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Review of Constructability and Operational Challenges faced by CCUS Projects

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

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REVIEW OF CONSTRUCTABILITY AND OPERATIONAL CHALLENGES FACED BY CCUS PROJECTS

IEAGHG has commissioned several technical studies linked to large CCS projects[1]. Although constructability and operational challenges have been identified in previous IEAGHG reports, some aspects were unique due to the locations where the large CCS projects were implemented. These included the status of the initial facilities and other techno-economic and financial aspects of the specific CCUS projects.

IEAGHG identified the need to provide a guide on constructability and operation for new CCS users. The objective of this study is to collect information from CCS projects to support the decisions during the transition from the planning to the execution phase.

This study analysed a complete list of large CCUS projects from which relevant experience could be extracted. The projects were divided into three categories: operating projects; under construction or at advanced development; and cancelled projects. Based on the analysed projects, this study has delivered an assessment of potential key areas for success, and a decision tool guide for future projects.

Key messages

- Key factors for the success of CCS projects include: integration of the CCS system and the original facility early in the project development process, previous testing of the capture system under the specific conditions of the original facility, (for example, fluegas composition, and temperature), and involvement of the stakeholders from the early stages of the project.
- The business case and coordination of the cross-chain (including capture, transport, and use/storage), are essential to maintain the operation of the CCS project within the designated time-line.
- Other aspects for success include a detailed planning simulation of the construction site management, plant commissioning, start-up, maintenance, shutdown and decommissioning.
- This investigation has identified several reasons for cancellation of CCS projects. These include: lack of long-term economic viability (including dependency on government subsidies and unexpected changes to government funding schemes); uncertainty around risk management and allocation; inadequate integration of the capture system with the original facility, or lack of planning in advance (including technical aspects not related to the CCUS system); and flawed design.
- The decision tool proposed in this study is based on the ability to make and then integrate individual decisions. The tool can generate favourable and less favourable

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[1] IEAGHG 015/06 Integrated Carbon Capture and Storage project at SaskPower's Boundary Dam Power Station; IEAGHG 2018/05 The Carbon capture project at Air's Products Port Arthur Hydrogen Production facility; and IEAGHG 2012/09 Barriers to implementation of CCS-Capacity and constraints

options for each decision. However, these selections need to be tailored to the site-specific conditions.
- Although the decision tool is presented as a linear process, some decisions could be taken in parallel or as an iterative process to find the optimum tailored design. The tool has the ability to refine initial decisions or retain selected decisions for later stages.

Scope of work

A team comprising Element Energy, Global CCS Institute and Air Products was commissioned by IEAGHG to provide a guide on constructability and operation for new CCS users.

The main objectives of this study are:

- to review constructability and operation issues in successful and cancelled large-scale CCUS projects;
- to analyse the main areas of attention related to the execution phase; and
- to provide a useful guide for project developers and other related activities such as comparison with ISO standards.

The aim of the guide is to provide material to aid potential developers with the planning phase of large-scale CCS facilities to ensure successful construction, commissioning and operation.

The contractor conducted a literature review and a series of interviews with 24 key stakeholders from the selected demonstration sites. Of the 22 projects included in the study, eight are fully operational[2].

The detailed decision chain guidance tool is based on lessons learned from operating projects as well as the reasons for project cancellations. For each decision, the tool generates guidance on the most appropriate options for different CCUS projects. Complementary information that needs to be considered during the decision process is identified.

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[2] At June 2020

Findings of this study

A complete list of CCS projects considered in this study is included in Table 1, including operating projects, projects in advanced development (which have yet to receive consent to proceed to a construction phase), and cancelled projects.

Table 1 Large scale CCS projects considered in this study

Group	#	Project	Country	Sector
Group 1: Operating Projects (constructability and operability assessment)	1	Al Reyadah CCUS Project	UAE	Iron and steel
	2	Boundary Dam Carbon Capture Project – SaskPower	Canada	Power generation (Coal)
	3	Quest carbon capture and storage project	Canada	Hydrogen production
	4	Port Arthur CCS Project	USA	Hydrogen production
	5	Petra Nova CCUS Project	USA	Power generation (Coal)
	6	Gorgon Carbon Dioxide Injection Project	Australia	Natural gas processing
	7	NET Power Clean Energy Demonstration Plant	USA	Power generation (Gas)
	8	Illinois Basin-Decatur Project (IBDP)	USA	Ethanol production

Group	#	Project	Country	Sector
Group 2: **Projects in advanced development** **(constructability assessment only)**	9	The CarbonNet Project	Australia	Power and hydrogen production (lignite)
	10	Port of Rotterdam CCUS Backbone Initiative (Porthos)	Netherlands	Various industries
	11	Fortum Oslo Varme Capture Plant	Norway	Waste-to-energy
	12	Norcem Brevik Capture Plant	Norway	Cement
Group 3: **Cancelled Projects** **(constructability assessment and reasons for cancellation)**	13	Peterhead CCS Project	UK	Power generation (Gas)
	14	White Rose CCS Project	UK	Power generation (Gas)
	15	Longannet CCS Project	UK	Power generation (Coal)
	16	Kingsnorth CCS Project	UK	Power generation (Coal)
Group 4: **Cancelled Projects** **(only reasons for cancellation)**	17	The Kemper County CCS Project	USA	Power generation (Coal)
	18	Full-scale CCS at Mongstad Project	Norway	Power generation (Gas)
	22	Texas Clean Energy Project (TCEP)	USA	Power generation (Coal)
	20	Vattenfall Nordjyllandsværket CCS Project	Denmark	Power generation (Coal)
	21	FutureGen 2.0	USA	Power generation (Coal)
	22	ROAD – Rotterdam Capture and Storage Demonstration Project	Netherlands	Power generation (Coal)

Each project was analysed through literature review and interviews with the key stakeholders. A further description of each facility, constructability and operability issues is included in the main report. Based on the collated information from Groups 1-2 (Table 1), the following lessons can be extracted:

- The success of a CCS project is dependent on the strength of the business case. Key criteria include the long-term economic viability, sustainable revenue streams, financial and regulatory support. A successful project must ensure the involvement of stakeholders and including local communities from the start of the project.
- The maturity of the capture technology is a key factor. The use of pilot scale tests on site-specific flue gas, and the related unique environment, has been a common success factor across all projects.
- The design of the full chain needs to include: access to flue gas; conditioning of CO_2; transport of CO_2; and CO_2 final destination/storage.
- For the construction phase, the impact of the site location must include planning, inter-related activities, transportation, permits, environmental assessment, and personnel availability.
- Modular and offsite manufactured units are potentially recommended. This approach helps to reduce risks with plant integration and commissioning.
- Coordination of timelines, effort and liabilities amongst different stakeholders across the CCS value chain, including the entire cross-chain (capture, transport, storage/use), is essential. CCS projects must ensure long-term steady demand in line with the capture operation.
- Integration of the capture system with the original plant is a key factor for its operability. That will impact on the processes, utilities, efficiency and the maintenance of the original plant’s flexibility.
- CCS projects must apply common construction best practices. Definition of security, HSE measures and site ownership should be communicated to all stakeholders
- The transition from planning to operation should minimize the interruption of the activities of the original facility. This must include clear procedures for normal, emergency start-up and shut-down. The related documentation must always be available for the operating crew.
- The CCS operation should be planned and simulated, including efficiency measures, maintenance programmes, personnel availability and operational capacity. Monitoring sensor installation and control rooms, as well as by-products and waste handling procedure, should be included in the planning.
- Early planning for site decommissioning and closure is essential for the management of liabilities, risk allocation and ownership.

From the cancelled projects, Groups 3-4 (Table 1), it is important to note that not all the projects were cancelled for similar reasons. Some projects were cancelled for more than one reason and unexpected changes to funding frameworks have had an impact on the continuity or viability of some projects. Based on the analysis conducted in this study the following potential reasons for cancellation can be extracted:

- Lack of long-term economic viability
- Over-reliance on government subsidies
- Uncertainty around risk management and allocation
- Risks compounded by multiple project developments at different stages of the value chain either not fully appreciated or inter-linked
- Not enough integration for the compatibility of the capture system with the original facility, or lack of planning in advance

- Unsuitable design which impacts on the construction and operation. That can be due to lack of integration of the capture system with the original facility and/or the scale up from pilot or demonstration to commercial scale.

Supported by the analysis of successful and cancelled projects, the contractor has provided a decision chain guidance tool. This tool is based on individual decisions, tailored to a variety of needs and constraints of typical CCS projects. These decisions are designed to cover various stages of the project, from planning and construction to commissioning and operation. An overview of this tool is included in Figure 1.

It should be stressed that decisions do not necessarily have to be taken as a linear process. Some decisions can be taken in parallel or within an iterative process to determine the optimum solution. Based on this decision chain guidance tool, the contractor has provided a guide for new entrants, which contains a sequence of decisions to consider (see Figure 2), and recommendations on actions to take into account along the planning and implementation of a CCS project.

For each decision the guidance tool provides recommended options for various types of CCUS projects, together with complementary information that will need to be considered during the decision process. This framework ensures that the planner:

- Is made aware of the most relevant decisions to be considered.
- Is advised on the best options for each decision, tailored to the characteristics of the project.
- Is informed on additional details that will need to influence each decision.

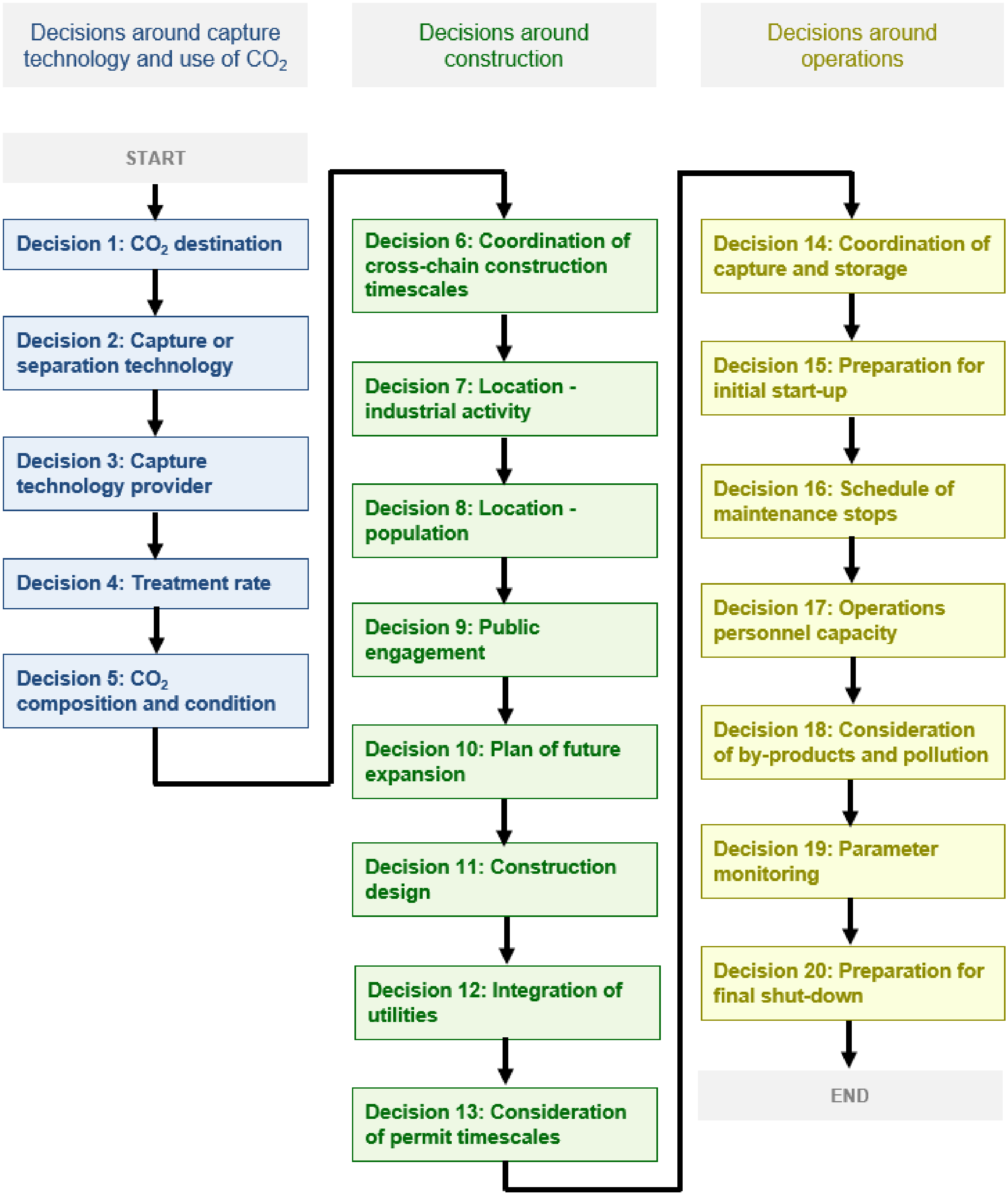
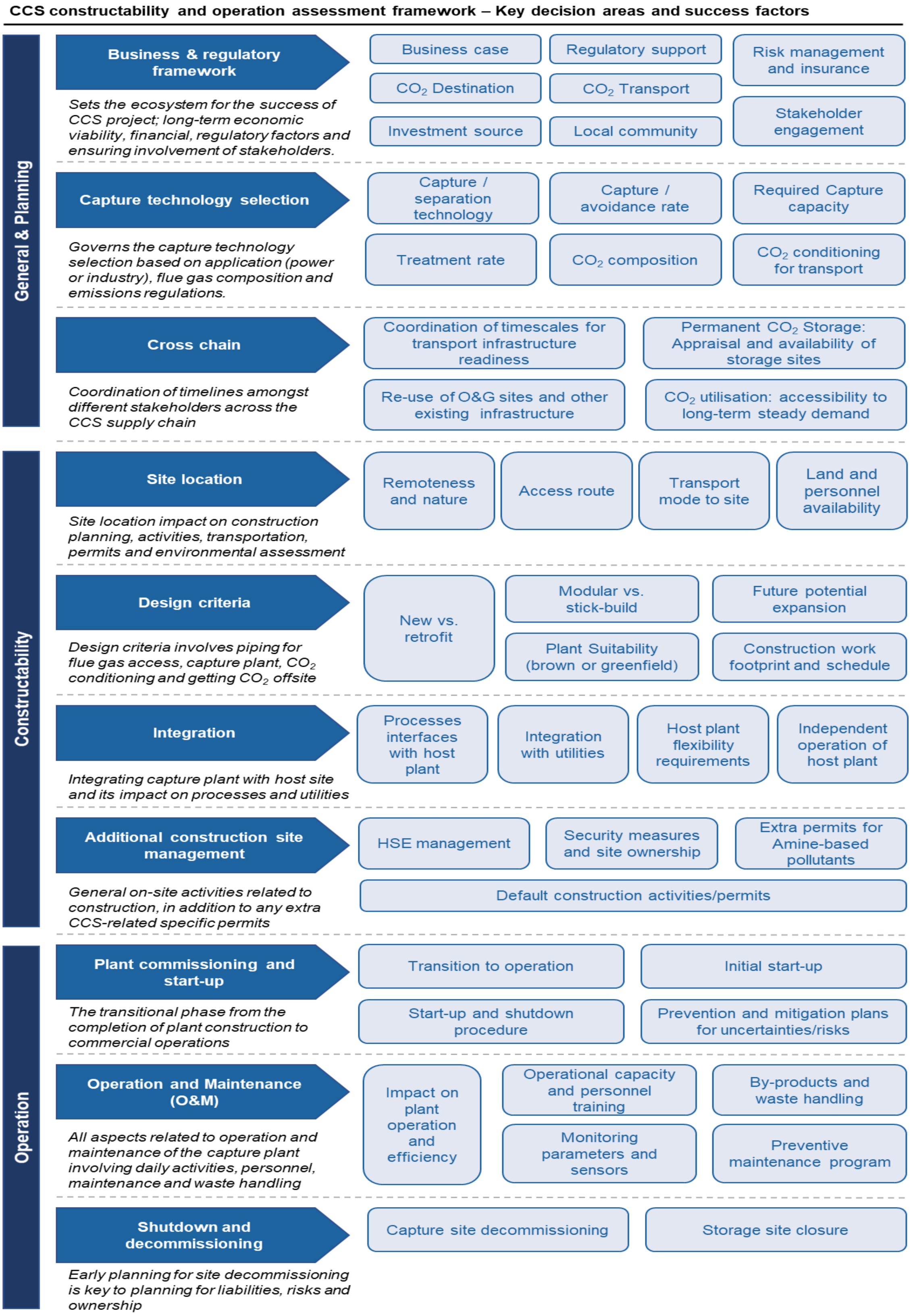


