currently at TRL4, but there are research projects to push it to TRL7 [72]. It is a type of oxy-fuel process without the need of a separation unit [73].

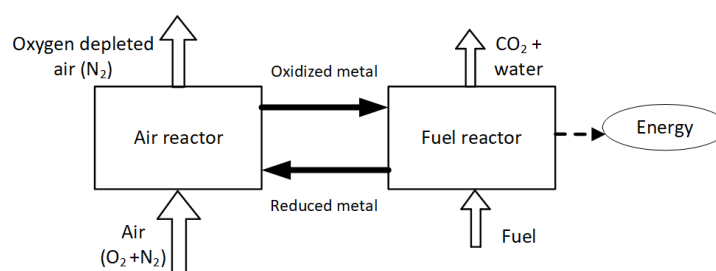


Figure 14 Chemical looping combustion<sup>17</sup>

In post-combustion *calcium looping* (CaO/CaCO<sub>3</sub>) the exhaust of the gas turbine enters a carbonator with CaO, which captures the CO<sub>2</sub>, reacting into CaCO<sub>3</sub>. CaCO<sub>3</sub> then is circulated to the calciner, where it is regenerated at a high temperature, releasing raw CO<sub>2</sub> for conditioning (and turning back to CaO) [74]. Thus, it is more likely to be applied as a retrofit technology, e.g. for cement.

## 4.8 Hlsarna

[Hlsarna](#) is an example of industry-specific technology, for iron and steel. In this technology, iron ore is fed to the high-temperature cyclone at the top of the reactor, where it is liquified such that it drips to the bottom of the reactor. Powdered coal is injected into the middle of the reactor, where it combines with the molten ore to produce pure liquid iron and CO<sub>2</sub>. It has been developed by Tata Steel (cyclone converter furnace) and Rio Tinto (smelter), and Tata Steel has full ownership of the patents. The pilot is in a Tata Steel plant in Ijmuiden (NL) and the maximum reported capacity (December 2017) is of 60,000 tonnes of liquid iron a year [75], [76].

## 4.9 CO<sub>2</sub> liquefaction (phase separation)

In low-temperature separation the CO<sub>2</sub> is cooled to the point where the CO<sub>2</sub> forms a liquid or a solid that can be separated. CO<sub>2</sub> liquefaction technology is suitable as a standalone for some applications where a fairly high CO<sub>2</sub> concentration is available in a stream, such as H<sub>2</sub> production with CO<sub>2</sub> capture

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<sup>17</sup> Figure made by Adriana Reyes Lúa, SINTEF Energy Research.



or in combination with membranes/PSA for post-combustion capture applications in a hybrid configuration. A commercial application of the technology is the AirLiquide CryoCap technology [77].

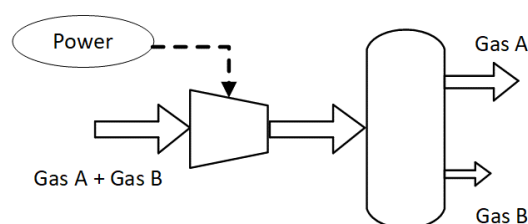


Figure 15 Phase separation through compression and cooling, CO<sub>2</sub> typically exits the separator as a liquefied gas (gas B), while more volatile compounds remain in the gas phase.<sup>18</sup>

## 4.10 CO<sub>2</sub> capture technology providers

Table 1 lists CO<sub>2</sub> capture technology providers offering industrial-scale solutions. The list should not be seen as exhaustive, but it reflects that there is a variety of technology providers in this field. Currently, most of the commercially available technologies are for post-combustion capture using liquid (amine) absorption. Each amine technology uses a proprietary solvent, which has an influence on both energy efficiency and CO<sub>2</sub> capture capacity. Energy integration may also differ among technologies. Furthermore, as can be seen in Table 1, there are providers of several other capture technologies on the market. As flue streams from different processes may have different characteristics (e.g. CO<sub>2</sub> content), it is not possible to single-out one technology as better than another.

Table 1 Industrial CO<sub>2</sub> capture technology providers

| Provider                                                     | Capture technologies                                             | Comments                                                                                                              |
|--------------------------------------------------------------|------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| <a href="#">Aker Solutions</a><br>(former Aker Clean Carbon) | Liquid absorption (amine)                                        | Mobile test unit (MTU) continuously operated since 2008.                                                              |
| <a href="#">BASF</a> and <a href="#">Linde</a>               | Liquid absorption (amine)                                        | <a href="#">OASE</a> <sup>®</sup> is a joint project between BASF and Linde; tested at pilot-scale.                   |
| <a href="#">Carbon Clean Solutions</a>                       | Liquid absorption (amine)                                        | Commercial technology is CDRMax <sup>™</sup>                                                                          |
| <a href="#">Fluor</a>                                        | Liquid absorption (amine) and physical solvents.                 | Econamine FG Plus <sup>SM</sup> (EFG+) is amine based and Fluor Solvent <sup>SM</sup> is based on a physical solvent. |
| <a href="#">GE</a> (former Alstom Carbon Capture)            | Liquid absorption (amine and chilled ammonia) and oxy-combustion | Also developing regenerative calcium cycles and chemical looping combustion.                                          |
| <a href="#">ION Engineering</a>                              | Liquid absorption (amine)                                        | Seeking for partners for commercialization, tested at TCM.                                                            |
| <a href="#">MHI</a> (Mitsubishi Heavy Industries)            | Liquid absorption (amine)                                        | The KM CDR PROCESS is used in Petra Nova power plant.                                                                 |

