INDUSTRIAL CO_2 CAPTURE PROJECTS: STATUS, LESSONS LEARNED AND NEEDS FOR PROGRESSING TOWARDS FULL-SCALE IMPLEMENTATION

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Abstract

Existing CO_2 capture projects are accumulating experience of adapting generalized results to individual projects, which will be extremely valuable for accelerating emerging CCS projects. Through knowledge-sharing, the CCUS Projects Network (CCUS PN) aims to speed up delivery of these technologies, which the European Commission recognizes as crucial to achieve the 2030 and 2050 climate targets. In this paper, we summarize learnings accumulated so far from industrial CO_2 capture projects across Europe, including CO_2 capture technology selection as well as CO_2 capture project development and implementation. CO_2 capture technologies are reaching maturity and defining the regulatory framework and providing tools for building a business case is becoming increasingly relevant for enabling full-scale implementation.

Keywords: *CCS, CO_2 capture, dissemination, regulations, full-scale implementation*

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C [1] has pointed out the need of reaching net-zero emissions by 2050. Three out of four of the presented mitigation pathways require major use of carbon capture and storage (CCS), including bioenergy with carbon capture and storage (BECCS), to limit global rise to 1.5 °C. In an European context, *A Clean Planet for All*, COM (2018) 733 [2], is the European strategic vision for a prosperous, modern, competitive and climate neutral economy which states that CCS deployment is necessary for tackling CO_2 emissions that cannot be cut through other means such as energy efficiency and renewable energy production. The European Green Deal and Climate Law are converting the political commitment to climate neutrality into a legal obligation and have led to the development of additional EU policy supportive of CCS. By 2030, Europe plans to cut emissions by at least 55% below 1990 levels, aiming to become the world's first climate-neutral continent by 2050 [3].

The CCUS Projects Network (CCUS PN) [4] is supported by the European Commission and represents and supports major industrial projects underway across Europe in the field of CCS and carbon capture and utilization (CCU). By sharing knowledge and learning from each other, the aim is that the CCUS PN members will drive forward the delivery and deployment of CCS and CCU, enabling Europe's member states to reduce CO_2 emissions from industry, electricity, transport, and heat. The CCUS PN is organized in three thematic working groups: Policy, regulation and public perception, CO_2 capture and utilization, and CO_2 transport and storage networks.

1.1 Methodology

This paper reflects input gathered from members of the CCUS PN by the CO_2 capture and utilization thematic working group. CCUS PN members focusing only on transportation and/or storage have not participated in this study. The paper summarizes lessons learned from CO_2 capture technology selection and capture project implementation, as well as from HSE (health, safety and environment) and regulatory work related to CO_2 capture. The paper also reflects input from the CCUS PN members on needs perceived as important for the realization of CO_2 capture at industrial scale. It should be highlighted that these projects are at different stages, which was reflected in the inputs received from the different projects. Contributing projects are listed in Table 1, but their inputs have been anonymized in the paper.

Table 1: Contributing CCUS Projects Network members in this paper.

Project name	Country
Acorn	United Kingdom
Fortum Oslo Varme (FOV)	Norway
Everest (Tata Steel)	Netherlands
LEILAC	Belgium and Germany
CarbFix	Iceland
Drax Bioenergy & CCS	United Kingdom
KVA Linth	Switzerland
Norcem	Norway

In addition, reports from first of a kind (FOK) projects worldwide (e.g. [5], [6],[7] [8], [9]) and the recently published report on lessons learned from the Norwegian Longship project [10] have been used as references. It has been noted that learnings can be, but are not always, common for several projects. This depends, *e.g.*, on the nature of the CO_2 sources, location and current maturity of the projects.

1.2 Structure of the paper

Figure 1 shows how the information is organized in this paper. Section 2 gives a high-level outlook of the status or large-scale CCUS projects, some of which are among the CCUS PN members. A summary of the CO_2 capture technologies currently relevant at industrial scale is also included in Section 2. Section 3 presents the lessons learned *so far* from the CCUS PN members, including the factors that have influenced the evaluation and selection of the CO_2 capture technology as well as the activities and lessons learned during project development and implementation. Section 3 also describes aspects that are considered for the whole project lifetime, from the selection of the CO_2 capture technology to the piloting, implementation, and operational phases. In Section 4, the paper summarizes the crucial needs and barriers identified in this work for the realization of CO_2 capture projects. Finally, Section 5 gives an outlook for the realization of industrial CO_2 capture projects.

