Industrial CO_2 capture projects: Lessons learned and needs for progressing towards full-scale implementation

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CO_2 capture and utilisation

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Disclaimer: Not all the lessons learned nor the future needs for project realization that are described in this report are necessarily relevant for all contributing projects. This report can be used as a reference for developing CO_2 capture projects, but each reader must carefully evaluate the relevance of the report contents relative to their specific project(s).

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About the CCUS Projects Network

The CCUS Projects Network comprises and supports major industrial projects underway 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.

http://www.ccusnetwork.eu/

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Executive summary

An aim of the CCUS Projects Network is to share knowledge and learnings, in order to drive forward the delivery of CCS and CCU and enable European countries to reduce CO_2 emissions from industry, electricity, transport and heat. Against this background, the present report synthesizes lessons learned by CCUS Projects Network members on CO_2 capture project development and implementation. Indeed, some of the network members have gathered significant knowledge during the development of their industrial-scale CO_2 capture projects, that they herewith share openly. The report summarizes lessons learned from CO_2 capture technology selection and capture project implementation as well as from HSE and regulatory work related to CO_2 capture. The report also presents input from the Network members on needs they perceive as important for the realisation of CO_2 capture at industrial scale.

Capture technology selection must be made for the specific plant in consideration. There are today several technology providers to select between. Piloting can provide confidence in a capture technology but also requires a collaborative effort between a wide range of stakeholders. Capture cost is a key decision factor but maintaining industrial plant operation and product quality is also essential. Selection of technology suppliers and partners in a capture project involves seeking a good long-term relationship, e.g. for solvent supply.

It is largely observed among CCUS PN members that HSE risks are known and can be handled, although special care must be taken to avoid amine emissions to the air.

A favourable policy and regulatory framework is essential for the large-scale deployment of CCS projects. There is, presently, sometimes a lack of sufficient regulations but the regulatory framework is continuously evolving.

For realising CO_2 capture at industrial scale, building a business case is essential, including access to funding and measures for generating income (e.g. EU ETS, contracts of difference, incentives for BioCCS). Also access to CO_2 transport and storage infrastructure, possibly as part of an industrial cluster, is of course important as well as strategic partnerships for risk sharing.

R&D needs for improving CO_2 capture have been identified, such as efforts to continue to decrease capture cost, but also to continue to improve the HSE and further reduce the risks of CO_2 capture and CO_2 management. Also there is a need to define BAT for pollution prevention as well as reliable and standardized measurements and methods to facilitate operation, reporting and compliance with regulations.

The report has been assembled with input from the following members of the CCUS Projects Network: Acorn, Carbfix, Drax Bioenergy & CCS, Everest (Tata Steel), Fortum Oslo Varme (FOV), KVA Linth, LEILAC and Norcem. Also the Gassnova report on developing the Longship project [1] has been an important reference.

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Industrial CO_2 capture projects: Lessons learned and needs for progressing towards full-scale implementation

1 Introduction

An aim of the CCUS Projects Network (CCUS PN) is to share knowledge and learnings, in order to drive forward the delivery of CCS and CCU and enable European countries to reduce CO_2 emissions from industry, electricity, transport and heat. Documentation of learnings is important, both to spread a wider understanding of the current status of existing CO_2 capture projects and the lessons they have gathered, and to facilitate the implementation of these and future projects.

The present report shares knowledge from the CCUS PN members on CO2 capture, more specifically on the lessons learned from developing industrial-scale CO2 capture projects. The report covers CO2 capture technology selection and project implementation learnings as well as HSE and regulatory aspects, and learnings from dissemination and communication activities. It is reflected by the contents of the report that most of the projects that have contributed with input have selected amine as their capture technology or may presently be considering it. It is the CCUS PN's ambition that the joint lessons from early CO2 capture movers that are gathered in this report will be useful for de-risking the development of future projects.

Furthermore, the report presents input from the project members on factors they perceive as important to be able to proceed towards realising CO_2 capture at industrial scale, such as building the business case, having access to CO_2 transport and storage infrastructure and risk sharing.

1.1 Report methodology

Input from members of the CCUS projects network for this report has been gathered (see list on Table 1), either via e-mail or through telephone interviews. Also, the recently published report on lessons learned from the Norwegian Longship project has been used as a reference [1]. It is not specified in the report which input comes from which project, since many, but not necessarily all, learnings are common for several projects. It should also be highlighted that these projects are at different stages, as reflected in the inputs received from the different projects.