Figure 1 Overview of the decision chain logic proposed in this study



CCS constructability and operation assessment framework – Key decision areas and success factors

Phase	Decision area	Description	Success factors
General & Planning	**Business & regulatory framework**	*Sets the ecosystem for the success of CCS project; long-term economic viability, financial, regulatory factors and ensuring involvement of stakeholders.*	Business case Regulatory support Risk management and insurance CO_2 Destination CO_2 Transport Investment source Local community Stakeholder engagement
	Capture technology selection	*Governs the capture technology selection based on application (power or industry), flue gas composition and emissions regulations.*	Capture / separation technology Capture / avoidance rate Required Capture capacity Treatment rate CO_2 composition CO_2 conditioning for transport
	Cross chain	*Coordination of timelines amongst different stakeholders across the CCS supply chain*	Coordination of timescales for transport infrastructure readiness Permanent CO_2 Storage: Appraisal and availability of storage sites Re-use of O&G sites and other existing infrastructure CO_2 utilisation: accessibility to long-term steady demand
Constructability	**Site location**	*Site location impact on construction planning, activities, transportation, permits and environmental assessment*	Remoteness and nature Access route Transport mode to site Land and personnel availability
	Design criteria	*Design criteria involves piping for flue gas access, capture plant, CO_2 conditioning and getting CO_2 offsite*	New vs. retrofit Modular vs. stick-build Future potential expansion Plant Suitability (brown or greenfield) Construction work footprint and schedule
	Integration	*Integrating capture plant with host site and its impact on processes and utilities*	Processes interfaces with host plant Integration with utilities Host plant flexibility requirements Independent operation of host plant
	Additional construction site management	*General on-site activities related to construction, in addition to any extra CCS-related specific permits*	HSE management Security measures and site ownership Extra permits for Amine-based pollutants Default construction activities/permits
Operation	**Plant commissioning and start-up**	*The transitional phase from the completion of plant construction to commercial operations*	Transition to operation Initial start-up Start-up and shutdown procedure Prevention and mitigation plans for uncertainties/risks
	Operation and Maintenance (O&M)	*All aspects related to operation and maintenance of the capture plant involving daily activities, personnel, maintenance and waste handling*	Impact on plant operation and efficiency Operational capacity and personnel training By-products and waste handling Monitoring parameters and sensors Preventive maintenance program
	Shutdown and decommissioning	*Early planning for site decommissioning is key to planning for liabilities, risks and ownership*	Capture site decommissioning Storage site closure

Figure 2 Assessment framework used for stakeholders interviews and to support the guide for new entrants

Comments from the reviewers

A review was undertaken by four recognised international experts from the industrial and consultancy sectors. The draft was generally well received, with reviewers remarking on the significant contribution of this report to future CO_2 capture projects.

Three reviewers provided further techno-economic information for general consideration and on specific large CCUS projects. The contractor took this information into account and further techno-economic data has been included in the final document.

One reviewer discussed the meanings of CO_2 use and CO_2 utilization. The contractor has included the definitions used, in the final version of this report.

One reviewer commented on the need to include more information about specific favourable business models for large CCS projects. Although the contractor has included some information about it, an exhaustive review of business models was out of the study's scope.

One reviewer commented on the need to include a discussion of strategies to reduce costs, on NOAK (n^{th} of a kind) plants, based on the learnings from FOAK (first of a kind). Although the contractor considered this comment, a further analysis was out of the study's scope.

One reviewer provided valuable comments on the application of the decision tool. Initially a linear decision process was proposed. The reviewer suggested that some decisions might be done in parallel and/or within an iterative strategy to optimize the final large CCUS project design and to cut down costs. This suggestion has been incorporated in the final report.

Conclusions

This study covers the analysis of successful and cancelled CCS projects, providing a useful tool for new entrants, to support their transition from planning to construction and from construction to operation.

Key factors for the success of CCS projects include early design which should include the integration with the original facility, previous testing under the specific conditions, and involvement of stakeholders from the early stages of the project. The business case and coordination of the cross-chain (including capture, transport, and use/storage) are essential to maintain the operation of the CCS project throughout its operational life. Other aspects will include detailed planning based on a simulation of the common construction site management, plant commissioning, start-up, maintenance, shut-down and decommissioning.

The reasons for cancellation include: lack of long-term economic viability (including dependency on government subsidies and changes on funding schemes); uncertainty around risk management and allocation; not enough integration of the capture system with the original facility, or lack of planning in advance (including technical aspects not related to the CCUS system); and flawed design which impacts on the construction and operation.

This study provides a decision tool guide for future large CCUS projects. However, it must be used with caution, as some decisions might be impaired if they are solely reliant on linear processing. Parallel or iterative approaches can enhance decisions. Additionally, the tool must be tailored to each project.

Recommendations

It is recommended that IEAGHG should continue to maintain a watching brief of large CCUS projects.

This study has collected valuable information from FOAK CCUS projects which will support SOAK (second of a kind) CCUS projects along the decision making process. Based on the results of this study, it is recommended:

- To explore business models used in CCUS projects particularly those which have led to successful large CCUS projects.
- To review the permits and regulations required to implement a large CCUS project.
- To review this document every 2-3 years, aiming to incorporate new learnings and update the guide for new users.

elementenergy

Review of constructability and operational challenges faced by CCUS Projects

A report for

IEAGHG

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Executive summary

The worldwide CO_2 capture capacity in 2019 is estimated at around 40 $MtCO_2$ per annum according to the latest status report published by the Global CCS Institute. A number of global energy models indicate that achieving a 2°C climate scenario requires the capture and sequestration of approximately 1,000-2,000 $MtCO_2$ per annum by 2030. This is the equivalent of fitting approximately 30 GW of power capacity with CCS each year, comparable to the peak annual coal or nuclear construction rate following the 1970s oil crisis. However, the current growth rate in CCS languishes far below the required level, having only doubled from a miniscule base in 15 years. The sector suffers from a high rate of attrition in moving from project initiatives to deployment. The sector is highly exposed to policy and regulatory risks, challenges in defining liabilities and, while a number of operational large scale CCS projects have been realised successfully, it is unfortunate that some first-of-a-kind coal and gas power CCS projects have been cancelled or experienced significant cost and/or time over-runs. This has impacted stakeholder confidence that projects can be delivered on time, to budget and to specification.

Successful and cancelled CCS projects can bring invaluable learnings for the planning of future projects and define a clear route for the construction and operation of the future CCS generation. On the one hand, constructability is considered as the anticipation of construction constraints and the identification of opportunities in order to improve the efficiency and effectiveness of a project, since they may influence the decisions taken during the project life cycle. On the other hand, the analysis of operational challenges focuses on key areas related to the execution phase of already implemented CCS projects (new construction and retrofitting).

Emerging from this narrative, IEAGHG identified the need to provide a guide on constructability and operation of large-scale CCS projects for new users. **Element Energy – supported by GCCSI and Air Products – were commissioned to carry out this study that aims to:**

1) Provide a comprehensive assessment of the constructability and operational factors for execution of large-scale CCS projects in power and industry.
2) Explore the reasons for the cancellation of non-completed CCS projects and potential solutions for the underpinning problems identified.
3) Deliver a step-by-step decision tool for new entrants in the CCS business scenario, providing guidance for the transition from planning to execution and from construction to operation.

Key success factors for constructability and operation of large-scale CCS projects

Through the course of this study, 22 projects were thoroughly investigated for different parameters and constraints related to constructability and operational challenges facing large-scale CCS projects. A map with the location of the considered large-scale CCUS sites is shown in Figure 0-1. The analysed projects included operating, in construction or planning and cancelled projects.

The analysis of these individual sites has produced a plethora of key learnings attributed to constructability and operation. These learnings were categorised under 10 key areas spanning the project phases from planning and construction to commissioning and operation as shown in Figure 0-2.

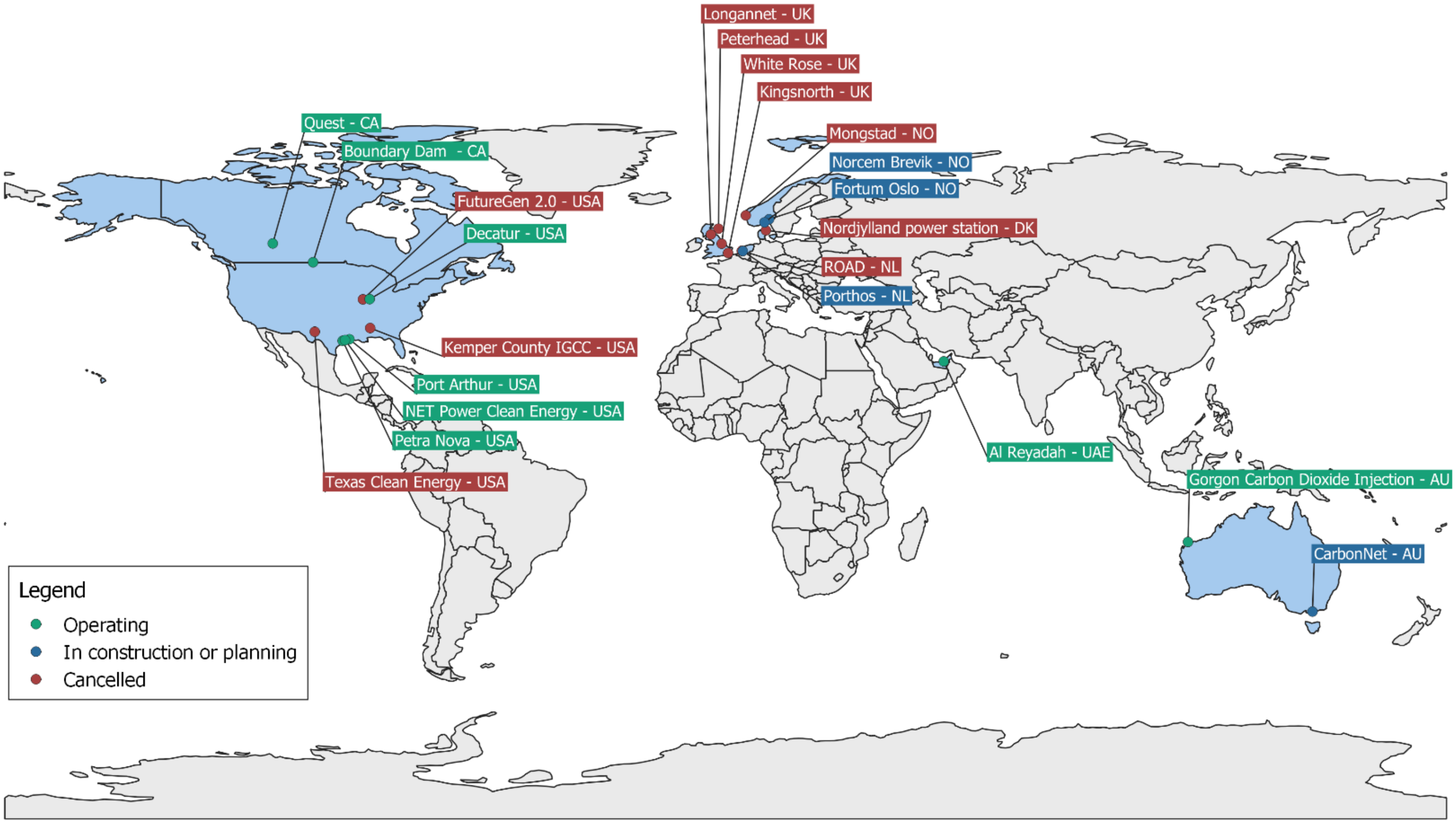


Figure 0-1: Location of investigated large-scale CCS sites

Summary of lessons learned on the constructability and operations of large-scale CCS projects

Business & regulatory framework

A successful CCS project must ensure a sound business case, long-term economic viability and revenue streams, financial & regulatory support and ensure involvement of all stakeholders including local community engagement in early stages of the project.