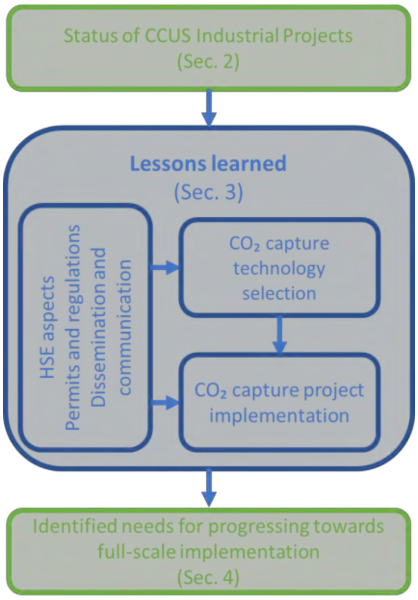

Figure 1: Organization of the paper.

2. Status of large-scale CO_2 capture projects and technologies

According to the Global CCS Institute (GCCSI), 26 commercial CO_2 capture facilities (≥400 kt per year) are currently operating worldwide, capturing 40 Mt of CO_2 every year, with most projects in North America, with 38 commercial facilities in operation or advanced development [11]. The CO_2 capture facility at Boundary Dam coal-fired power plant in Canada was the world's first fully integrated and full-chain industrial-scale CO_2 capture and storage facility, with CO_2 capture retrofitted to a coal-fired power plant [7]. Currently, the Gorgon Carbon Dioxide Injection facility on Barrow Island, Western Australia, is the largest dedicated geological storage operation in the world with a capacity of up to 4 Mt CO_2 per year [11][12].

2.1 Large scale CCUS projects in Europe

In 1996, Sleipner, in Norway, was the first site where CO_2 was injected into a dedicated storage site (opposed to Enhanced Oil Recovery, EOR) and the first industrial-scale CCS project worldwide. Currently, Sleipner (storing 1 Mt per year) and Snøhvit (storing 0.7 Mt per year), also in Norway, are the only industrial-scale operating CCS projects in Europe, and still among the few worldwide facilities with dedicated geological storage [11]. In both facilities, CO_2 is separated from natural gas and injected back into formations for storage.

Several other CO_2 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. According to the GCCSI [11], besides Sleipner and Snøhvit, there are 11 commercial facilities in construction, or at various stages of development, which are targeting operation before 2030 in Europe, specifically in the United Kingdom, Ireland, the Netherlands and Norway, where the government has shown support for realizing CCS projects. In late 2020, the Norwegian government granted funding for 73% of the Norcem Brevik project through the Norwegian Longship project [13]–[16]. In 2020 the British government announced funding for CO_2 capture clusters in the UK [17]. Some of these CCS projects in development are part of the CCUS PN, namely Fortum Oslo Varme, Norcem Brevik, Drax Bioenergy & CCS, Ervia and Acorn [4] and have provided input reflected in this paper (see Table 1). There are also projects and CCS initiatives (e.g. [18], [19]) not included in the aforementioned report with a large potential for CO_2 capture that may also be realized before 2030. Some relevant emerging projects in Europe were not included in the GCCSI report because the expected captured CO_2 is less than 400 kt per year.

Figure 2: Existing onshore infrastructure will bring CO_2 captured in the Grangemouth cluster to the St Fergus Terminal (pictured[1]) in the Acorn project in Scotland, UK.

[1] Picture taken from www.geograph.org.uk/photo/1695742
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2.2 CO_2 capture technologies

Here we briefly introduce CO_2 capture technologies currently relevant for or developing towards commercial-scale applications. The described technologies should reflect relevant options for large-scale applications. Examples of emerging technologies not *currently* relevant for large-scale applications are electrochemical separation, microbial and microalgae, and direct air capture (DAC) [20].

Post-combustion CO_2 capture with amine solvents (liquid absorption) is currently the most mature CO_2 capture technology, and it has been demonstrated at full scale [21], reaching a Technology Readiness Level (TRL) 9. In this technology, CO_2 is removed from the flue gases when it reacts in a vessel with a (generally amine-based) solvent to form an intermediate compound, which is fed to a second vessel, where the solvent is regenerated with heat, producing the original solvent and a high-purity CO_2 stream. It can be implemented as a retrofit option.

With *solid sorbents* the CO_2 adsorbs 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 [20]. Vacuum-swing adsorption (VSA), is the CO_2 capture technology implemented in the Air Products Steam Methane Reformer facility for hydrogen production at the Valero Port Arthur Refinery in Texas (1 Mt CO_2 per year) [9].