Table 1 Contributing CCUS Projects Network members and contact persons

Project name	Country	Contributors
Acorn	UK	*Charlotte Hartley and William Hazell*
Fortum Oslo Varme (FOV)	Norway	*Jørgen Thomassen*
Everest (Tata Steel)	Netherlands	*Carl van der Horst*
LEILAC	Belgium & Germany	*Daniel Rennie*
CarbFix	Iceland	*Kári Helgason*

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Project name	Country	Contributors
Drax Bioenergy & CCS	UK	*Carl Clayton*
KVA Linth	Switzerland	*Stefan Ringmann*
Norcem	Norway	*Per Brevik*

1.2 Report structure

Figure 1 shows the structure of the report. Chapters 2,3 and 1 present the lessons learned from the CCUS PN members. Chapter 2 focuses on the factors that have influenced the evaluation and selection of the CO_2 capture technology among the contributors of this report. Chapter 3 describes the activities and lessons learned during project development and implementation. Chapter 1 describes aspects that are considered for the selection of the CO_2 capture technology and continue to shape the project during the piloting, implementation and operational phases. These include the regulatory and HSE (health, safety, and environment) aspects as well as communication and dissemination. In Chapter 5, the report highlights the crucial needs and barriers identified by the CCUS PN members for the realisation of CO_2 capture projects. Finally, Chapter 6 outlines the main conclusions of this report and gives an outlook for the realisation of CO_2 capture projects. A glossary with the abbreviations used in this report is included in Chapter 0.

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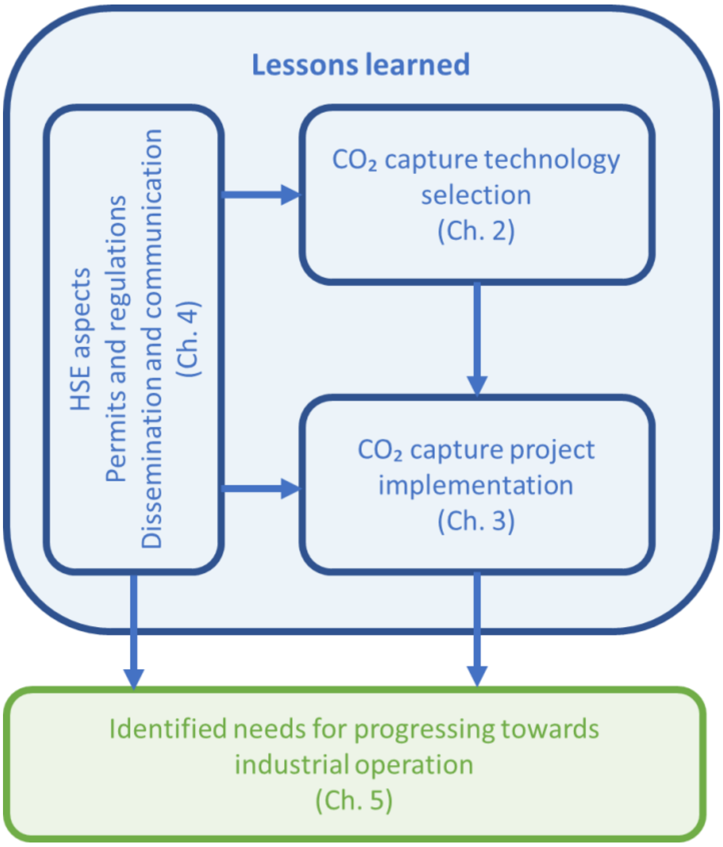

Figure 1 Structure of the report

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2 CO_2 capture technology selection

The selection of CO_2 capture technology is a major decision typically taken during the concept phase [1]. It is observed by some CCUS PN members that having previous project development and management experience within a company will tend to provide more realistic cost estimates for CO_2 capture. I.e. companies implementing CO_2 capture that have solid industrial experience can build on their existing project-developing knowledge and skills.

In order to select the most appropriate CO_2 capture technology for a project, different technologies are evaluated considering technical factors and costs. Section 2.1 outlines some technical aspects that CCUS PN members have considered during the technology evaluation phase. Section 2.2 gives an outlook of costs as a decision factor and the importance of integration for cost reduction.