Capture technology selection

Testing different capture technologies prior to commercial scale on own flue-gas is a key success factor. In some industries, utilisation of an in-house capture technology can make the business case more viable.

Cross-chain coordination

Critical coordination of timelines, efforts, liabilities amongst different stakeholders across the CCS value chain.

Site location

The impacts of a specific site location must be accounted for in the construction planning, activities, transportation mode, permits, environmental assessment and personnel availability.

Design criteria

A typical full-chain CCS project will involve four key design pieces that need to be designed carefully: access to flue gas, conditioning of CO_2, transport of CO_2 offsite and its final storage/destination.

Plant integration

Integrating capture plant with the host site in terms of processes and utilities will have an impact on plant operation, efficiency and flexibility.

Construction site management

Common construction best practises are applicable for a large-scale CCS project. Clear definition of extra security, HSE measures and site ownership should be communicated to all stakeholders.

Plant commissioning and start-up

Interruption should be minimised through intensive planning of the transition-to-operation phase. Clear procedures for normal and emergency start-up and shutdown must be available for the operating crew at all time.

Operation and Maintenance (O&M)

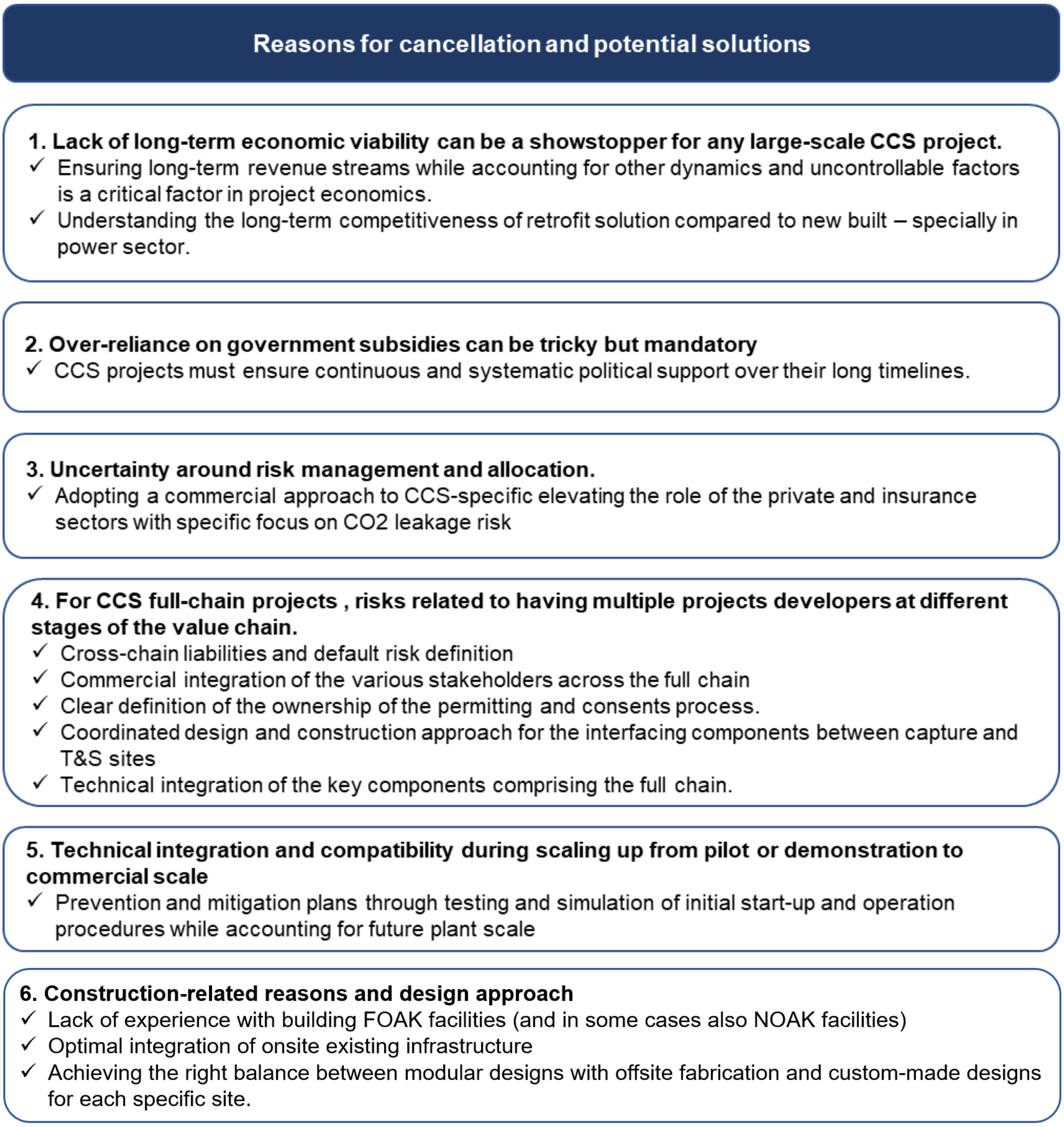
Planning and simulations should be in place whenever possible to account for all operational aspects.

Shutdown and decommissioning

Early planning for site decommissioning and closure is key to managing liabilities, risk allocation and ownership.

Figure 0-2: High level overview of key learnings related to constructability and operation of CCS projects

Reasons for cancellation and potential solutions



Reasons for cancellation and potential solutions

1. Lack of long-term economic viability can be a showstopper for any large-scale CCS project.
- ✓ Ensuring long-term revenue streams while accounting for other dynamics and uncontrollable factors is a critical factor in project economics.
- ✓ Understanding the long-term competitiveness of retrofit solution compared to new built – specially in power sector.

2. Over-reliance on government subsidies can be tricky but mandatory
- ✓ CCS projects must ensure continuous and systematic political support over their long timelines.

3. Uncertainty around risk management and allocation.
- ✓ Adopting a commercial approach to CCS-specific elevating the role of the private and insurance sectors with specific focus on CO2 leakage risk

4. For CCS full-chain projects , risks related to having multiple projects developers at different stages of the value chain.
- ✓ Cross-chain liabilities and default risk definition
- ✓ Commercial integration of the various stakeholders across the full chain
- ✓ Clear definition of the ownership of the permitting and consents process.
- ✓ Coordinated design and construction approach for the interfacing components between capture and T&S sites
- ✓ Technical integration of the key components comprising the full chain.

5. Technical integration and compatibility during scaling up from pilot or demonstration to commercial scale
- ✓ Prevention and mitigation plans through testing and simulation of initial start-up and operation procedures while accounting for future plant scale

6. Construction-related reasons and design approach
- ✓ Lack of experience with building FOAK facilities (and in some cases also NOAK facilities)
- ✓ Optimal integration of onsite existing infrastructure
- ✓ Achieving the right balance between modular designs with offsite fabrication and custom-made designs for each specific site.

A decision chain guidance tool

This tool guides the reader through a series of decisions as shown in Figure 0-3 and provides information on each of the key decisions individually, tailored to a variety of needs and constraints of typical CCS projects. The decisions are designed to cover various stages of a CCS project from planning and construction to commissioning and operation. Although organised in a sequential order, some of the key decisions may need to be evaluated in an iterative process. While early decisions pose constraints to others further down the line, some decisions can be put on hold and multiple options can be explored.

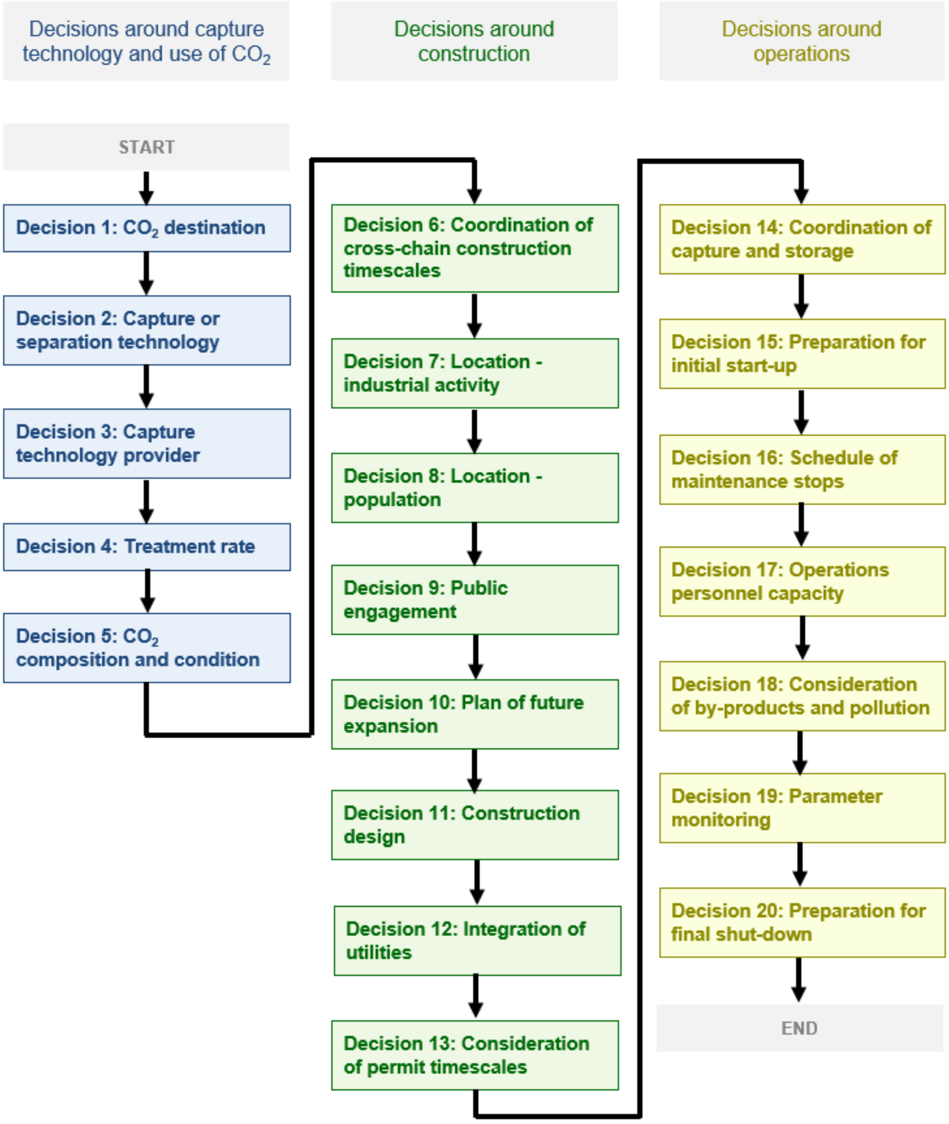


Figure 0-3: Overview of decision chain logic

A user guide to large-scale developers

In addition to this report, a clear and easy-to-understand guide for future new entrants in the CCS business and large-scale project developers has been created. The guide aims to advise the reader on the decisions that need to be made during the planning phase of a large-scale CCS facility and that are most crucial to ensure its successful construction, commissioning, and operations. It includes the detailed decision chain guidance tool as well as the aforementioned lessons learned from operating projects and summary of reasons for cancellation. The guide can be used as a standalone document for quick assistance or complemented with this report for a more comprehensive standpoint.