Membranes are thin barriers over which one species is more mobile than others which allows the specific separation of species in a gas mixture. CO_2 selective membranes typically produce a CO_2 enriched stream at low pressure and a CO_2 depleted stream at high pressure [22]. Membranes are used in the FPSO vessels in the Petrobras Santos Basin in Brazil (4.6 Mt CO_2 per year) to separate CO_2 from natural gas; but in general, membranes have a TRL of 6, and the process itself has a lower TRL [20]. American membrane producer MTR report on their website about a plan for construction, installation and operation of a large scale membrane pilot system [23].

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 and produce power or heat. With this scheme, the produced flue gas mainly contains CO_2 and water (steam), which can be separated via cooling and a CO_2 compression and purification unit. Oxycoal power plant technologies are reported to be under trials to establish TRL 8 during the period from 2016 to 2020 [24]. Oxyfuel cement production is being investigated [25], [26]. *Chemical looping combustion* is a type of oxy-fuel process without the need of an air separation unit [27]. Here, a metal-metal oxide system is used to transport oxygen from the air to the fuel, avoiding direct contact, also producing almost pure contains CO_2 and water (steam). There are research projects to push this technology to TRL 7 [28].

In *post-combustion calcium looping* the flue gas enters a carbonator with CaO, which captures the CO_2, reacting into $CaCO_3$, which is circulated to the calciner, where it is regenerated at a high temperature, releasing raw CO_2 for conditioning (and turning $CaCO_3$ back to CaO) [29]. This technology is more likely to be applied as a retrofit.

In *low-temperature separation* processes the CO_2 is cooled such that CO_2 forms a liquid or a solid that can be separated. This technology is suitable as a standalone for some applications where a high CO_2 concentration is available in a stream, such as H_2 production with CO_2 capture or in combination with membranes or adsorption (PSA). A commercial application of the technology is the AirLiquide CryoCap technology [30].

There are also *industry specific technologies*, such as *HIsarna*, developed by Tata Steel and Rio Tinto for the production of pure liquid iron and CO_2 [31], [32]. Another industry specific technology is the direct separation process [36] developed by the *LEILAC* project to capture unavoidable CO_2 process emissions in the cement and lime industries, also producing highly concentrated CO_2.

3. Lessons learned

This section outlines the main lessons learned so far by the CCUS PN members while developing CO_2 capture projects. We first describe the lessons learned regarding aspects that are relevant throughout the complete project lifetime. We then go through the lessons learned with respect to CO_2 capture technology selection and project implementation, which is the current phase for most of the CCUS PN members.

3.1 Factors relevant for the complete project lifetime

Aspects such as the regulatory framework or the communication strategy shape the project from the beginning, influencing the selection of the technology. These aspects are also present during the implementation of the project and impact the operational and decommissioning phases of the project.

3.1.1. Permits and regulations

A favorable policy and regulatory framework is crucial for the large-scale deployment of CCS projects. Project developers, vendors and contractors as well as authorities are only starting to accumulate experience regarding CO_2 capture projects. Identifying and contacting the relevant authorities for permitting regarding air, water, noise, and environment should be one of the first actions when developing any industrial project. The regulatory environment is continuously evolving, as discussed further in this paper. This situation can make it challenging to contact vendors and get bids when regulations are not fully in place. Therefore, regulation agencies, project developers and vendors should work together to find a balance that protects the environment without unnecessarily curtailing or stopping CCUS markets.

3.1.2. Health, Safety and Environment (HSE)

From experience in other industries, unplanned HSE events such as leakages or accidents are highly publicized and may damage a whole industry. A HSE responsible of coordinating and documenting all HSE activities should be part of the core team in an industrial capture project

[10]. Documentation can be done through a Management Study Report, which includes a scope of responsibilities, as well as a health and safety plan, and an environmental plan. These documents are not static and should be continuously refined and updated.

Industrial HSE standards and practices have proven useful on pilot plants and industrial-scale projects, although specific limits for CO_2 management still need to be defined. Capture projects may be directly connected to large-scale intermediate storage and transportation of CO_2 to a port or to a storage site, which may become a concern for third parties.

Measurement, monitoring and verification (MMV) or monitoring, verification and accounting (MVA) plans are important for stakeholder acceptance and to ensure that the CO_2 capture and transport facilities, as well as the storage site perform as expected [33] [9].

In this regard, tools for estimating emissions and modelling leakages, including amine emission to the air or large CO_2 leakages, as well as property databases specific for CO_2, solvents and solvent degradation by-products should be further developed.