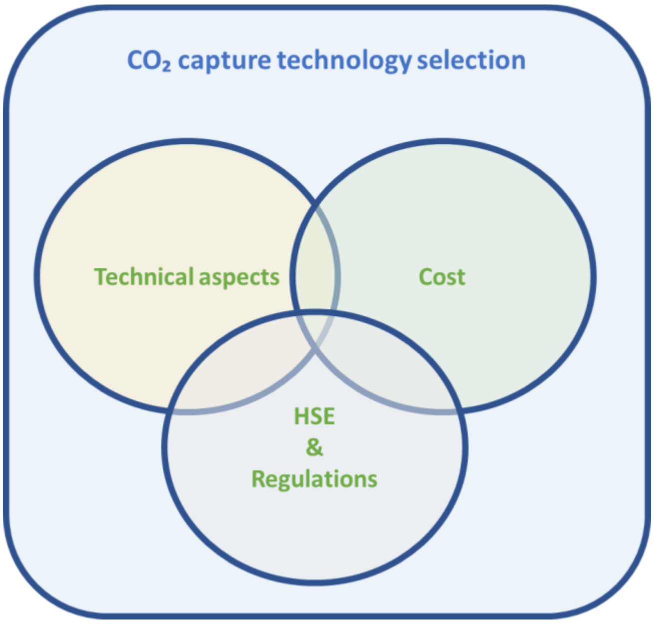

Figure 2 Factors affecting technology selection

2.1 Evaluating CO_2 capture technology

A natural decision factor when evaluating candidate technologies is the ability to capture CO_2 when considering a specific set of flue gas characteristics, such as CO_2 concentration and impurities, and also flue gas pressure and temperature. In this regard, the technology should be able to achieve the required CO_2 capture efficiency[1], as there may be large variations among technologies (e.g. 60% -90% capture). Different technologies also achieve different CO_2 purities in the captured CO_2 stream, and the target will depend on the downstream requirements for the captured CO_2 (transport/storage/use requirements).

[1] There are several ways of calculating CO_2 capture efficiency. A simple definition is the flow of captured CO_2 divided by the CO_2 flow in the flue gas supply [20]. This is also often referred to as capture rate in the literature.

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When CO_2 is captured downstream the process (post-combustion capture), projects have typically started with an open approach and gone through a decision process evaluating different types of technologies at different TRL levels (usually TRL 3 to 8/9). In some cases, this assessment of technologies has been done using government support (e.g. CLIMIT Demo projects in Norway). As most of the presently existing projects are first of a kind (FOK) projects, technology readiness, maturity, references, and previous operating and project experience have been key factors in this first screening. Use of unproven or new technology will add risk and uncertainty and will require technology qualification [1]. In more advanced CO_2 capture projects, piloting has provided confidence in the selected technology and supplier as well as operating experience. Piloting a new technology requires a lot of very flexible, agile work, preferably based on a very collaborative approach with industry, researchers, consultants, and a wide range of stakeholders to ensure that all interests are being met (not just the industry user interests). Moreover, the use of proven technologies may reduce the need for a long piloting phase.

2.2 Capture cost – a natural decision factor

Expected capital (CAPEX) and operating (OPEX) costs are key factors when evaluating and selecting the CO_2 capture technology. Cost is influenced by technical aspects of the CO_2 capture technology and design decisions, such as energy requirements, integration, and solvent price (if using a solvent-based technology).

Efficient and cost-effective operation and quality of the industrial product (e.g. cement, steel, heat, power) is the main priority for industries and therefore, ideally, a CO_2 capture technology should not only have a minimum impact on production costs but also be efficient, simple to integrate and to operate without jeopardizing the industrial production. With lower TRL technologies, projects consider that it is important to understand the assumptions and considerations related to the cost estimates that are presented when they are in dialogue with potential suppliers. With mature capture technologies, it is the integration of the technology in the industrial plant that raises the largest cost-related questions among projects.

2.2.1 The importance of heat integration to reduce costs of amine-based capture

Energy requirement is one of the most important performance parameters that are mentioned for CO_2 capture technologies. Amine capture is energy intensive and despite being mature, there is still continuous R&D activity to reduce the heat requirement by using advanced solvents [2]. Thus, efficient heat integration is paramount 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 [1]. It should be noted that integration opportunities are different for different industrial sites. Both integration with the host plant and between the different parts of the capture and CO_2 processing should be investigated to find the optimum heat integration opportunities. It should also be noted that in some areas and industry sectors, seasonal variations may affect heat integration possibilities.

2.2.2 Plant integration for reducing costs

Besides heat integration, other integration opportunities are on electricity consumption (e.g. for CO_2 compression), water (both usage and treatment) and flue gas arrangement. Overall, for CO_2 capture

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retrofit, the local conditions such as the extent to which existing infrastructures can be used should be considered. The space required for capture (footprint) vs. available space on site may sometimes be a decisive factor. Space is required not only for the CO_2 capture plant, but also for CO_2 purification, liquefaction, compression), storage, loading and support equipment). In some projects, a modular set-up and the possibility to increase the capacity of both the production plant and the CO_2 facilities may also play a role in the decision process.

In some projects, there is the possibility of developing a new process paradigm in which CO_2 capture is efficiently integrated with the industrial core process. In such industry-specific cases, focus has been on developing the new industrial process.

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3 CO_2 capture project implementation

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 modernisation projects at the industrial sites, i.e. design and construction of CO_2 capture and conditioning facilities can be put in a context of modernisation plans of the overall industrial site.

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. CCUS PN members have observed that a risk-based approach to development is beneficial to prioritise and schedule activities.

3.1 Capture technologies are available

The landscape of CO_2 capture has changed rapidly over the past few years, and there are today several technology suppliers that offer commercial CO_2 capture technologies [3]. None of the CCUS PN members have mentioned the lack of capture technologies availability at scale as a hurdle that needs to be overcome to realise a full-scale project. It is today possible to get commercial bids from several technology suppliers. More technologies, including industry-specific alternatives (e.g. LEILAC technology [4]) are being developed [3]. In this regard, undertaking R&D activities in parallel with structured engineering processes may be challenging, but critically important. Partners implementing new technologies have observed that a wide collaboration of partners in a project can provide very significant insights and rapid development.