Contents

Acronyms

AI	Artificial Intelligence
CAD	Canadian Dollar
Capex	Capital expenditure
CCGT	Combined Cycle Gas Turbines
CC(U)S	Carbon capture (utilisation) and storage
CfD	Contract for difference
CO_2	Carbon dioxide
DOE	Department of Energy
EC	European Commission
EIA	Environmental Impact Assessment
EOR	Enhanced oil recovery
ETS	Emissions trading system
FID	Final investment decision
EU	European Union
FEED	Front End Engineering Design
FOAK	First of a kind
GCCSI	Global CCS Institute
GHG	Greenhouse Gas
GW	Gigawatt

H_2S	Hydrogen Sulfide
HSE	Health, Safety and Environment
IEA	International Energy Agency
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
LCOE	Levelised cost of electricity
MMV	Measurement, Monitoring and Verification
MW	Megawatt
MWh	Megawatt Hour
OEMs	Original Equipment Manufacturers
OPEX	Operational expenditure
O&G	Oil & Gas
R&D	Research and development
SMR	Steam Methane Reformation
T&S	Transport and storage
US	United States of America
WEO	World Energy Outlook

1 Introduction

1.1 Background and project context

A number of international assessments, including IPCC Assessment Reports and IEA scenarios have shown that deployment of CCS is essential. For instance, modelling has shown that the exclusion of CCS from the portfolio of low-carbon technologies has a much greater impact on the cost of meeting a 2 °C scenario than the exclusion of any other technology option. Additionally, the deployment of CCS is expected to have even greater significance in meeting a 'well below 2 °C' scenario. Hence, the urgency of action on CCS cannot be overstated. A recent IEA publication[1] estimates that with limited CO_2 storage, the global cost of decarbonisation could increase by $4 trillion. Hence, there is a growing recognition that CCS is a cost-effective and readily available way to decarbonise power and energy-intensive industries.

It also became widely acknowledged that CCS deployment needs to accelerate significantly if it is to play a role in combatting climate change. The worldwide CO_2 capture capacity in 2019 is estimated at around 40 $MtCO_2$ per annum[2]. A number of global energy models indicate that achieving a 2 °C climate scenario requires the capture and sequestration of approximately 1,000-2,000 $MtCO_2$ per annum by 2030[3]. This is the equivalent of fitting approximately 30 GW of power capacity with CCS each year, comparable to the peak annual coal or nuclear construction rate following the 1970s oil crisis. However, the current growth rate in CCS languishes far below the required level, having only doubled from a miniscule base in 15 years. The sector suffers from a high rate of attrition in moving from project initiatives to deployment. The sector is highly exposed to policy and regulatory risks, challenges in defining liabilities and while a number of operational large scale CCS projects have been realised successfully, it is unfortunate that some first-of-a-kind coal and gas power CCS projects have been cancelled or experienced significant cost and/or time over-runs. This has impacted stakeholder confidence that projects can be delivered on time, to budget and to specification.

Successful and cancelled CCS projects globally can bring invaluable learnings for the planning of future projects and define a clear route for the construction and operation of the future CCS generation through a constructability and operation assessment. Constructability is considered as the anticipation of construction constraints and the identification of opportunities in order to improve the efficiency and effectiveness of a project, since they may influence the decisions taken during the project life cycle. On the other hand, the analysis of operational challenges focuses on key areas related to the execution phase of already implemented CCS projects (new construction and retrofitting).

In the past, IEAGHG commissioned several technical studies linked to large CCS projects[4,5]. Moreover, an analysis of the equipment supply and capacity constraint which will impact the CCS implementation was included in the study "Barriers to implementation of CCS-Capacity and constraints"[6]. Although constructability and operational challenges have been identified in those reports, some aspects were unique for those locations and status of the initial facilities. IEAGHG identified the need to provide a

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[1] IEA report: Exploring Clean Energy Pathway: The role of CO_2 storage

[2] The Global Status of CCS: 2019 Report

[3] Energy Technology Perspectives 2017, 2DS and BSDS scenarios; www.iea.org

[4] IEAGHG 2015/06 Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station, 2015

[5] IEAGHG 2018/05 The Carbon capture project at Air's Products Port Arthur Hydrogen Production facility, 2018

[6] IEAGHG 2012/09 Barriers to implementation of CCS-Capacity and constraints

guide on constructability and operation for new users, and commissioned Element Energy to undertake this study.

1.2 Study objectives and key deliverables

The primary objective of this study is to provide a comprehensive assessment of the constructability and operational factors for execution of large-scale CCS projects in power and industry. It develops a decision framework to inform planning, construction, commissioning and operation of future CCS projects, based on lessons learned from previous CCS projects. This constructability and operability decision framework identifies **key decision areas and success factors** – combining project characteristics, constraints and possible choices – that govern a large-scale CCS project. The study builds on up-to-date knowledge, information collected through a thorough literature review process, detailed project analysis, and the engagement of expert stakeholders involved in major CCS projects worldwide in different phases: development, construction, and operation. The study also explores the reasons for the cancellation of non-completed CCS projects and potential solutions for the underpinning problems identified. The main output of this study will be a comprehensive guide for new entrants in the CCS business scenario, providing guidance for the transition from planning to execution and from construction to operation, and on how to maintain stable operation along the plant life. Other public activities such as standardization can also benefit from this guide.

1.3 Overarching approach and structure of the report

The overarching study approach is composed of four main steps, accompanied by extensive stakeholder engagement and expert reviews, as follows:

1. Review of all the ongoing, planned, in construction, and cancelled CCS projects worldwide.
2. Defining the key factors governing constructability and operation of a large-scale CCS project.
3. Detailed project analysis for ongoing and cancelled projects to identify lessons learned and reasons for cancellation.
4. Composition of decision chain guidance tool to guide new users through various steps of planning and execution of a large-scale project. The decision chain guidance tool provides a chain of decisions. For each decision, guidance is provided on the most appropriate options for various types of CCUS projects, together with complementary information that will need to be considered during the decision process.

Appendix 5.1 details the methodology followed in this study. The methodology section presents the work done in four key areas: 1) literature reviews listing the key databases consulted during the initial horizon scanning task, 2) constructability and operation assessment framework showing a list of the parameters relevant to a large-scale CCS project that can contribute to its success, 3) stakeholder engagement and finally 4) experts review done by Element Energy's partners in this study as well as IEAGHG internal reviewers

The rest of this report is structured into 4 sections as follows

Section 2 shows detailed analysis of key projects. The selected projects were operating sites, sites in planning or construction and cancelled projects. At the end of the section, a consolidated list of lessons learned related to constructability and operational aspects is presented followed by a summarised list of common reasons for cancellation.

Section 3 presents the decision chain guidance tool that can be used by new entrants in the CCS business to navigate through key decisions and choices in construction, commissioning, execution and operation.

Finally, Section 4 summarises the key conclusions and recommendations for further work. Section 5 is an appendix that contains the methodology, assessment framework used in the stakeholder engagement interviews, along with a list of sites and interviewees in each site.

A user guide to new entrants

In addition to this report, a clear and easy-to-understand guide for future new entrants in the CCS business and large-scale project developers has been created. It advises on all transition steps, from planning, through construction to stable operation. The guide will include the decision chain guidance tool, key lessons learned from operating projects and summary of reasons for cancellation. The guide can be used as a standalone document for quick assistance or complemented with this report for a more comprehensive standpoint.

2 Overview and learnings from successful and cancelled projects

Throughout this study, large-scale CCS projects have been analysed for constructability and operability assessment as well as main reasons for cancellation for projects that passed FEED study but never reached operation stage. As discussed in the methodology chapter shown in Appendix 5.1, the analysis was conducted through literature review, investigation of individual projects and a series of interviews with key sites presented in 5.3. This chapter presents the findings from each individual project analysis followed by key learnings related to constructability and operational challenges. The final section of this chapter presents a consolidated list of the reasons for cancellation.

2.1 Overview of CCS projects worldwide

A map with the location of the considered large-scale CCS sites is shown in Figure 2-1. The map reports operating sites in green, sites in planning or construction in blue and cancelled projects in red. Additionally, a complete list of the considered CCS projects is reported in Table 2-1.

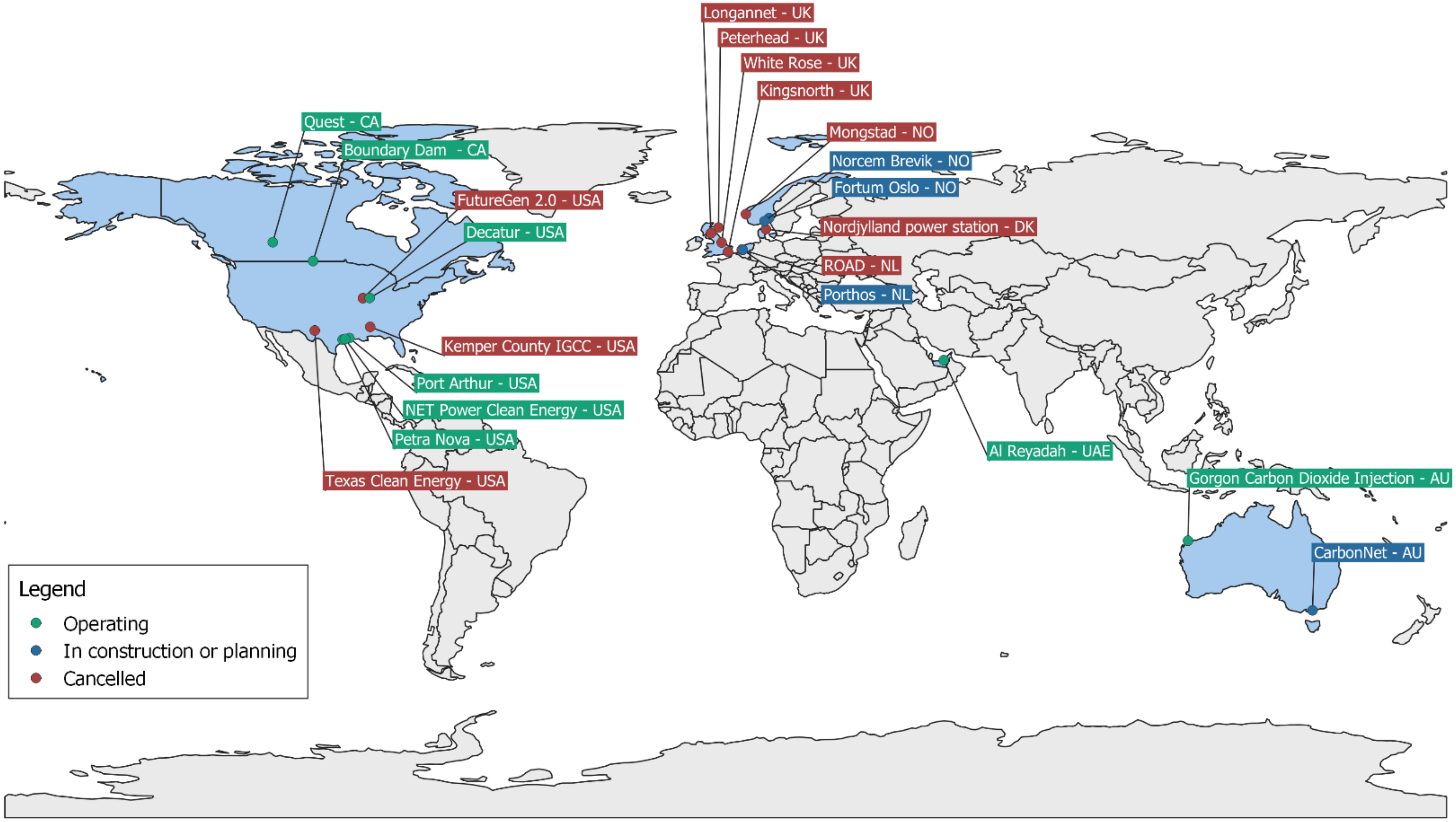

Figure 2-1: Location of investigated large-scale CCUS sites

Table 2-1: list of projects analysed based on status

Group	#	Project	Country	Sector
Group 1: Operating projects (constructability and operability assessment)	1	Al Reyadah CCUS Project	UAE	Iron and steel
	2	Boundary Dam Carbon Capture Project – SaskPower	Canada	Power generation (Coal)
	3	Quest carbon capture and storage project	Canada	Hydrogen production
	4	Port Arthur CCS Project	USA	Hydrogen production
	5	Petra Nova CCUS Project	USA	Power generation (Coal)
	6	Gorgon Carbon Dioxide Injection Project	Australia	Natural gas processing
	7	NET Power Clean Energy Demonstration Plant	USA	Power generation (Gas)
	8	Illinois Basin-Decatur Project (IBDP)	USA	Ethanol production
Group 2: Projects in construction or advanced development (constructability assessment only)	9	The CarbonNet Project	Australia	Power and hydrogen production (Coal)
	10	Port of Rotterdam CCUS Backbone Initiative (Porthos)	Netherlands	Various industries
	11	Fortum Oslo Varme Capture Plant	Norway	Waste-to-energy
	12	Norcem Brevik Capture Plant	Norway	Cement
Group 3: Cancelled projects (constructability assessment and reasons for cancellation)	13	Peterhead CCS Project	UK	Power generation (Gas)
	14	White Rose CCS Project	UK	Power generation (Gas)
	15	Longannet CCS Project	UK	Power generation (Coal)
	16	Kingsnorth CCS Project	UK	Power generation (Coal)
Group 4: Additional cancelled projects (reasons for cancellation only)	17	The Kemper County CCS Project	USA	Power generation (Coal)
	18	Full-scale CCS at Mongstad Project	Norway	Power generation (Gas)
	19	Texas Clean Energy Project (TCEP)	USA	Power generation (Coal)
	20	Vattenfall Nordjyllandsværket CCS Project	Denmark	Power generation (Coal)
	21	FutureGen 2.0	USA	Power generation (Coal)
	22	ROAD – Rotterdam Capture and Storage Demonstration Project	Netherlands	Power generation (Coal)

2.2 Detailed projects analysis

2.2.1 Al Reyadah CCUS Project [7, 8]

General information

Al Reyadah CCUS Project is considered the 1st fully commercial CO_2 capture project in the iron and steel industry and the 1st commercial CCS project in the Middle East region. It is an integrated commercial-scale project, located in Mussafah, Abu Dhabi, United Arab Emirates, to capture CO_2 from the flue gas of an Emirates Steel production facility and inject the CO_2 for EOR activities. The main objectives of the project are to reduce the carbon footprint of the United Arab Emirates, implement EOR in subsurface oil reservoirs, and free up natural gas that would have been used for oil field pressure maintenance. The Al Reyadah Project includes capture, transport, and injection of up to 800,000 tonnes per year of CO_2 (processed at the required specifications and pressure) and is part of an overall master plan which could also create a CO_2 network and hub for managing future CO_2 supply and injection requirements in the United Arab Emirates.