3.1.3. Dissemination and communication

Industries implementing CO_2 capture projects are aware that results-sharing and public acceptance are not only beneficial but fundamental. As shown in Figure 3, besides the internal communication, plans and results can typically be shared with different stakeholders, such as government, academia, the general public, or other industrial CO_2 capture projects.

Figure 3: Stakeholders with whom results and plans typically can be shared.

In general, CCUS PN members have positive experiences engaging with stakeholders and have used every opportunity to share knowledge. Most projects are being deployed in existing industrial facilities, and the local public is aware of the benefits that a CO_2 capture project could bring to the region. In advanced projects, such as Boundary Dam in Canada, the public commitment to directly address stakeholder concerns regarding the level of investment and a central vision to reach a CO_2 capture goal was a successful tactic to overcome difficulties [34].

A majority of the existing CO_2 capture projects have been at least partially funded by national or EU government schemes. Therefore, dissemination is typically an important activity within these projects, and they are obliged to provide open access key knowledge deliverables to government representatives.

Knowledge sharing among CO_2 capture projects, as well as partnership-based cooperation among plant operators and industrial associations, can be decisive to bring forward emerging CO_2 capture projects, for example, by having accessible cost information regarding comparable projects. Currently, several CO_2 capture projects include running a pilot plant onsite before the investment decision of constructing the industrial-scale CO_2 capture plant. Accumulated piloting and industrial operation experience, including HSE, can reduce or eliminate the need for on-site pilot periods, reducing project implementation costs and accelerating deployment. First-of-a-kind (FOAK) projects, such as the one in the Boundary-Dam power station in Canada, have shared that the learning curve for operation has been a factor for a challenging undertaking [34]. Therefore, best practices guidance and knowledge sharing among projects for safe operation, solvent degradation reduction, and pollution prevention will certainly pave the way for the deployment of CO_2 capture.

An important aspect that should be considered is that results sharing should be timely and, depending on the project stage, within reasonable agreements that do not affect tender processes or interfere with intellectual property (IP) rights, not only of the project owner, but also of the technology providers.

3.2 CO_2 capture technology selection: main decision factors

The selection of CO_2 capture technology is a major decision typically taken during the concept phase [10]. Companies implementing CO_2 capture that have solid industrial experience can build on their existing project-developing knowledge and skills. Figure 4 depicts important factors influencing technology selection. Technical aspects, cost, and compliance with regulations are natural decision factors when evaluating candidate technologies.

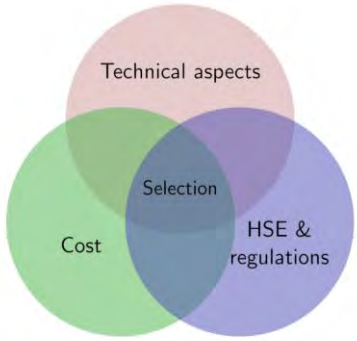

Figure 4: Decision factors affecting CO_2 capture technology selection.

3.2.1. Evaluation of capture technology

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_2, flue gas composition (CO_2 concentration), temperature, pressure, flowrate, and type of industrial CO_2-emitting facility being considered for capture, where the availability of waste heat is an important parameter.

The selected technology should have the ability to capture CO_2 when considering a specific set of flue gas characteristics, such as CO_2 concentration and impurities, as well as flue gas pressure and temperature. The technology should be able to achieve the required CO_2 capture rate and required CO_2 purity, which will depend on the downstream (transport/storage/use) requirements for the captured CO_2.

As most of the presently existing projects are FOAK projects, technology readiness, maturity, references, and previous operating and project experience have been key factors in this first screening, reducing risk and uncertainty [10]. Piloting has been used to provide confidence in the selected technology as well as operating experience.

3.2.2. Capture cost

Expected capital (CAPEX) and operating (OPEX) costs are key factors when evaluating and selecting the CO_2 capture technology. Capture cost is influenced by technical aspects of the CO_2 capture technology and design decisions, such as energy requirements, integration, and the price of consumables (solvents, sorbents). The selected technology should be not only efficient but also simple to integrate and to operate without jeopardizing the industrial production. Uncertainties in this regard are mitigated with higher TRL technologies, which are being chosen in the projects currently being developed and close to implementation.