3.2 Selecting technology suppliers and partners

CCUS PN members have found it beneficial to have several technology suppliers involved at an early phase in projects, from which it is possible to set up a short-list before the final technology selection. Partners implementing new technologies have observed that a wide collaboration of partners in a project can provide very significant insights and rapid development.

There is a large amount of available pilot results[2] and 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 [1].

A technology provider should be able to issue and back up performance guarantees [1], for example, in terms of CO_2 capture rates, operability, and ability to comply with regulations. CCUS PN members have noticed that vendors are increasing their financial and technological capabilities, which is fundamental for guaranteeing their technology and ensuring a good long-term relationship. 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

[2] For example, TCM public results [21].

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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, and the vendors are not necessarily the same. CO_2 conditioning for ship transportation will often require CO_2 liquefaction and storage at large-scale, which is still a niche market. Therefore, industries implementing capture projects for ship transport need to find competent partners for the construction of CO_2 liquefaction and storage facilities. Some projects have chosen to have a single FEED contractor, which will be the formal interface with the technology vendors.

More advanced projects, which currently are FOK projects, have shared that it has been challenging to keep the cost level from the FEED study. Thus, contractual and commercial requirements should be clarified with shortlisted technology suppliers. Vendors and contractors should clarify which risks and guarantees they are willing to take and the related costs, which is also linked to what risks the buyer is willing to take. It is expected that cost estimates will become more accurate as more CCUS projects are implemented and experiences are gained.

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4 Factors relevant for the complete CO_2 capture project life cycle

Aspects such as HSE considerations and the regulatory framework shape the project from the beginning, as they influence the selection of the technology, are present during the implementation of the project (e.g. contracts, FEED studies, building) and impact the operational and decommissioning phases of the project. Communication, both with other projects and with the public, is also an important project life cycle aspect.

The following sub-sections reflect some of the lessons learned by the CCUS PN members so far with respect to these aspects. It should be noted that these CO_2 capture projects have not reached the industrial operational phase and operational experience is mainly from piloting.

4.1 HSE in CO_2 capture projects

HSE is and will continue to be fundamental for all CO_2 capture projects. HSE performance comprises various aspects such as emissions to air, hazardous compounds in effluents, noise, smell, fire hazard, high pressure, and explosion hazard. From experience in other industries, unplanned HSE events such as leakages or accidents are highly publicised and may damage the whole industry. A HSE responsible should be part of the core team in an industrial capture project to follow up from the feasibility study through FEED [1]. The responsible should document and coordinate HSE related activities. HSE lessons learned for amine and non-amine technologies, as well as for CO_2 storage and transportation are described below. HSE regulatory aspects are mentioned in Section 4.2.

4.1.1 Documentation and HSE studies

Developing a Management Study Report before the FEED, both for pilot and industrial-scale operations, has proved to be a successful approach for CO_2 capture facilities. This document may include a scope of responsibilities, as well as a health and safety plan, and an environmental plan. These documents are not static and are continuously refined. Standard industrial HSE practices such as undertaking hazard and operability (HAZOP) as well as Environmental Aspects Identification (ENVID) studies should be followed through the design, construction, and operational phase. Not all activities during the operational phase of pilot plants can be foreseen, and ad-hoc activities require a fully documented HSE assessment. In some projects, a project integrator, such as Gassnova[3], is involved. In this cases, this entity should perform its own HSE activities (e.g. HAZID, HAZOP, ENVID) [1].

A practical aspect that has been mentioned by CCUS PN members is that, as in other types of industrial projects, they have found important to ensure enough working space and emergency exit routes around equipment that may need frequent servicing, as well as assuring that appropriate personal protective equipment is available.

[3] A project integrator coordinates and leads the work on benefit realization. Among others, this role may include responsibilities such as definition of, and follow-up on, studies through the whole project, performing audits, evaluation of deliveries, performing HSE activities and developing and maintaining an overall project schedule. For more information, see the Gassnova website [22] and the Developing Longship report by Gassnova [1].

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4.1.2 CO_2 capture HSE learnings

Both for amine and non-amine technologies, results sharing and HSE benchmarking is valuable for project development, as it may reduce (or eliminate) the need of on-site piloting and can be a useful tool for decision making and streamlining project development. An overview of HSE learnings for amine and non-amine CO_2 capture technologies is given below.

4.1.2.1 Amine-specific HSE learnings

Amine technologies are currently the most mature alternative for large-scale CO_2 capture, and pilot plant experience has given confidence to go forward to an industrial scale. Industrial HSE standards and practices have proven useful on pilot plants and most probably be applicable to industrial-scale projects, although specific limits for CO_2 management still need to be defined. Tools for estimating emissions and property databases specific for CO_2, solvents and solvent degradation by-products should however be further developed.