- **Status**: started operation in 2014 and fully operational by 2016.
- **Capture capacity:** up to 800 ktCO_2/year.
- **CO_2 destination**: the captured CO_2 will be used for EOR activities in the Abu Dhabi National Oil Company's nearby oil fields

Lessons learned

Concept

- Financing: The project is commercially funded with no Governmental Subsidies. The project is a part of a bigger vision working towards multiple industrial scale CCUS projects and CO_2 pipeline network, aimed at reducing the carbon footprint in line with ADNOC's 2030 Strategy and Abu Dhabi Vision 2030.
- Capture technology: Amine solvent-based absorption/regeneration using MDEA.
- An extensive FEED study was carried out prior to moving to construction. During the FEED stage, there was a recommendation to opt for a two trains design for maximum plant availability, this will provide a reasonable level of redundancy for the reciprocating compressor – a maintenance-prone component. However, during the EPC phase, the design was changed to single train due to commercial reasons.

Construction & Operation

- A critical factor in the design of the capture system is to ensure there is no water/moisture in the CO_2 transferred through the pipelines. This can cause corrosion, hydrate formation and slug flow during transport and injection. Installation of moisture analyser upstream of the transfer pipeline should be considered in design. For gas stream dehydration the project chose to use a molecular sieve over triethylene glycol (TEG), which is most commonly used in commercial CO_2 injection operations.
- Intensive stakeholder management was involved in this project, with four operating companies (Emirates Steel, ESNAAD, GASCO (Pipeline Corridor) and ADCO). Each company had differing objectives, competency levels, delivery timelines and priorities of work, so strict coordination was a challenge.

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[7] Carbon Sequestration Leadership forum: https://www.cslforum.org/cslf/Projects/AlReyadah

[8] Case Study: Al Reyadah CCUS Project

- Due to the dominance of oil and gas in the region, industry standards for material selection were biased towards hydrocarbon rather than CO_2.This had to be considered during the design and EPC phases to ensure the right materials for the specific application in steel industry and CO_2 transport were used.
- There was insufficient experience for delivering a CCUS project with new/unfamiliar contractors/vendors, this required having in place the contingency plans for a possibility of cost and schedule overruns.

2.2.2 Boundary Dam Carbon Capture Project – SaskPower[9, 10]

General information

Boundary Dam Power Station is the first coal-fired power station in the world to successfully use Carbon Capture and Storage (CCS) technology by retrofitting and life extending its Power Unit 3 (BD3) operated by SaskPower. The overall cost was around CAD 1.5 billion out of which CAD 240 million were provided by the Canadian Federal Government. The main project driver was to produce power at a value that was equivalent to a new build natural gas combined cycle plant by realising value from the existing infrastructure in BD3,and generating revenue streams from the sale of three valuable by-products: carbon dioxide, sulphuric acid and fly ash over the 30 years economic lifetime of the project.

- **Status**: Commercial operation start in October 2014
- **Capture capacity**: Nameplate capacity 1 $MtCO_2$/year. Plant is running at reduced capacity, due to low oil prices. Captured ~3 $MtCO_2$ by late 2019.
- **CO_2 destination**: CO_2-EOR (41-mile pipeline to the Weyburn Field in Saskatchewan) or permanent storage on-site (Aquistore).

Lessons learned

Concept

- A success factor is the continuous accountability from all parties. In the Boundary Dam case, there was willingness by the utility company, backed by national emissions limitations with a strong provincial political backing, as well as financial aid from the Federal Government.
- Business case: BD3 had a strong business case with no reliance on continued government funding. However, during the oil prices decline, the CO_2-EOR revenues were impacted negatively, there was a modest project cost over-run, and the alternative option for natural gas generation has become increasingly attractive, which lead to a renegotiation of contracts.
- Older unit required refurbishment. Investment utilised instead for the installation of CCS, which also extends the lifetime in which the unit is allowed to operate.

Construction & Operation

- Improved efficiency and continuous operation of the power plant was a governing design factor. This led to boiler and turbine upgrades for increased efficiency as well as better steam and thermal integration and the capability to handle powering up or down the capture plant independently.

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[9] Life Cycle Assessment of Post-Combustion CO_2 Capture and CO_2- Enhanced Oil Recovery based on the Boundary Dam Integrated Carbon Capture and Storage Demonstration Project in Saskatchewan. Available at: https://doi.org/10.1016/j.egypro.2014.11.776

[10] IEAGHG 2015/06 Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station, 2015

- Modular designs and off-site manufacturing are advisable, not only for the cost considerations but also for personnel allocation. In times of high oil and gas activity, construction workers and operational crews can be very challenging to find, which was the case in western Canada during BD3 construction.
- Initial start-up and transition to operation can be tricky for companies outside the oil and gas or refining industries. In this case, detailed start-up plan, dedicated transition to operation staff and use of simulators (a virtual carbon capture plant) to assess the start-up procedures were developed to help overcome the lack of operational capacity.
- Training of operators continued during commissioning and augmented the initial training which was generated by an external company. For a FOAK plant, this was an added value leading smooth start-up and operation.
- Change management can be needed in FOAK projects as there can be possible change in design, equipment adjustments, and construction plans throughout the project due to a variety of technology, procurement and corporate policy requirements.
- The characteristics of the actual flue gas will determine the degradation rate of amines. In BD3 case, the amine degradation was multiples of the original design after operation started. The increased rate of amine degradation was believed to be caused by contaminants in the flue gas such as ash or residues from the flue gas desulfurization system. This is a type of risk that can be managed through testing capture technology on actual flue gas to understand the long-term degradation effects.

2.2.3 Quest carbon capture and storage project [11, 12, 13]

General information

Quest is the world's first commercial scale application of CCS technology in an oil sands operation. Using Shell's ADIP-X Amine solvent, CO_2 is captured from the Athabasca Oil Sands Project (AOSP) Scotford Upgrader's hydrogen manufacturing units that produce an average of 255,000 bbl/day of synthetic crude oil. The main target of the project is to reduce the CO_2 emissions from oil sands, helping Shell in obtaining regulatory approvals from the Canadian Government. According to a detailed Environmental Assessment (EA) study carried out on all parts of the project, there is no further adverse environmental impacts. The EA included capture infrastructure, pipeline, injection wells and storage. The total cost of the project was $1.35 billion and is expected to generate revenue from sales of carbon credits with a potential of CO_2-EOR once the infrastructure is ready.

- **Status**: operating since November 2015.
- **Capture capacity:** over 1 $MtCO_2$/Year, this represents 35% of upgrader emissions. Over a 25 years lifetime, the total captured CO_2 is expected to exceed 27 $MtCO_2$.
- **CO_2 destination**: the captured CO_2 will then be transported by pipeline to injection sites within 80 km of the upgrader facility and stored in saline formations more than 2 km underground.

Lessons learned

Concept

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[11] https://www.shell.ca/en_ca/about-us/projects-and-sites/quest-carbon-capture-and-storage-project.html

[12] Case study: Shell Canada – Public Engagement Report

[13] The Quest for less CO_2: Learning from CCS implementation in Canada Report

- A clear and profitable business case for a large developer is the key driver for CCS project. In Shell's case, this was carbon credits.
- For a single developer, early engagement of high-level management, stakeholders, local community, assigning the team for FEED is key to project delivery.
- Local Community engagement**:** Mixed local community perception: Industrial area was on board, more reluctance from farmers against pipeline laying. Mostly overcome through face-to-face meetings, engagement though NGOs and explaining risks.

Construction & Operation

- For an experienced oil and gas company, construction and project development is usually not the complex part. Usually, internal buy-in, plant integration, clear maintenance plan with OEMs, and involving all stakeholders early on is what requires most of the planning. The learning from this project helped achieve 20-30% cost reduction for future projects.
- The optimal mix of modular and stick-built designs can deliver the best cost-efficient results. In Quest, high levels of modularisation were used. However, there was a need for a stick-built compressor that required some equipment modifications for a successful integration of the capture plant.
- There was vigilant requirement for MMV in this project. It was important to monitor the CO_2 storage for any leakage, given carbon credits were a key revenue for this project. Other factors like impact on vegetation were assessed as well as continuous monitoring of CO_2.
- In certain industries, by-products need to be taken into consideration. Understanding these by-products is important to assess the need for extra construction planning and permitting.

2.2.4 Port Arthur CCS project [14,15]

General information

Port Arthur, located in Texas, USA, is the first commercial-scale Steam Methane Reformer (SMR) hydrogen production facility to deploy carbon capture and storage. The project shows a successful partnership between industry, represented in Air Products and Denbury Onshore, Academia through University of Texas, and consultant and contractors in various project phases. However, Air Products remained the owner, operator and the developer of the project. The total cost of the project was around $431 million out of which DOE provided a funding of $284 million (66%).

- **Status**: operating since 2013.
- **Capture capacity:** 1 $MtCO_2$/year
- **CO_2 destination**: captured CO_2 will be piped over a 101-150 km pipeline and injected for EOR in Denbury's onshore operations.

Lessons learned

Concept

- There was a clear business case for Air Products based on four key success factors: 1) a justified case for capital investment, 2) sustainable revenue stream through a long-term buyer

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[14] IEAGHG 2018/05 The Carbon capture project at Air's Products Port Arthur Hydrogen Production facility, 2018

[15] OSTI.GOV 2018 Demonstration of Carbon Capture and Sequestration of Steam Methane Reforming Process Gas Used for Large-Scale Hydrogen Production https://www.osti.gov/biblio/1437618

for the CO_2 to be utilised in EOR operations, 3) highly incentivised project and 4) long-term plant operation.

- Using in-house capture technology was a turning point in the project success. Instead of relying on on-the-shelf technologies, Air Products had modified their Vacuum Swing Absorption (VSA) technology to be adopted in their Port Arthur CCS plant which impacted the overall project cost.

Construction & Operation

- Project success was highly facilitated by the location. The existing resources and shared infrastructure by Air Products and Denbury Onshore minimised the costs and risks and facilitated the sale of CO_2 to EOR operation.

- The integration of capture plant within existing facility added some complexity which was mitigated by modularity. During both commissioning and construction, a staged approach was adopted which helped in early identification and mitigation of problems as project progresses.

- Key design criteria: Capture plant was independent from the host plant which is a main design factor for a production facility. This proved valuable when Air Products had to shut down the capture plant for 1.5 month for troubleshooting purposes without impacting their Hydrogen production operation.

2.2.5 Petra Nova CCUS Project[16, 17, 18, 19]

General information

The Petra Nova project in Texas is the world's largest carbon capture facility at a coal-fired power plant. The project partners are NRG, JX Nippon and Hilcorp. The capture plant is built on NRG's power station, and CO_2 is captured via post-combustion from a 240 MW slipstream at the WA Parish Unit 8 (640 MW). It uses a process jointly developed by Mitsubishi Heavy Industries and the Kansai Electric Power Co., utilizing a high-performance solvent to separate the CO_2 from the flue gas produced by conventional coal combustion. The total project cost approximately USD 1 billion.

- **Status**: Operating since 2017.
- **Capture capacity**: ~1.8 $MtCO_2$/year
- **CO_2 destination**: captured CO_2 is transported through a 130 km pipeline to Hilcorp's West Ranch Oil Field for EOR activities.

Lessons learned

Concept

- Design: The capture unit is a retrofit, with a separate gas-fired cogeneration unit producing steam for solvent regeneration, as well as power for the process. This means that the power plant itself is not impacted by the capture system (i.e. there is no parasitic load on the power unit itself). This is important for NRG as a merchant power producer, since it wants its power production to have 100% availability, as it cannot pass the capture costs to its customers.

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[16] NRG Energy testimony at the US Senate Committee on Energy and Natural Resources

[17] https://www.eia.gov/todayinenergy/detail.php?id=33552

[18] OSTI.GOV 2014 W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project Phase 1 Definition https://www.osti.gov/biblio/1126723

[19] OSTI.GOV 2017 W.A. Parish Post Combustion CO_2 Capture and Sequestration Project Final Public Design Report https://www.osti.gov/biblio/1344080

- Commercial agreements: There were several economic agreements associated with Petra Nova project: 1) NRG and JX Nippon each invested ca. USD 300 million, 2) it benefitted from a USD 190 million grant from the Clean Coal Power Initiative (CCPI) programme from the US Department of Energy and 3) Japan's export credit organisation JBIC and Mizuho Bank provided USD 250 million in loans.
- A critical characteristic of the project is that all key project elements are within the same economic unit, hence revenue from EOR is directly benefitting the whole chain. This is in contrast with most other CCUS projects where there is a commercial arrangement between the producer and the user of the CO_2.
- Project drivers: Federal tax credit for CO_2 injection for EOR (USD 10 per tonne when the project started) provided an additional incentive.