Energy requirement is one of the most important performance parameters for CO_2 capture technologies. Thus, efficient heat integration is a key aspect to reduce operating costs. For example, in the Longship project, efficient heat integration made it possible to reduce the energy input to the chain with 42% in the Fortum Oslo Varme (waste to energy) case and with 74% in the Norcem (cement) case [10]. Besides heat integration, other integration and optimization opportunities are on electricity (e.g. for CO_2 compression), water (both usage and treatment) and pre-conditioning of flue gas coming from different stacks within the same industrial facility.

3.3 CO_2 capture technology implementation: selecting suppliers and partners

CO_2 capture projects that are close to implementation today are in general retrofit projects. In some cases, these are not the only ongoing retrofit or modernization projects at the industrial sites. Therefore, design and construction of CO_2 capture and conditioning facilities should be put in a context of modernization plans of the overall industrial site. This will impact, for example, the availability of utilities or the design basis for the CO_2 capture plant.

CCUS PN members have observed that appropriate project planning arrangements and revision of relevant internal protocols should be started early as possible. As some aspects of the project such as legislation or some technological aspects may not be defined at the beginning of the project, collaboration and flexibility are key for both team interactions and project management. For example, key success factors of projects such as the CO_2 capture plant in the Valero refinery in Texas were related to coordination and partnership between the technical team, site host, consultants and contractors [9].

Based on publicly available pilot results (e.g. [35]) or shared knowledge among CO_2 capture projects, some projects have initiated a tender process around a type of capture technology, without an on-site piloting phase. Projects reaching the contract phase have found it highly beneficial to develop a contract strategy that ensures competition for the detailed engineering and construction of the major parts of the system.

A technology provider should be able to issue and back up performance guarantees [10], for example, in terms of CO_2 capture rates, operability, and ability to comply with regulations. In this regard, CO_2 capture projects that are implementing amine-based capture technologies are also considering the long-term availability of the required solvent and possible future dependence on suppliers. Thus, reliable, well-established vendors that have developed mature technologies are preferred, as this relationship will most likely be a long-term one.

CO_2 capture projects often involve both CO_2 capture and conditioning (e.g. liquefaction), and the vendors are not necessarily the same. Therefore, industries implementing capture projects for ship transport need to find competent partners for the construction of CO_2 liquefaction and storage facilities.

More advanced projects, which currently are FOAK projects, have shared that it has been challenging to keep the cost level from the Front-End Engineering Design (FEED) study. Thus, contractual and commercial requirements, as well as assumptions and uncertainties, should be clarified with shortlisted technology suppliers. It is expected that cost estimates will become more accurate as more CCUS projects are implemented and experiences are gained.

4. Identified needs for full-scale implementation

To reach industrial-scale operation, CCS projects must be developed along several axes, including securing funding for construction and operation. Timing with respect to access to funding, implementation of necessary regulations and access to transport and storage infrastructure is important, as well as good models for risk sharing. Furthermore, it is generally observed that political support and implementation plans are necessary on all levels: regional (e.g. EU), national, and local [36].

4.1 Building the business case

Technology improvements will be important cost-reduction factors for new projects. Capital expenses may be reduced for current technologies through stepwise learning from one project to the next. Reductions in operating costs can be achieved, for example, by identifying better heat integration solutions.

Supporting policy and regulatory frameworks as well as financing instruments are a pre-requisite for building the business case for new capture projects. Currently, the EU Emissions Trading System (ETS) [37] contributes to a business case, since emission allowances can be traded rather than surrendered at the end of each year if CO_2 has been captured, transported and stored in compliance with the Monitoring and Reporting Regulation (MRR) [38]. However, the current EU ETS scheme only covers CO_2 captured from *fossil* emission sources, and therefore incentives for investing in BioCCS could help trigger CO_2 *removal* (negative emissions). Early movers in CO_2 capture implementation can to some extent be supported from additional sources such as the Innovation Fund [39], and there are also examples of government support for realizing early CCS projects, such as in the Norwegian Longship project that was launched in September 2020 [13]–[15] with the budget approved by the Norwegian Parliament on December 14, 2020 [16], or the recent announcement of the British government to fund CO_2 capture clusters in the UK [17]. Further and future steps and additional mechanisms, such as contracts for difference, tax or emissions credits or appropriate carbon taxes [11], can also be envisaged to accelerate CCS implementation.

4.1.1. Risks sharing

There are many risks for early industrial movers in CO_2 capture. The risk of failing should be shared, which could be addressed through strategic partnerships. Governments (local, EU) can contribute to the risk-taking capacity. For example, in the Longship project, risks are shared between the Norwegian state, Northern Lights and the industries (Norcem and FOV) [15]. FOAK projects require more time for commissioning and start-up than conventional projects [8]**.** Projects may need recognition from investors that they will not yield normal returns. As such, the financial world and government have an opportunity to take responsibility in sharing the risk for CCS.