<sup>18</sup> Figure made by Rahul Anantharaman, SINTEF Energy Research.





|                                                |                                                 |                                                                                                                                                                                                                   |
|------------------------------------------------|-------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <a href="#">Shell</a> (former Cansolv)         | Liquid absorption (amine)                       | Shell technologies are installed in Boundary-Dam, Gorgon (Australia) and Quest                                                                                                                                    |
| <a href="#">Toshiba</a>                        | Liquid absorption (amine)                       | Pilot plant capturing 10 ton CO <sub>2</sub> /day. Large scale plant capturing 500 ton CO <sub>2</sub> /day from thermal plant in Japan under construction. <a href="#">Operation expected to start in 2020</a> . |
| <a href="#">CO<sub>2</sub> Solutions</a> (CSI) | Absorption (carbonic anhydrase (CA))            | Commercial version <a href="#">in softwood kraft pulp mill</a> in Canada                                                                                                                                          |
| <a href="#">Air Liquide</a>                    | <a href="#">Physical absorption</a>             | Rectisol™ is conceived as an acid gas removal process, which can be used for CO <sub>2</sub> capture. It is licensed by Linde and Air Liquide.                                                                    |
| <a href="#">Honeywell UOP Selexol™</a>         | Physical absorption                             | The <a href="#">Selexol™</a> process is conceived as an acid gas removal process, which can be used for CO <sub>2</sub> capture. The solvent is a mixture of the dimethyl ethers of polyethylene glycol.          |
| <a href="#">Honeywell UOP Benfield™</a>        | Physical absorption                             | Used in some BECCS projects. Uses using hot potassium carbonate                                                                                                                                                   |
| <a href="#">Linde</a>                          | <a href="#">Physical absorption</a>             | Rectisol™ is conceived as an acid gas removal process, which can be used for CO <sub>2</sub> capture.                                                                                                             |
| <a href="#">Air Products</a>                   | <a href="#">Pressure swing adsorption (PSA)</a> | Vacuum swing adsorption (VSA) in the Valero Refinery is a variation of PSA by Air Products.                                                                                                                       |
| <a href="#">Svante</a>                         | <a href="#">(Nano) solid adsorbents</a>         | Developed as post-combustion solution for flue gases from of cement, steel, ammonia, aluminium, methanol and hydrogen                                                                                             |
| <a href="#">MTR</a>                            | Membranes                                       | Developed for post-combustion CO <sub>2</sub> capture of industrial flue gases, such as power plants, cement plants and steel plants.                                                                             |
| <a href="#">Air Liquide</a>                    | <a href="#">CO<sub>2</sub> liquefaction</a>     | Cryocap™ was developed to capture CO <sub>2</sub> from H <sub>2</sub> production.                                                                                                                                 |
| <a href="#">Air Products</a>                   | <a href="#">Oxyfuel</a>                         | Non-ferrous and ferrous case studies are provided on the website.                                                                                                                                                 |
| <a href="#">Linde</a>                          | <a href="#">Oxyfuel</a>                         | TRL 8 for oxyfuel see section 4.6.                                                                                                                                                                                |

## 5 Concluding remarks

With the aim to provide evidence that CO<sub>2</sub> capture is technically feasible and progressing, this report has summarized publicly available information of operating industrial-scale CO<sub>2</sub> capture projects and a selection of emerging industrial CO<sub>2</sub> capture and CCS projects in Europe. The facilities described in this report, as well as other emerging projects, are relevant for the demonstration of technologies and economic viability of CO<sub>2</sub> capture, which is one of the seven strategic blocks described in **A Clean Planet for All**, COM (2018) 733 [1].

Improving CO<sub>2</sub> capture through cost cuts and reduced energy penalty is a vast field of RD&I, only briefly summarized in this report, including how Technology Centre Mongstad can contribute to advancing CO<sub>2</sub> capture from amines as well as other CO<sub>2</sub> capture technologies.



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A list of technology suppliers providing CO<sub>2</sub> capture technologies on the market has been assembled. This list shows that a range of technologies is commercially available, and ready for deployment, once a market for CO<sub>2</sub> capture technologies begins to develop.

The existing and emerging technologies for CO<sub>2</sub> capture are a necessary element for realizing CCS as a means to reduce anthropogenic CO<sub>2</sub> emissions and combat global warming, but not sufficient in itself – CO<sub>2</sub> transport and storage must obviously also be implemented for realizing CCS. The Global CCS Institute [2] and Scottish Carbon Capture & Storage [26] maintain databases with information on large and medium-scale operating and planned CO<sub>2</sub> capture projects, including transport and storage projects currently being developed, such as the Projects of Common Interest (PCIs) in Europe.

Additionally, for realizing CO<sub>2</sub> capture and storage, business models and financial viability as well as the necessary legal and regulatory frameworks must be in place. Public acceptance is also crucial. Within the CCUS Projects Network, these topics are subject to knowledge sharing, with the aim to speed up delivery of CCS and CCU, which the European Commission recognises as crucial to achieving 2050 climate targets.



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