Special care must be taken to avoid amine emissions to the air. However, amine emissions can be understood and controlled at a low level. CCUS PN members have experienced that continuous monitoring (CEMS) of amine emissions per minute, down to a concentration of 5ppb is possible. However, regulations requiring "average over a period" reports rather than peaks would facilitate the future implementation and operation of carbon capture plants.

Amines may react in the process or in the atmosphere post-emission to form new substances. Amine solvents degrade with impurities such as SOx and NOx, which are common in industrial flue gases from which CO_2 is captured. Degraded amine has reduced performance and therefore degradation should be monitored and understood to have the appropriate make-up. Degraded amine (and/or other solvents) needs to be adequately handled and disposed. Further, correct personal protective equipment (PPE) needs to be in place and used properly when handling both virgin and degraded amine.

In the presence of NOx, amines may generate nitrosamines and nitramines as by-products with potential mutagenic and carcinogenic properties. These substances may be emitted to the air or appear as products in photo-oxidation of amines emitted to atmosphere [5], [6]. The inability to minimize these emissions can be a showstopper for a project and rigorous monitoring methods have been developed to evaluate the toxicity of these substances and to monitor and minimize these emissions [1]. However, CCUS PN members have noticed that existing models for dispersion and deposition of nitrosamines and nitramines can provide different results. Therefore, further research and consulting with experts in the field (researchers and academia) is advised.

4.1.2.2 HSE learnings from non-amine technologies

Non-amine capture technologies are reaching high TRL, also among the CCUS PN members, and represent a feasible alternative in some industries. Their reliability and risks should be compared to the established amine process. Defining an appropriate benchmark regarding HSE risks and emissions will prove highly beneficial for these technologies and will become a valuable tool for emerging projects to decide on the appropriate CO_2 capture technology.

Some non-amine technologies require higher pressure operations and the existence of toxic gases at elevated pressure should then be considered when performing HSE analyses. In some capture

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technologies, hydrates ("ice") may be formed, and the system should be designed with the aim of preventing their formation.

4.1.3 HSE aspects from CO_2 storage and transportation.

Capture projects may be directly connected to large-scale intermediate storage and transportation of CO_2 to a port or to a storage site. Depending on the area, storage of CO_2 in large quantities may become a concern for third parties. When storing CO_2 nearby domestic housing, schools, hospitals or commercial areas, the possibility of rapid large volume CO_2 leakages needs to be assessed and mapped together with the topography. Standard industry tools and analysis methods for high-volume leakages have been developed for hydrocarbons and toxic substances but some CO_2 behaviours differ from those of these substances. For example, CO_2 is not flammable. It is also heavier than air and therefore it will accumulate at low points. It has been observed among the CCUS PN members that atmospheric dispersion simulations are in general based on very rough models, and results from different models can vary significantly. Aspects such as the frequency for leakages and lethality levels of CO_2 is uncertain. Specific properties of CO_2 will also affect design decisions such as material selection and zone classification [1]. Therefore, tools, databases, and dispersion models specific for CO_2 should be further developed.

Projects that have the possibility of truck or pipeline transport from the CO_2 capture plant to the port have found that truck transport is less risky than pipeline transport in case of transport through densely populated areas.

4.2 Permits and regulations

A favourable policy and regulatory framework is crucial for the large-scale deployment of CCS projects in this decade. Legal challenges, as well as the need of coordination at EU level and political support have been outlined in other documents such as the SET-Plan IWG 9 report published this year[4] (see

[4] SET-Plan Implementation Working Group 9 CCUS Report "Key enablers and hurdles impacting CCUS deployment with an assessment of current activities to address these issues" (2020).

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Appendix A). Here, we outline some practical aspects that the CCUS PN members have identified that are relevant during the implementation of CO_2 capture projects.

Regulatory work is time consuming and it should be initiated as soon as possible. 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. It is observed among some network members that it can be challenging to contact vendors and get bids when regulations are not fully in place. This means also that it can be difficult to select among vendors, since they preferably should be able to comply with regulations, and if regulations are not in place, warranties cannot be agreed upon. An alternative for the time being is to make educated and well-informed best guesses and have a good dialogue with all relevant authorities.

Project owners have found useful to create a checklist together with regional government representatives for permitting. The textbox below lists some regulations that may be considered when implementing CCUS projects.