4.2 Access to CO_2 transport and storage infrastructure

The widespread development of CO_2 infrastructure (primarily pipeline and ship, but also in some cases train or truck) will be a key enabling step for CO_2 capture implementation. Access, tariffs, and liabilities must be appropriate for all users and not inhibit the fast and widespread uptake of carbon capture across Europe and the globe.

Industry coordination and mobilization of industry-wise resources can support the development of new projects [36]. Development and implementation of capture in industrial clusters as the one depicted in Figure 5, with a joint backbone infrastructure can be seen as an enabler. This may require dedicated development of, for example, loading and offloading systems for truck or train transport. In some cases (e.g. Acorn [40]), existing infrastructure developed for other uses may be used. Available CO_2 transport and storage capacity needs to be sufficient for CO_2 captured from industrial sites. Joint transportation and storage facilities reduce costs [33][41]. This means that transport and storage projects that oversize their capacity, such as Northern Lights in Norway [42], are a prerequisite for the development of industrial CO_2 capture projects, which will eventually will lead to reduced costs.

Implementation plans for capture projects must be developed to match with the timing of infrastructure implementation and an appropriate regulatory framework. The major hurdle for cross-boundary ship transport of CO_2 was resolved in 2019 with the provisional application of the 2009 amendment to article 6 of the London Protocol [43].

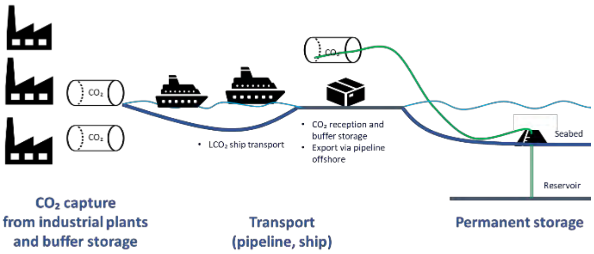

Figure 5 Example of shared infrastructure scheme (inspired by the Northern Lights [44] project).

4.3 R&I needs for improving CO_2 capture

Beyond the needs of current projects there is a need for improving knowledge and generating innovations in the field of CO_2 capture, for realizing future CCS projects with reduced costs and risks. Currently, amine-based CO_2 capture is the most mature alternative and has been successfully tested or implemented in different facilities. However, other technologies or technology synergies may be more convenient for some industries or applications. Some identified R&I needs are:

- Capture technologies and technology integration that significantly reduce capital and operating expenses.
- Improving models for CO_2 dispersion and large-scale leakages, as well as for dispersion and deposition of nitrosamines and nitramines, which are tools for HSE and risk analyses.
- Defining best available technologies (BAT) for pollution prevention, as well as reliable and standardized measurements and methods appropriate for the different technologies and processes to facilitate operation, reporting and compliance with regulations. This goes hand in hand with increasing knowledge with respect to measurement techniques and instrumentation for monitoring flow and CO_2 concentration in the different streams.

5. Final remarks

Knowledge sharing with all stakeholders brings benefits such as accelerating emerging projects and increasing public acceptance. Improving CO_2 capture through cost cuts and reduced energy penalty is a vast field of RD&I. The existing and emerging technologies for CO_2 capture are a necessary element for realizing CCS as a means to reduce anthropogenic CO_2 emissions and combat global warming, but not sufficient in itself – CO_2 transport and storage must obviously also be implemented for realizing CCS.

Additionally, for realizing CO_2 capture and storage, business models and financial viability as well as the necessary legal and regulatory frameworks must be in place. A favorable policy and regulatory framework is essential for the large-scale deployment of CCS projects, as well as good collaboration between project owners and governments for permitting, which should be started early in the project.

Timing is critical: it is difficult for a company to make a final investment decision if the business case is pending, the regulatory framework is uncertain or complementary CO_2 transport and storage infrastructure may be unavailable or insufficient.

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References

[1] J. Rogelj *et al.*, '"Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development" in Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathw', 2018.

[2] European Commission, 'A Clean Planet for All. A European strategic long-term vision for a prosperous, modern, competititve and climate neutral economy', COM(2018) 773, 2018.

[3] European Commission, 'EU climate action and the European Green Deal', 2020. [Online]. Available: https://ec.europa.eu/clima/policies/eu-climate-action_en.