Construction & Operation

- The Petra Nova project has shown that a post-combustion CCUS project can be made to work economically; it also clearly showed that a large CCUS project can be built to schedule and to budget.
- This was achieved through establishing interfaces between 5 key areas: 1) Design of the interface with the host coal-fired power plant, 2) installation of the carbon capture technology at commercial scale, 3) design and build an 81-mile CO_2 pipeline, 4) preparation of a large oil field for the new oil production from EOR operation and 5) re-establish a pipeline link to the crude oil market as the previous facilities were abandoned earlier.

2.2.6 Gorgon Carbon Dioxide Injection Project [20]

General information

The Gorgon Carbon Dioxide Injection Project is the world's largest commercial-scale CO_2 injection project based in Western Australia on Barrow Island. The Gorgon project develops two main fields: the Gorgon field that produces natural gas with on average 14% naturally occurring reservoir CO_2 and of the Jansz field which has less than 1% of CO_2. This leads to a 7% CO_2 that needs to be separated from the gas stream prior to its liquefaction and processing to avoid it freezing into solid.

The project is a joint undertaking of Chevron, Shell, ExxonMobil, Osaka Gas, Tokyo Gas and JERA. It aims to capture and permanently store CO_2 from gas production activities at the Gorgon Project, which is expected to have an economic lifetime of 40+ years. The Australian government has committed $60 million to the Gorgon Carbon Dioxide Injection Project through the Low Emissions Technology Demonstration Fund (LETDF).

- **Status**: Operating.
- **Injection capacity**: 3.4 to 4 $MtCO_2$/year of carbon dioxide removed from gas extracted from the reservoir.
- **CO_2 destination**: Producing gas fields are located 200km away from the coast and emissions will be injected and permanently stored in the Dupuy Formation, located in proximity to the gas processing plant on Barrow Island (2km deep).

Lessons learned

Concept

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[20] Gorgon CO_2 injection project fact sheet

- Separation: CO_2 separation is a technical requirement for the site, as CO_2 in the incoming natural gas must be removed before processing into LNG to avoid freezing.
- Storage: The driver for CO_2 injection and storage underground was a voluntary undertaking with the aim to reduce the carbon footprint of gas processing activities. A law mandating the CO_2 storage from Gorgon project in Australia was put forward at a later stage.
- Cross-chain risk management was critical for the site. This was important to minimise exposure to financial risk associated with timescale coordination for the construction of the capture facility in sync with storage site appraisal.

Construction & Operation

- The location of the project on Barrow Island – an “A class” nature reserve – imposed very strict environmental regulations on construction approvals and permitting, a key factor to be considered in planning. Site remoteness also required optimised planning for staff travel and freight schedules to ensure optimised performance.
- Timescales for exploration and appraisal of CO_2 storage wells outside of the O&G industry are critical. Timelines can be ~10 times longer than for the construction of the capture facility and can take up 10-20% of the project budget.
- For a large-scale complex project like the Gorgon Carbon Dioxide Injection Project, lengthy commissioning and start-up was essential to ensure safe operations of the injection project over its 40+ year operations life. Whilst strict planning can successfully prevent most problems, mitigation plans are key to deal with some unavoidable cost/time overruns due to unforeseen reasons.
- Community and stakeholder engagement plans were arranged for reaching out to the community and engage in open dialogue to build trust.
- Performance monitoring plans are in place for optimal operation, including injection operations data and compliance with approval conditions, storage reservoir monitoring and near surface groundwater and soil gas monitoring data.
- Post-injection decommissioning and site closure plans are already in place as part of the project planning.

2.2.7 NET Power’s Clean Energy Demonstration Plant [21, 22, 23, 24, 25]

General information

Net Power’s Clean Energy Demonstration plant is the first natural gas power plant based on the Allam Cycle. While the current pilot plant has a capacity of 50MW, a scale up to a FOAK commercial plant of around 300MW is in planning, with a detailed FEED recently completed in 2017. NET Power is currently engaging with a potential partner for the upscaled commercial project, with the aim to begin operations in 2022. The upscaling provides a big potential for reduced CAPEX, with estimated costs for the construction of the facility of about $1,000 /kW.

- **Status:** Operation started in 2018

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[21] https://www.netpower.com/technology/

[22] Forbes Article: Net Zero Natural Gas Plant -- The Game Changer

[23] https://www.power-technology.com/projects/net-powers-clean-energy-demonstration-plant-la-porte-texas/

[24] https://www.powermag.com/inside-net-power-gas-power-goes-supercritical/

[25] Power Magazine 2019: 300-MW Natural Gas Allam Cycle Power Plant Targeted for 2022 https://www.powermag.com/300-mw-natural-gas-allam-cycle-power-plant-targeted-for-2022/

- **Capture capacity:** 0.89 $MtCO_2$/year for the commercial-scale plant.
- **CO_2 destination:** There are multiple potential destinations for CO_2. These can be either permanent storage, utilisation or use for EOR applications. Given the geographical location in the US, EOR is the most likely initial choice of destination.

Lessons learned

Concept

- The new power plant has a competitive advantage based on LCOE level while achieving zero emissions.
- EOR is a potential revenue stream in addition to by-products like nitrogen, argon and oxygen as industrial feedstocks. The design concept allows the products from the air separation unit to remain available even if CO_2 cycle failed.
- There was a very positive perception from local community due to the 'no-pollutants' advantage.

Construction and Operation

- The plant has a considerably small footprint of 13-15 acres, yet all general construction considerations apply.
- Sequenced construction of air separation unit followed by power plant depends on weighing the revenue stream from selling the by products from air separation vs. the cost savings that can be achieved through synergies in construction of both units simultaneously.
- The start-up and operation procedure are similar to a conventional power plant, therefore no competency issues should be experienced during early project stages.
- In terms of operational capacity, a team of 23 persons can run a full-size plant – this low requirement of personnel will have positive impacts on OPEX.
- The plant design is highly resilient which makes it robust enough in a system heavily relying on renewables.

2.2.8 Illinois Basin-Decatur Project (IBDP) [26, 27]

General information

The Illinois Basin-Decatur Project is a demonstration project aiming to prove that CO_2 can be injected and stored safely, permanently, and economically. It has developed an integrated industrial CCS system from source to reservoir. The project is led by Midwest Geological Sequestration Consortium and Illinois State Geological Survey. Trimeric Corporation was responsible for the process engineering design of compression and dehydration facility and worked closely with Archer Daniels Midland Company (ADM) which carried out the construction and operation of the host facility.

- **Status**: Design and construction of compression, dehydration and transportation facilities completed in 2011, followed by 3 years of injection until 2014.
- **Capture Capacity**: 1 $MtCO_2$/year (net capture and storage of 913 $ktCO_2$ (1 $MtCO_2$ stored minus 87 $ktCO_2$ emissions from electrical equipment). This will be followed by 7 years of monitoring post-injection until April 2021.
- **CO_2 Destination:** Permanent storage in the Mt. Simon sandstone saline reservoir in Decatur, Illinois.

Lessons learned

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[26] https://www.netl.doe.gov/sites/default/files/2018-11/Illinois-Basin-Decatur-Project.pdf

[27] Illinois Basin – Decatur Project: Process Design and Operation of Carbon Dioxide Surface Facilities Report

Concept

- Facility design was dependent on research purposes. The relatively short term of the project operations and led to choices during planning that aimed at minimizing CAPEX at the expenses of a higher OPEX.
- Consideration of several configurations to optimize equipment and operations costs, accounting for design reliability, flexibility, safety and complexity. Due to uncertainty on CO_2 injection specifications, the design required high flexibility.

Construction & Operation

- There was a requirement for a clear CO_2 specification from the early stages of the project due to the impact on individual components.
- Permitting time has proven to be very critical as it has impacted key delivery dates, but also the warranty durations and validity of some equipment. Hence, there is a need for setting realistic timelines accounting for variability within delivery lead times, weather, permitting and personnel availability.
- The project developed and implemented a rigorous and extensive monitoring, verification, and accounting (MVA) program, including seismicity monitoring, 3D seismic surveying and vertical profiling, soil flux monitoring, atmospheric monitoring, shallow groundwater monitoring, and deep subsurface monitoring and fluid sampling. This has resulted in a pathway for commercial usage of Mt. Simon sandstone reservoir.

2.2.9 The CarbonNet Project [28, 29]

General information

The CarbonNET project is investigating the potential for a commercial-scale CCS Network. The Network aims to bring together multiple capture projects in Victoria's Latrobe Valley, transporting CO_2 via a shared pipeline and injecting it into deep underground, offshore storage sites in Bass Strait. The location selected for this project is Gippsland which is recognized as a world-call location offering a significant potential for CCS in terms of storage availability and suitability for CO_2 Storage.

- **Status**: in 2017 the Victorian and Commonwealth governments agreed to progress CarbonNet to Stage 3 – Project Development and Commercial Establishment
- **Capture capacity**: planned to be 5 $MtCO_2$/yr
- **CO_2 destination**: the captured CO_2 will be permanently stored in the offshore storage sites in Bass Strait.

Lessons learned

Concept

- A key aspect of the feasibility study is to propose a range of relevant CO_2 capture impurities. This will allow a range of potential industries, technologies, and application to participate. However, this had a major design implication that needed to be addressed in the FEED study (discussed in the next section)
- The CarbonNet project carried out a techno-economic analysis of the benefits of an increased H_2S specification (instead of a default assumption for the need of H_2S and CO_2 separation).

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[28] GCCSI Report on Development of a CO_2 specification for a CCS hub network.
[29] https://earthresources.vic.gov.au/projects/carbonnet-project

In some processes, there is a combined stream of H_2S and CO_2 that can have a techno-economic advantages for certain pre-combustion applications.

Construction & Operation

- The changed specification of the H_2S will entail an economic trade-off between reduced costs for construction and operation of sulphur recovery plant or sulphur disposal equipment and the sale of sulphur products.
- In the same manner, the changed specification of CO_2 impurities will have wider implications on the design to ensure acceptability of the maximum allowable CO_2 limits at each stage of the project. This includes: 1) pipeline acceptability, 2) HSE certifications, 3) storage site acceptability and 4) individual components of the capture plant and on the overall stream pressure and temperature.
- The changed specification for H_2S and CO_2 will also impact operation in both normal and changing operating conditions like equipment failure, shutdowns and line venting.

2.2.10 Port of Rotterdam CCUS Backbone Initiative (Porthos)[30, 31, 32]

General information

Porthos is one of the first CCS projects in Europe. The project aims to construct CO_2 transport and storage infrastructure between the Port of Rotterdam and depleted gas fields beneath the North Sea. The project is Led by the Port of Rotterdam Authority, Energie Beheer Nederland B.V. (EBN) and N.V. Nederlandse Gasunie. The total length of the CO_2 infrastructure is around 55 km. The CO_2 source will be the industrial facilities in the Port of Rotterdam area which is responsible for 17% of the total CO_2 emissions in Netherlands. Porthos is considered as one of the Projects of Common Interest (PCI) as categorized by the EC. The project will not consider CO_2 storage under the British sector of the North Sea. However, at later stages, there might be potential for CO_2 imports from Antwerp or the German Ruhr area for permanent storage.

- **Status**: in planning
- **Capture capacity**: for this project, the stated capture capacity is for the pipeline infrastructure. The shore-based pipeline has the capacity of 5 $MtCO_2$/year at 40 bar.
- **CO_2 destination:** captured CO_2 from various industrial sites will be stored in the P18 fields, 21 km off the Dutch coast which has an overall 37 Mt of storage capacity.

Lessons learned

Concept

- **Permitting**: the project follows a special procedure called State Coordination Scheme which is intended to enable faster decisions to be taken on large European and national energy projects, without impacting a careful decision-making process.
- **Integration plan**: there will be a clear integration plan formulated by the ministers of Economic Affairs & Climate Policy and Interior & Kingdom Relations. The plan will show the location of the CO_2 infrastructure and compressor station and will be made available for consultation.

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[30] CSL Forum Update on Porthos Project.
[31] https://www.rotterdamccus.nl/en/the-project/
[32] Official Porthos project brochure

Construction & Operation

- The project will entail a great deal of construction on land for the pipeline corridor. Hence, during this phase, all activities related to groundwater extraction, noise, dust and the presence of soil contaminants should be considered.
- For the section of the pipeline beneath the seabed, a non-disruptive construction method will be adopted to ensure minimum impact on sea life.
- Rigorous safety standards will be in place for the pipeline and compressor station and will be under supervision of the government. At later stages of the project, system monitoring will be shared with the commercial operator of the CO_2 T&S infrastructure once the project goes in commercial stage.
- The EIA study of this project will consider both temporary and permanent effects of the pipeline construction. Temporary effects are these related to the construction activities, while the more permanent impacts are related to longer term consequences for example the heating of the ground because of the CO_2 pipeline.