Textbox 1 Regulations to consider when implementing CCUS projects

- Planning and building regulations
  - Area planning (zoning)
  - Requirements for design and construction
  - Regulations for building permit
  - Requirement for relevant competence of contractors
  - Requirement for third-party control
- Pollution control regulations
  - Flue gas changes
  - Environmental risk assessment
  - Handling polluted soil
  - Relevant competences for involved parties
  - Monitoring effluents and emissions (including those related to solvents)
- Fire and explosion prevention regulations
  - Competence requirements for engineering, design, manufacturing, installation, operation, changes, repairs, maintenance and control
  - Risk assessment to eliminate undesirable incidents and reduce the probability and consequence for undesirable incidents
  - Technical demands for execution and barriers
  - Adequate emergency preparedness plans
  - Adequate documentation
- Working environment regulations
  - The architectural, technical or organisational choices made
  - Risk factors relevant for the work to be carried out; these are to be described and considered
  - The time necessary for planning and executing the various work
- Climate change regulations
- CO_2 transport regulations (e.g. through populated areas)

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CCUS PN members highlighted that the regulatory environment is continuously evolving. The maturity of regulations is not the same in every country. Regulations on declaration of solvents and emission of solvents or solvent by-products (e.g. nitrosamines) are either developing or non-existing in some countries.[5] Establishing limits is not straightforward. For instance, "amine" is a generic term and chemical, physical and toxicity properties of amines vary. This evolving environment brings challenges to project developers, as it affects vendor selection and investment decisions in terms of required infrastructure. In this uncertain regulatory environment, best available technology (BAT) guidance can be a useful tool to evaluate vendors. Regulation agencies, project developers and vendors should work together to find a balance that protects the environment without unnecessarily curtailing or stopping CCUS markets. Monitoring and verification methods and regulations are also under development. It should be noted that not all capture technologies can be monitored in the same way; so, monitoring requirements (as well as measurement methods) for non-amine technologies should also be given attention.

Several members have noted that there are many HSE aspects that are not yet defined in regulations such as limit values and analysis methods. It should also be noted that regulations differ among countries.

There are different amine-based solvents and countries have different requirements with respect to emission limits [1]. Piloting of amines at a specific industry may be necessary to qualify the solvent from the perspective of emission requirements. For example, in Norway, for governmental support and qualification, there are stringent requirements on quality assurance and control. Accredited measurement personnel and companies should be selected to do measurements and analysis.

Flow measurement on flue gas with variations in composition, especially water content, can be difficult and expensive to handle on pilot plants. This may be the case also on industrial-scale CO_2 capture plants. Therefore, regulations should consider this when defining limit values.

4.3 Dissemination and communication

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. Deliverables may include design aspects of the CO_2 capture plant, and in some cases, redacted FEED studies, third-party verification reports and EFTA Surveillance Authority (ESA) decision documents are publicly available.

CCUS PN members are aware that results-sharing and public acceptance are not only beneficial but fundamental. The projects have positive experiences engaging with stakeholders and have used every opportunity to share knowledge for different groups including the general public, students on all levels, academia, and the government.

[5] For example, Regulators in the UK are consulting on new environmental assessment limits for amines.

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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.

Key learning points with regards to results sharing include:

- Early, consistent, transparent, and wide engagement of all interested stakeholders has been of great mutual benefit.
- The need to communicate clearly has shaped the direction of some projects.
- Involving trusted partners, such as NGOs, to aid with public acceptance has been beneficial.
- Active participation in consortia, webinars, industry partnerships, and public events provides feedback and facilitates support of stakeholders.

4.3.1 Results sharing among projects

Knowledge sharing among CCS projects[6], as well as partnership-based cooperation among plant operators and industrial associations has been key in bringing forward CO_2 capture projects and bringing CCS up to speed to be able to reach climate goals.

Having accessible cost information regarding comparable projects has been useful for emerging projects. Existing projects are accumulating experience of adapting generalized results to individual projects, which will be extremely valuable for accelerating future CCS projects.

Currently several first-of-a-kind (FOK) projects include running a pilot plant onsite before the investment decision of constructing the industrial-scale CO_2 capture plant. This requires resources in terms of time and budget. With a rapid increase in deployment of industrial projects, 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. Best practices guidance and knowledge sharing among projects for safe operation and pollution prevention will certainly pave the way for the deployment of CO_2 capture.

4.3.2 Results sharing with academia and the public

High public acceptance towards proposed technological solutions is vital for the success of CCS projects. Projects have the experience that sharing the nature of the capture technology with the public, such that they understand the implications and benefits of implementing CCS facilitates public acceptance. Most projects are being deployed in existing industrial facilities, and local public is in general aware of the benefits that a CO_2 capture project could bring to the region.

Public engagement events and media participations have been well received. Due to local interest, and an increasing media interest, the LEILAC project for example has opened an on-site Visitor Centre at the Lixhe cement plant in Belgium. Since then, the project has taken the step of making an active

[6] This knowledge sharing is since 2019 facilitated by the CCUS Projects network (https://www.ccusnetwork.eu/) and was in 2009-2016 facilitated by the EU CCS Demonstration Project Network (https://www.ccusnetwork.eu/knowledge-hub/eu-ccs-demonstration-project-network-2009-2016)

effort to not just promote its own results, but all major European initiatives and engage in a wider stakeholder engagement effort.