[4] 'CCUS Projects Network', 2021. [Online]. Available: www.ccusnetwork.eu/.

[5] International CCS Knowledge Centre, 'Boundary Dam CCS Project', 2019. [Online]. Available: https://ccsknowledge.com/bd3-ccs-facility. [Accessed: 11-Nov-2019].

[6] IEAGHG, 'Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station', 2015.

[7] IEAGHG, 'The road to deploying Carbon Capture + Storage at SaksPower', *Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station*, 2015. [Online]. Available: https://ccsknowledge.com/pub/documents/publications/saskpower-boundry-dam/Deploying Carbon Capture.pdf. [Accessed: 21-Nov-2019].

[8] N. Shimokata, 'Petra Nova CCUS Project in USA', 2018.

[9] IEAGHG, 'The Carbon Capture Project at Air Products' Port Arthur Hydrogen Production Facility', 2018.

[10] Gassnova SF, 'Developing Longship- Key Lessons Learned', 2020. [Online]. Available: https://gassnova.no/wp-content/uploads/2020/11/Gassnova-Developing-Longship-FINAL-1.pdf.

[11] Global CCS Institute, 'Global Status of CCS 2020', 2020. [Online]. Available: https://www.globalccsinstitute.com/resources/global-status-report/.

[12] Global CCS Institute, 'World's 19th large-scale CCS project begins operation in Australia'. [Online]. Available: https://www.globalccsinstitute.com/news-media/latest-news/worlds-19th-large-scale-ccs-project-begins-operation-in-australia/.

[13] Gassnova SF, 'CCS Norway', 2020. [Online]. Available: https://ccsnorway.com/. [Accessed: 12-Apr-2020].

[14] Regjeringen (Norwegian Government), 'The Government launches "Longship" for carbon capture and storage in Norway', 2020. [Online]. Available: https://www.regjeringen.no/en/aktuelt/the-government-launches-longship-for-carbon-capture-and-storage-in-norway/id2765288/.

[15] Norwegian Ministry of Petroleum and Energy, 'Longship – Carbon capture and storage', *Meld. St. 33 (2019–2020) Report to the Storting (white paper)*, 2020. [Online]. Available: https://www.regjeringen.no/contentassets/943cb244091d4b2fb3782f395d69b05b/en-gb/pdfs/stm201920200033000engpdfs.pdf.

[16] Regjeringen (Norwegian Government), 'Funding for Longship and Northern Lights approved', 2020. [Online]. Available: https://www.regjeringen.no/en/aktuelt/funding-for-longship-and-northern-lights-approved/id2791729/.

[17] Prime Minister's Office (UK), 'PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs', *Climate change and energy - Press release*, 2020. [Online]. Available: https://www.gov.uk/government/news/pm-outlines-his-ten-point-plan-for-a-green-industrial-revolution-for-250000-jobs.

[18] Preem, 'Preem Progress Book - Sustainability Report 2019', *The target is set: Climate neutral by 2045*, 2019. [Online]. Available: https://www.preem.com/globalassets/om-preem/hallbarhet/hallbarhetsredovisning/preem_sustainability_report_2019_eng.pdf. [Accessed: 14-Sep-2020].

[19] Port of Gothenburg, 'CinfraCap', 2020. [Online]. Available: https://www.portofgothenburg.com/about-the-port/the-port-is-growing/cinfracap/. [Accessed: 14-Sep-2020].

[20] A. Cousins, P. Feron, J. Hayward, K. Jiang, and R. Zhai, 'Further Assessment of Emerging CO_2 Capture Technologies for the Power Sector and their Potential to Reduce Costs', 2019.

[21] E. I. Koytsoumpa, C. Bergins, and E. Kakaras, 'The CO_2 economy: Review of CO_2 capture and reuse technologies', *J. Supercrit. Fluids*, vol. 132, pp. 3–16, Feb. 2018.

[22] M. Voldsund, K. Jordal, and R. Anantharaman, 'Hydrogen production with CO_2 capture', *Int. J. Hydrogen Energy*, vol. 41, no. 9, pp. 4969–4992, Mar. 2016.

[23] Membrane Technology Research, 'Large Pilot Testing of the MTR Membrane Post-Combustion CO2 Capture Process', 2020. [Online]. Available: www.mtrinc.com/news/large-pilot-testing-of-the-mtr-membrane-post-combustion-co-2-capture-process/. [Accessed: 12-Feb-2020].