2.2.11 Fortum Oslo Varme capture plant [33, 34]

General information

The Fortum Oslo Varme capture project is a part of the Norwegian Government full-scale carbon capture and storage (CCS) project in Norway. The capture plant will be retrofitted on the waste-to-energy plant at Klemetsrud. The facility incinerates more than 400,000 tonnes of waste per year and uses the waste heat to produce electricity and district heating purposes in the city of Oslo. The plant has a potential to be carbon-negative with CCS since 50% of the waste incinerated at the plant is of biological origin.

- **Status**: Grants are obtained for FEED study. The Norwegian Parliament is expected to make an investment decision for the project in 2020/2021. The project will then be able to commence operations in 2024.
- **Capture technology:** based on Shell's Cansolv technology and aims to capture 90% of the CO_2 in the flue gas based on an earlier pilot testing.
- **Capture capacity:** planned to be 400,000 tCO_2/year i.e. 90%, of the waste-to-energy plant's CO_2 emissions in 2024.
- **CO_2 destination:** The captured CO_2 will be transported by ship from the capture plant to an onshore facility on Norway's west coast for temporary storage. From there, the liquified CO_2 will then be transported via pipeline to a subsea reservoir in the North Sea for permanent storage. The T&S infrastructure side of the project is known as Northern lights.

Lessons learned

Concept

- Project financing: The project is highly reliant on government funding making it financially sustainable.
- Technology choice: The amine-based technology was chosen due to its maturity and successful implementation in two other plants in Canada. Even though the technology had

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[33] https://www.fortum.com/media/2018/11/full-scale-carbon-capture-and-storage-ccs-project-initiated-norway

[34] https://www.forskningsradet.no/contentassets/3fb0ac44a9c5479f8aca0fb12eadd133/johnny-stuen-fortum-oslo-varme-klemetsrud-energigjenvinningsanlegg-med-ccs-efk2019-.pdf

already been tested and proved on other operating facilities, learning from additional testing on the Waste-to-energy plant's own flue gas during the planning phase turned out to be deemed crucial for the project success with regards to emissions.

- It is always advisable to look into different capture technology suppliers. This can ensure the selection of the best technology including the more innovative and emerging ones.

Construction & Operation

- In full-scale CCS projects, detailed planning is required to align timescales between capture facilities and the T&S infrastructure side of the project.
- It was very important to allocate risk responsibility and define management measures for all steps of CO_2 shipping early in the planning phase. In fact, CO_2 transportation for the Northern Lights Project involves few stages, comprising CO_2 handling and temporary onshore storage prior to permanent offshore storage.
- Construction-related success factors are very similar to those of a common chemical plant. Having an experienced industrial partner developing the project can lead to more efficient planning and execution phases.
- Local community engagement was achieved through yearly meetings, open tours for the plant to raise awareness for the need of the project in addition to regular emails and social media communications on the project progress.
- Projects with significant level of governmental involvement usually experience higher levels of constraints and restrictions on the choice of technology and project partners which can render the project less cost-efficient. For a FOAK plant this can be useful, however; more freedom in the choice of project parameters can be a better way for the future.
- Modular approach is always advisable and should be prioritised whenever allowed by the logistics, local transportation regulations and trailer sizes.

2.2.12 Norcem Brevik capture plant [35, 36]

General information

The Norcem Brevik capture project is the second capture facility within the full-scale CCS project led by the Norwegian government. This will be a FOAK project retrofitting a capture plant on the Norcem Brevik cement plant owned by Heidelberg Cement currently producing around 1.3 million tonnes of cement annually. The cement plant aims to reduce its process emissions. On the other hand, combustion emissions were minimised through 75% reliance on alternative fuels. The project aims to be operating as one of the "most environmentally friendly cement plants in the world" and is economically driven through the avoidance of CO_2 and the costs associated with EU ETS.

- **Status**: FEED study is finished. The Norwegian Parliament is expected to make an investment decision for the project in 2020/2021. The project will then be able to commence operations in 2023/2024.
- **Capture technology:** based on Aker's absorption technology. This was tested in a pilot facility on the actual flue gas from the cement production plant.
- **Capture capacity:** 400,000 tCO_2/year which represents around 50% of the total plant emissions.

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[35] Full scale CCS Norway feasibility study Report

[36] GCCSI webinar Q&A with Per Brevik

- **CO_2 destination:** The captured CO_2 will be transported by ship from the capture plant to an onshore facility on Norway's west coast for temporary storage. From there, the liquified CO_2 will then be transported via pipeline to a subsea reservoir in the North Sea for permanent storage. The T&S infrastructure side of the project is known as Northern Lights.

Lessons learned

Concept

- Technology choice: Four different capture technologies from different suppliers were put into test using the actual flue gas from the cement plant prior to final technology decision. In this case, technology testing on the own flue gas was crucial for technology choice.
- High level of involvement from the Norwegian government was critical in granting the FID and project kick-off. This emphasises the importance of a supporting government and in-place regulatory framework for commercial-scale CCS projects.

Construction & Operation

- Extra footprint needed for the capture facility might impose a requirement for extra site preparation and demolishing work in case of space limitation. In Norcem Brevik, retrofitting the existing cement plant required extra space of 4000 m^2.
- For retrofitting facilities in production, a critical phased design approach needs to be followed. This will ensure minimal impact on the cement production efficiency and avoiding plant stops for commissioning. For Heidelberg, revenues from cement production is the key value stream that needs to be maintained at all times.
- Minimal interaction between the capture and the host facility – in this case the cement production plant – is another key design aspect critical for operating the two plant independently.
- Interim CO_2 conditioning and storage on site before shipping to its destination has to be considered in construction design. In Norcem Brevik plant, the CO_2 was stored in liquefied state under 16 bar at -26 °C. This required extra permits according to Norwegian regulations.
- Utilities needed to power the capture plant can represent a huge overhead operating cost on the host facility. For Norcem Brevik plant, this was a key factor in deciding the initial capture capacity of the project. Heat recovery units will be installed to ensure waste-heat is optimally used.

2.2.13 Peterhead CCS Project [37, 38]

General information

Peterhead projects would be the world's first-of-a-kind (FOAK) commercial scale demonstration of post combustion CCS in a gas-fired power plant from an existing 400 MW combined cycle gas turbine (CCGT) located at SSE's Peterhead Power Station in Aberdeenshire, Scotland. 90% of CO_2 in the flue gas will be captured by an amine technology developed by a Shell subsidiary, compressed and treated on site. The project aimed to complete engineering design in 2016 and commission by 2020. There was a plan for the Goldeneye pipeline and the surrounding storage sites to be used by other industrial sites for clustering. Peterhead was a finalist of the UK CCS Commercialization Programme, which aimed to give up to £1 billion grant for early CCS demonstration projects.

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[37] Peterhead CCS Project - Site Selection Report

[38] Peterhead CCS Project - FEED Lessons Learned Report

- **Status**: Cancelled - Initially, planning was approved in 2015, FID was expected in 2017 and operation was planned to start 2020.
- **Capture capacity:** 1 $MtCO_2$/year over a period of 15 years
- **CO_2 destination**: The captured CO_2 would be transported via a short (22 km) new offshore pipeline to the existing Goldeneye pipeline, to be transported and stored in Goldeneye depleted hydrocarbon reservoir.

Reason(s) for cancellation

In 2015, the UK Government unexpectedly withdrew funding for the CCS competition 6 months before it was to be awarded, leading to cancellation of both Peterhead and White Rose shortlisted projects.

Lessons learned and factors leading to cancellation

Concept

- The specific nature of this project and its developer were unique and categorized as “the exception that proved the rule”. Shell had some special drivers for the project, as it was going to be a single developer which: (1) controls the full chain assets, (2) has the competence and capacity to deliver the full chain, (3) has the financial capacity for 100% equity investment, (4) has a strategic interest to deliver CCS projects, (5) has sufficient knowledge and confidence in CO_2 storage, (6) has sufficient stature to attract wider industry participation.

Construction and other aspects:

- Permitting for FOAK plant is lengthy and costly. The number of commercial stakeholders from which a permit must be obtained for a CCS project should not be underestimated.
- Complex decisions around liability distribution – specially around CO_2 storage, which was insurable – should be communicated along the stakeholder chain, especially when capture and T&S sites are operated by different companies.
- Through local community engagement, there was a better acceptance of retrofit projects than greenfield. In both cases, the engagement with the local community and transparency were crucial, especially when utilising amines close to homes. Plotting amine transport routes and ensuring safety was crucial in inhabited areas.
- There are major differences between the power sector and O&G. This includes risk perception, project delivery approach, design and cost benefit analysis. O&G tend to have a higher tolerance for risk taking with a stricter approach in applying industry standards.
- For FOAK projects, delivery delays should be expected. Therefore, mitigation plans should be in place.

2.2.14 White Rose CCS Project [39]

General information

White Rose is an integrated full-chain CCS project comprising a new coal-fired Oxy Power Plant (OPP) and a T&S network that will transfer the carbon dioxide from the OPP by pipeline for permanent storage under the southern North Sea. The OPP is a new state-of-the-art ultra-supercritical power plant with oxyfuel technology of up to 448 MWe gross electrical output (>300 MW net) that will capture around 90% of CO_2 emissions and is also designed to have the option to co-fire biomass. The plant is expected to operate at baseload but will also prove its ability for flexible operation. Similar to

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[39] White Rose project - Full-chain FEED lessons learnt Report

Peterhead, White Rose was a finalist of the UK CCS Commercialization Programme, which aimed to give up to £1 billion grant for early CCS demonstration projects.

The project was Consortium-led through Capture Power Limited (CPL) and National Grid Carbon Limited (NGC). The project is developed by CPL, which consists of GE, Drax and BOC. The CO_2 T&S operations are sub-contracted to NGC, which is an independent subsidiary of National Grid. NGC further sub-contracts Endurance storage site operations to CSL.

- **Status**: Cancelled - FEED awarded in 2014, planning approval was planned in 2015.
- **Capture capacity**: 2 $MtCO_2$/year
- **CO_2 Destination**: Captured CO_2 to be transported through 73 km onshore and 90 km offshore pipelines and stored permanently at the Endurance site.

Reason(s) for cancellation

In 2015, the UK Government unexpectedly withdrew funding for the CCS competition 6 months before it was to be awarded, leading to cancellation of both Peterhead and White Rose shortlisted projects.

Lessons learned and factors leading to cancellation

Concept

- Commercial agreements: CPL will make revenues from electricity sales at a pre-determined CfD strike price (expected to be in the £150-200 /MWh range as set out in the commercialisation programme), while NGC will charge system use fees for the T&S infrastructure.
- Financing: CPL is funded 35% through base equity, 3rd party equity and government grants, and 65% through debt finance.

Construction and other aspects:

Cross-chain liabilities and risk sharing:

- 3rd party debt providers were uncomfortable taking the balance of cross-chain risks on a FOAK CCS project. This showed a need for a single developer and proposing the need for a simpler structure for this type of full-chain projects in the future
- Bringing together a combination of the power industry, chemical industry and offshore hydrocarbon industry under a governmental procurement framework was challenging and would require a dedicated framework to define communication, risk allocation and management.
- Identifying the need for a 'de-risking' tool giving further recognition to the fact that the CCS market was 'broken' and therefore required government funding to initiate its delivery.

Technical design and integration:

- Full-chain FFED study and coordination of procurement activities become of supreme importance to ensure a high degree of system interfacing and operation coordination is in place.
- The capture site and the T&S infrastructure were managed by different operators. Therefore, a regime for the co-ordination of maintenance and outage periods between the two sides of the chain was necessary.

2.2.15 Longannet CCS Project [40, 41, 42, 43]

General information

Longannet CCS project was a planned Capture plant for the Longannet Coal-fired 330 MW power station in Fife, Scotland using Aker Clean Carbon's post combustion capture technology. The project received £1 billion funding from the UK former Department of Energy and Climate Change (DECC) and was led by a consortium of Scottish Power (SP), Shell, National Grid and Aker Clean Carbon.

- **Status**: Officially cancelled on Oct 2011. Initially planned to start in 2014.
- **Capture capacity:** planned 2 MtCO_2/year
- **CO_2 destination**: The captured CO_2 would then be piped in the North Sea depleted oil and gas fields via Shell's Goldeneye platform for permanent storage (similar to Peterhead project)

Reason(s) for cancellation

- The withdrawal of the main project partners Scottish Power (SP), Shell and National Grid (NG) due to the lack of availability of public financing. The initial funding requested was £1.5 billion which was not fulfilled by public financing. Following that, DEEC diverted the £1bn allocated funding to other CCS projects.

Lessons learned and factors leading to cancellation

Concept

- Longannet planning was one of the most extensive studies that offered clarity on how the full CCS chain works of the most. The planning study took an overall of four years.
- Pipeline length transporting CO_2 for the final storage destination was relatively very long – more than 260 km. This made the overall economic case for the project not viable.

Construction and other aspects:

A cross-consortium including SP, Shell and NG was formed for managing the project and bringing forward key learnings associated with Longannet project. Key lessons were grouped as follows:

- Mobilisation: There is a need for an appropriate mobilisation lead period to establish consortium relationships, process and system prior to FEED.
- Stakeholder engagement**:** Early engagement is necessary for key decision makers, serious management for buy-in, internal planning teams and procurement, local communities, regulators and potential partners.
- Communication & Collaboration**:** Strong leadership, planning and cross-consortium communication is required.
- Competitive Procurement: it is important to recognize the restrictions imposed by trying to develop a demo project within the bounds of a competitive procurement framework.
- Adapting to Uncertainty: this can be any uncertainty affecting regulations, permitting process, scope, budget and political landscape.