Several CO2 capture projects are active in academic fora, such as the IEA GHGT7 and TCCS8 conference series as well as scientific journals. Here they share project scopes, pilot campaign results and other research activities. Outstandingly, some projects have initiated conferences such as the "Innovation in Industrial Carbon Capture Conference"[7], developed by the LEILAC project, which was held in 2018 and 2020. Some projects, especially those heavily involved in technology development, have been active publishing in academic journals9, which serves to build confidence and support for the projects.

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[7] International Energy Agency, Greenhouse Gas Control Technologies Conference [23].

[8] Trondheim CCS Conference [24]

[9] For example, TCM [21], Carbfix [25], Leilac [26]

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5 Identified needs for progressing towards industrial operation

Realising CO_2 capture as the first step of a CCS chain is more than just identifying and selecting the technology, and installing CO_2 capture an industrial site. To reach industrial-scale operation, CCS projects must be developed along several axes, including cutting costs when possible and securing funding for construction and operation. Also, 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, although it is not elaborated on below, it is generally observed that political support and implementation plans are very important on all levels: EU, national, and local.

5.1 Building the business case: cutting cost, EU ETS, access to funding

A primary hurdle to overcome for industrial CO_2 capture projects in order to build a business case is cost. CAPEX may be the easiest to decrease for current technologies such as amines, through stepwise learning from one project to the next, and some reductions in OPEX can be achieved (for example by identifying better heat integration solutions in the case of amines). It is perceived by some of the CCUS PN members that for future projects more of a "quantum leap" may be required for more significant OPEX reductions in terms of reduced energy consumption.

The EU Emissions Trading System (ETS) [8] 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) [9]. The current EU ETS scheme only covers CO_2 captured from fossil emission sources, and it is mentioned by some of the CCSU PN members that incentives for investing in BioCCS could help trigger Carbon Dioxide Removal (a.k.a. negative emissions). Early movers in CO_2 capture implementation can to some extent be supported from additional sources such as the Innovation Fund [10], and there are also examples of government support for realising early CCS projects, such as in the Norwegian Longship project that was launched in September 2020 [11]–[13] with the budget approved by the Norwegian Parliament on December 14, 2020 [14], or the recent announcement of the British government to fund CO_2 capture clusters in the UK [15]. Further and future steps and additional mechanisms, such as contracts for difference, can also be envisaged to accelerate CCS implementation. Access to more direct funding/risk capital can also be an enabler, as well as additional funding schemes to achieve cuts in hard-to-abate emissions.

It is observed that timing is crucial: it is difficult for a company to make a final investment decision if the business case is uncertain.

5.2 Access to CO_2 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. As for the business case, timing is crucial: CO_2 infrastructure must be available to receive, transport and store the CO_2 when a capture project is put into operation, to have some return of investment e.g. under the ETS.

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Development and implementation of capture in industrial clusters with a joint backbone infrastructure is happening in Europe and seen as an enabler. It is observed by some members that the physical connections to a backbone transport infrastructure may be capture-project specific and may require dedicated development of e.g. loading/offloading systems for truck or train transport. There must be a matching in capacity between CO_2 captured from industrial sites and the available CO_2 transport and storage capacity. This means that transport and storage projects that oversize their capacity are a prerequisite for the development of industrial CO_2 capture projects.

Implementation plans for capture projects must be developed to match with the timing of infrastructure implementation and an appropriate legal/regulatory framework. It is observed that the major hurdle for cross-boundary ship transport of CO_2 was resolved in 2019 with the provisional application of the 2009 amendment to the article 6 of the London Protocol [16].

5.3 Risks and risk 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. For example, in the Longship project, risks are shared between the Norwegian state, Northern Lights and the industries (Norcem and FOV) [13]. Projects may need recognition from investors (e.g. banks) that they will not yield normal returns. As such, the financial world has an opportunity to take responsibility in sharing the risk for CCS. It is also observed that each early mover needs that the other early movers are successful, e.g. from an HSE perspective; if there is a failure in one project, it is not unlikely that other projects will suffer.

5.4 R&D 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 realising 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. For example, membrane technologies or fuel cells (SOFCs and MCFCs) may be an alternative to concentrate CO_2 [17], as a synergy with other CO_2 capture technologies or other CO_2 uses. A brief overview of emerging and industry-specific CO_2 capture technologies, some of which are still in development phase, is available in a previous CCUS PN thematic report [3]. CCUS PN members mentioned the need for:

- Capture technologies and technology integration that significantly reduce CAPEX and OPEX
- Improving models for dispersion and deposition of nitrosamines and nitramines.
- Improving knowledge regarding models for CO_2 dispersion and large-scale leakages, which are tools for HSE and risk analyses.
- Defining 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.