[24] M. A. Nemitallah *et al.*, 'Oxy-fuel combustion technology: current status, applications, and trends', *Int. J. Energy Res.*, vol. 41, no. 12, pp. 1670–1708, Oct. 2017.

[25] ACT, 'AC^{2}OCem', *Accelerating Carbon Capture using Oxyfuel Technology in Cement Production*, 2020. [Online]. Available: http://www.eu-projects.de/ac2ocem/ACOCem/tabid/1009/Default.aspx. [Accessed: 12-Feb-2021].

[26] M. Voldsund *et al.*, 'Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation', *Energies*, vol. 12, no. 3, p. 559, Feb. 2019.

[27] Ø. Langørgen, 'Chemical Looping Combustion 150 kW pilot unit at SINTEF'. [Online]. Available: www.sintef.no/en/all-laboratories/eccsel-norway-ccs-ri/chemical-looping-combustion-150-kw-pilot-unit-at-sintef/. [Accessed: 26-Nov-2019].

[28] 'CHEERS Project', *Chinese-European Emission-Reducing Solutions*, 2019. [Online]. Available: http://cheers-clc.eu/. [Accessed: 15-Nov-2019].

[29] D. Berstad, R. Anantharaman, and K. Jordal, 'Post-combustion CO_2 capture from a natural gas combined cycle by CaO/CaCO3 looping', *Int. J. Greenh. Gas Control*, vol. 11, pp. 25–33, Nov. 2012.

[30] 'AirLiquide'. [Online]. Available: www.airliquide.com/magazine/cryocap-co2-cold-capture-system-unlike-any-other-in-the-world. [Accessed: 15-Nov-2019].

[31] Tata Steel, 'HIsarna'. [Online]. Available: www.tatasteeleurope.com/en/innovation/hisarna. [Accessed: 21-Nov-2019].

[32] Tata Steel, 'HIsarna: game changer in the steel industry', *Hisarna factsheet*, 2017. [Online]. Available: www.tatasteeleurope.com/static_files/Downloads/Corporate/About us/hisarna factsheet.pdf. [Accessed: 21-Nov-2019].

[33] IEAGHG, 'The Shell Quest Carbon Capture and Storage project', 2019.

[34] C. Preston, C. Bruce, and M. Monea, 'An Update on the Integrated CCS Project at SaskPower's Boundary Dam Power Station', in *14th Greenhouse Gas Control Technologies Conference (GHGT-14)*, 2018.

[35] TCM, 'Vitenskaplige artikler', *Catching for future*. [Online]. Available: https://catchingourfuture.no/#artikler. [Accessed: 13-Nov-2019].

[36] J. Burnham, O. Debande, O. Jones, J. M. C. Mihai, and I. Temperton, 'Report on Innovative Financial Instruments for the Implementation of the SET Plan, First-Of-A-Kind projects', 2013.

[37] European Commission, 'EU Emissions Trading System (EU ETS)', 2020. [Online]. Available: https://ec.europa.eu/clima/policies/ets_en. [Accessed: 12-Apr-2020].

[38] European Commission, 'Monitoring, reporting and verification of EU ETS emissions', 2020. [Online]. Available: https://ec.europa.eu/clima/policies/ets/monitoring_en. [Accessed: 12-Apr-2020].

[39] European Commission, 'Innovation Fund', 2020. [Online]. Available: https://ec.europa.eu/clima/policies/innovation-fund_en. [Accessed: 12-Apr-2020].

[40] PaleBlueDot, 'Project overview', *Acorn CCS & Acorn Hydrogen*. [Online]. Available: https://pale-blu.com/acorn/. [Accessed: 20-Nov-2019].

[41] S. Roussanaly *et al.*, 'Towards improved cost evaluation of Carbon Capture and Storage from industry', *Int. J. Greenh. Gas Control*, 2021.

[42] Equinor ASA, 'Northern Lights Contribution to Benefit Realisation', 2019. [Online]. Available: https://ccsnorway.com/wp-content/uploads/sites/6/2020/07/Northern-Lights-Contribution-to-Benefit-Realisation-sladdet-versjon-1.pdf.

[43] International Maritime Organization, '41st Consultative Meeting of Contracting Parties to the London Convention and the 14th Meeting of Contracting Parties to the London Protocol (LC 41/LP 14) 7-11 October 2019', *Carbon Capture and Sequestration*, 2020. [Online]. Available: https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/LC-41-LP-14-.aspx.

[44] 'Northern Lights Project', 2020. [Online]. Available: https://northernlightsccs.com/en. [Accessed: 14-Sep-2020].