6 Conclusion

This report gathers knowledge related to the development of European CO_2 capture projects and the observed needs that projects have for proceeding towards implementation. Input for the report has been provided by members of the CCUS Projects Network, and also the Gassnova report on developing the Longship project [1] has been an important reference. The report summarizes lessons learned from CO_2 capture technology selection and capture project implementation as well as from HSE and regulatory work related to CO_2 capture.

Capture technology selection must be made for the specific plant in consideration, considering, for example, the specific flue gas characteristics and required CO_2 purity. There are today several technology providers to select between. Piloting can provide confidence in a capture technology but also requires a collaborative effort between a wide range of stakeholders. Cost is a key decision factor both for the capture technology itself, but it is also important that cost effective industrial plant operation and product quality can be maintained. Energy-efficient integration of CO_2 capture is also important, e.g. for heat-requiring technologies such as amines. It is observed by CCUS PN members that selection of technology suppliers and partners in a capture project involves seeking a good long-term relationship, e.g. for solvent supply.

HSE in CO_2 capture projects comprise various aspects such as emissions to air, hazardous compounds in effluents, noise, smell, fire hazard, high pressure, and explosion hazard. It is largely observed that HSE risks are known and can be handled, although special care must be taken to avoid amine emissions to the air.

A favourable 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. It has been observed by the CCSU PN members that there is sometimes a lack of sufficient regulations (e.g. regarding permissible emissions form amine capture) but the regulatory framework is continuously evolving.

Results sharing is fundamental for successful projects: results should be disseminated among CCUS projects, with stakeholders, with the public and in the academic field.

To realise CO_2 capture at industrial scale, building a business case is essential, including access to funding and measures for generating income (e.g. EU ETS, contracts of difference, incentives for BioCCS). Also access to CO_2 transport and storage infrastructure, possibly as part of an industrial cluster, is of course important as well as strategic partnerships for risk sharing.

R&D needs for improving CO_2 capture have been identified, such as efforts to continue to decrease capture cost, but also to continue to improve the HSE and further reduce the risks of CO_2 capture and CO_2 management. Improving dispersion and deposition models for nitrosamines and nitramines, and improving models for dispersion and large-scale leakage for CO_2.. Also the need to define BAT for pollution prevention as well as reliable and standardized measurements and methods to facilitate operation, reporting and compliance with regulations.

7 Glossary and abbreviations

a.k.a.	Also known as
BAT	Best available technology
BioCCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture utilisation and storage
CCUS PN	CCUS Projects Network
CEMS	Continuous emission monitoring systems
CO_2	Carbon dioxide
EFTA	European Free Trade Association
ENVID	Environmental aspects identification
ESA	EFTA surveillance authority
ETS	Emissions trading system
EU	European Union
FEED	Front-End Engineering Design
FOK	First of a kind
FOV	Fortum Oslo Varme
GHG	Greenhouse gas
HAZID	Hazard identification
HAZOP	Hazard and operability
HSE	Health, safety and environment
IP	Intellectual property
IWG	Implementation working group
MCFC	Molten-carbonate fuel cells
MRR	Monitoring and reporting regulation
NGO	Non-governmental organization
NOx	Nitrogen oxides
OPEX	Operating expenditure
ppb	Parts per billion
PPE	Personal protective equipment
R&D	Research and development
SET Plan	(European) Strategic Energy Technology Plan
SOFC	Solid oxide fuel cell
SOx	Sulfur oxides
TRL	Technology readiness level

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Appendix A

From November 2019 through May 2020, the Strategic Energy Technology Plan (SET-Plan) Implementation Working Group (IWG) 9 [18] arranged a series of four webinars under the title "Defining gaps and R&I priorities enabling CO_2 capture in Europe". Key stakeholders, mainly from industry and public funding agencies, presented projects and views, and participated actively in discussions during the webinars [19]. Some outcomes related to R&I needs for CO_2 capture in industry, that are relevant in the context of this report are included in the textbox below.

Textbox 2 Identified gaps and R&I priorities enabling CO_2 capture in Europe [19]

- CO_2 capture in industrial clusters
  - Integration and synergies with other sectors and renewable solutions
  - Process intensification, including utilisation of waste heat
  - Retrofitability, part-load operation and flexibility
  - Buffer storage and shared transportation infrastructure
  - Treatment of waste products from capture plants
  - Degradation and life span of capture technologies
  - Business models
- Cost reduction of CO_2 capture technologies
  - High-TRL CO_2 capture technologies (from TRL 5-6 to TRL 7-9)
  - Next generation CO_2 capture technologies
  - Modularization of capture technologies
- Standardisation and legislation issues related to CO_2 capture
  - Standardised CO_2 specifications
  - Incentives for carbon negative solutions and CCU
  - Standardised methods for measuring the biogenic/fossil CO_2-ratio
  - Data on emissions from CO_2 capture technologies
  - Harmonizing legal standards and regulations relevant for the development of a European CO_2 transport- and storage- network

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