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[40] https://sequestration.mit.edu/tools/projects/longannet.html

[41] https://www.scottishpower.com/news/pages/scottishpower_comment_longannet_power_station_230315.aspx

[42] Project Data files: https://www.bgs.ac.uk/ukccs/accessions/projects.html#

[43] http://www.zeroco2.no/projects/scottish-power-cockenzie-and-longannet-post-combustion-project

2.2.16 Kingsnorth CCS Project [44], [45]

General information

The Kingsnorth CCS project is E.ON's plan to the construction of a 1600 MW two-unit coal-fired power plant with CCS. E.ON's project partners were Arup responsible for project management, the Electric Power Research Institute for technology sharing, Mitsubishi Heavy Industries providing the carbon capture technology, Penspen, E.ON Gas Storage taking care of the CO_2 storage part and Foster Wheeler Energy for the plant engineering and FEED.

- **Status**: Cancelled in 2010.
- **Capture capacity:** 20 million tonnes of CO_2 over a period of 10-15 years
- **CO_2 destination:** Captured CO_2 would then be piped through a 270 km pipeline from Kingsnorth to a depleted Hewett gas field in the southern North Sea.

Reason(s) for cancellation

- The project faced a lot of eeconomic hurdles to the construction of the power plant. As a consequence, the project was withdrawn from the UK Government CCS Competition.

Lessons learned and factors leading to **cancellation**

Concept

- Power plant flexibility needs to be maintained, which can be challenging with a capture plant. This a key design aspect.
- For Kingsnorth, there was a plan to demolish units 1-4 of the existing plant. This provided an opportunity for existing infrastructure re-use and potential interconnection of utilities between the power plant and CCS plant. This was one of the key learnings for brownfield sites.

Construction and other aspects:

- Space constraints at the Kingsnorth site forced the split of the absorption and regeneration units in the design of the new capture plant. In this case, compact designs – contrary to what is usually preferred during construction – was not the optimal design approach.
- A conceptual design approach was followed dividing the project to two technical areas: 1) Pipeline & Platform and 2) Wells & Storage. This helped to carefully identify problems in the interfaces from capture to pipeline and through to wells injection and final storage. This emphasized the need for addressing the interface at various stages comprehensively in the later stages of FEED.
- Dedicated Operational Safety Working Group (OSWG) was formed early to assess HSE, CO_2 hazards on-site, monitoring and performing dispersion modelling.
- Changing regulation was a key barrier in the consent process specially for offshore platform and piping part of the project.

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[44] https://webarchive.nationalarchives.gov.uk/20130104023654/http://www.decc.gov.uk/assets/decc/11/ccs/chapter1-3/key-knowledge-reference-book.pdf
[45] http://www.zeroco2.no/projects/e.on-2013-kingsnorth-post-combustion-project

2.2.17 The Kemper County CCS Project [46, 47, 48, 49]

General information
The project was located in Kemper County, Mississippi. The construction of the 582 MW power plant started in 2010, with the aim of gasification of cheap local brown coal using proprietary gasification technology. The plant was to capture around 65% of the CO_2 content of the resulting syngas's, to ensure that the plant's emissions would correspond to those of a modern natural gas combined cycle plant per MWh. Annual capture was planned to be ca. 3 million tonnes. The overall cost planned to be \$3bn, Cost overruns reached \$7.5bn by 2017. The overall project received \$270 million support from US DOE Clean Coal Power Initiative (CCPI) round 2. • **Status**: Cancelled in 2017. During project start-up Mississippi Power announced that it would abandon the operation of the gasification plant and the Kemper power plant would simply run on natural gas, due to availability of cheap shale gas and coal becoming less economically viable. • **Capture capacity**: 3 $MtCO_2$/Year • **CO_2 destination:** The captured CO_2 would then be piped to oil production sites for EOR operations.
Reason(s) for cancellation
• High reliance on complex new – at the time - technology led to extensive time and cost overruns. • The reduction in the price of natural gas due to the shale gas boom rendered the economic case for power from coal gasification less competitive. Additionally, a higher need for flexibility in generation increased the attractiveness of gas power plants.
Lessons learned and factors leading to cancellation
• Initially, the project had three pillars for the initial go-ahead. Firstly, a clear economic driver was present as Mississippi Power would sell power to the grid as well as CO_2 for EOR operations. Secondly, technology push motivated by the desire to commercialize a new gasification technology: Transport Integrated Gasification (TRIG) which qualified for CCPI award, investment tax credits and loan guarantee. • However, technical integration was the showstopper for Kemper. Implementing multiple first-of-a-kind technologies and the complexity of integrating them together, especially in moving from a pilot plant to a scale of nearly 600 MWe led to large time and cost overruns. • In addition to technical-related issues, Kemper county faced a regulatory flow in the electricity markets. Given the Mississippi Power electricity will be sold to markets across the South which are largely closed to competition, this has hugely impacted the tolerance for risk-taking by the project players.

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[46] https://www.southerncompany.com/newsroom/2017/june-2017/0628-kemper.html

[47] https://spectrum.ieee.org/energywise/energy/fossil-fuels/the-three-factors-that-doomed-kemper-county-igcc

[48] https://www.osti.gov/biblio/1080351

[49] OSTI.GOV 2012 Kemper County IGCC Project Preliminary Public Design Report https://www.osti.gov/biblio/1080351

2.2.18 Full-scale CCS at Mongstad Project [50]

General information

The full-scale CCS project at Mongstad was a scale up of the initial Technology Center Mongstad (TCM) which was a test facility aiming to improve CO_2 capture technology. The scale-up project planned to build two capture plants for the exhaust gases from a Residue Catalytic Cracker (RCC) and Natural Gas Combined Heat and Power (CHP) plant. For this purpose, the Mongstad project used two different post-combustion technologies: Alstom chilled Ammonia and Aker amine-based technology. The phase 1 TCM was a joint venture between the Norwegian state, Statoil, Shell and Sasol.

- **Status:** In September 2013, the Norwegian Oil and Energy Ministry announced that it had dropped plans for the full-scale CCS plant at the Mongstad refinery. However, the TCM continued operating and has become a testing facility.
- **Capture capacity:** No official figure publicly available for the full-scale project.
- **CO_2 destination:** For the TCM, the captured CO_2 is vented in the atmosphere.

Reason(s) for cancellation

In 2013, it was decided to discontinue work on phase 2, due to two key reasons. First, the full reliance on government subsidy was not possible with the expectations of rising costs and a long-term project. Secondly, there were doubts around the the future viability of the Mongstad refinery impacting the investment in the second phase of the project.

Lessons learned and factors leading to cancellation

- The project driver was the Norwegian government goal to "realize at least one full-scale CCS demonstration facility by 2020". For this purpose, TCM was the anchoring project for the current full-chain CCS project in Norway:
    - It provided access to two different, real-life flue gases from power plant and RCC which provided flexibility for vendors to test and improve their technologies. In this case Aker, Alstom and Shell made use of the test facility.
    - It led to the initiation of the pre-feasibility study on potential full-scale CCS projects in Norway in 2015. It recommended three demo projects in the Cement, Ammonia and Waste-to-Energy sectors, which today materialised to Fortum Oslo and Heidelberg Cement anticipated capture plants discussed earlier in this section.
- The TCM brought forward some important construction and operation-related learnings:
    - Custom-designs can hugely impact project cost. In the Mogstad project case, the custom-designed chilled ammonia plant required onsite fabrication which led to increased cost.
    - Monitoring can add a high price tag. At the time of full-scale project development there was a requirement for a state-of-the-art control rooms that impacted the overall cost.

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[50] http://www.zeroco2.no/nyheter/zero-denounces-cancellation-of-full-scale-ccs-at-mongstad

2.2.19 Texas Clean Energy Project (TCEP) [51, 52]

General information

TCEP was planned to be a 400 MW coal-based integrated gasification combined cycle (IGCC) with fully integrated CO_2 capture plant. The Pre-Combustion technology based on Siemens IGCC and Linde Rectisol acid-gas capture technology aiming to capture 90% of the CO_2. The overall cost was planned to be \$1.98bn. However, the cost overruns reached \$3.98bn by 2015. The project had many partners including Summit Power Group, Siemens, Fluor, Linde, R.W. Beck, Blue Source and Texas Bureau of Economic Geology. In 2010, the project received \$450 m support from US DOE Clean Coal Power Initiative (CCPI) round 3.

- **Status**: Cancelled in May 2016.
- **Capture capacity**: 2 $MtCO_2$/year
- **CO_2 Destination**: the captured CO_2 was planned to be utilised for EOR activities in the Permian Basin

Reason(s) for cancellation

- The continuous delays in delivery caused the project cost to increase significantly leading the DOE to question the project viability altogether and to withdraw federal grant funding.

Lessons learned and factors leading to cancellation

As a poly-generation project – producing electricity, urea and CO_2 – there was a clear business case through the below revenue streams:

- A 25-years power purchase agreement with CPS Energy of San Antonio, Texas, to buy 200 MW of power from the TCEP Project.
- A 15-years contract for the purchase of CO_2 between Summit, Blue Strategies LLC and Whiting Petroleum Corporation.
- A long-term contract to purchase the 750,000 tonnes fertiliser that the plant will be capable of producing annually.

- Getting private investors to commit was a key impediment to the project. Government grant was able to cover the early stage development costs, but the missing piece for TCEP was the equity partners needed to complete the financing of the project.
- Gasification plants technology has proven costly to implement. The decline in oil and natural gas prices has also impacted the revenues from the CO_2-EOR and urea sales which eventually rendered the potential poly-generated products of less value.

2.2.20 Vattenfall Nordjyllandsværket CCS Project [53] [54] [55]

General information

Vattenfall – the main project developer – had planned to establish a full-scale, post-combustion plant to capture CO_2 at their 410 MW Nordjylland Power Station in Aalborg. The plant was the world's most-efficient power plant, yet one of the largest emission sources in Europe responsible for 2.8

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[51] https://www.power-technology.com/projects/texas-clean-energy-project/

[52] https://www.energy.gov/fe/texas-clean-energy-project

[53] https://www.airclim.org/sites/default/files/documents/APC-28-lost-hopes-ccs.pdf

[54] https://group.vattenfall.com/siteassets/corporate/investors/annual-reports/2009/annual_report_2009.pdf

[55] http://www.zeroco2.no/projects/nordjylland-power-station

$MtCO_2$/year. The plant consumes 800,000 tonnes of bituminous coal per year and operates at 91% efficiency. The main purpose of the demo facility was to achieve a significant reduction in energy loss during the capture process and was expected to have a capital cost of 2 billion DK.

- **Status**: postponed indefinitely in December 2009.
- **Capture capacity**: 1.8 $MtCO_2$/year
- **CO_2 Destination:** The captured CO_2 planned to be transport through a 30 km pipeline and stored in a 1-2 km deep aquifer in Vedsted geological structure.

Reason(s) for cancellation

- A struggling financial situation in Vattenfall led to the decision to cancel the project in Denmark. Vattenfall has instead planned to consolidate all CCS efforts in Germany.

Lessons learned and factors leading **to cancellation**

- Local communities around Aalborg, which would have hosted the storage facility, created the organisation “No to CO_2 Storage”, protesting against the project due to fears of CO_2 leakage from the onshore storage site. This was handled very well through local community engagement. Vattenfall established a “Contact Group” and met the opposition in regular public meetings, giving information about the R&D results on storage security at Vedsted.
- Key performance issues needed to be considered in the design to count for capacity loss problem, which was one of the demo project objectives as well as the ability to maintain high flexibility and ensure the possibility of capture plant shut down to accommodate peak loads.
- The plant proximity to the Vedsted CO_2 storage constituted a geographic advantage that was rare. However, extensive studies were needed to ensure viable high-quality storage facility is available in terms of capacity, injectivity and structural containment. This was proven through a combination of 2D and 3D geological surveys. This added to the overall project cost.

2.2.21 FutureGen 2.0 [56]

General information

FutureGen 2.0 is an implementation of an oxy-fuel combustion technology to retrofit unit 4 of Ameren’s Meredosia coal-fired power plant. The plant was expected to have a new boiler, air separation unit, CO_2 purification and compression unit to deliver 90% CO_2 capture. FutureGen 2.0 was led by an alliance of many parties: FutureGen alliance, US Department of Energy, State of Illinois, Ameren Energy Resources, Babcock &Wilcox and Air Liquide. Its total costs were estimated at $1.65 bn out of which, the US DOE provided up to $1bn in financial assistance.

- **Status**: Construction started in September 2014 and officially cancelled in 2016.
- **Capture capacity** :1.1 $MtCO_2$/year
- **CO_2 Destination**: The captured CO_2 will be transported through a 30-mile underground pipeline to a permanent storage in deep saline aquifers in Morgan County, Illinois.

Reason(s) for cancellation

- In 2015, US DOE announced it was withdrawing the federal funds allocated for the project, concluding the project was highly unlikely to meet the September 2015 deadline to spend the funds (before federal funding expires).

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[56] https://thinkprogress.org/futuregen-dead-again-obama-pulls-plug-on-nevergen-clean-coal-project-674558dd83a3/

Lessons learned and factors leading to cancellation

- Main driver was political. FutureGen 2.0 was going to be a large-scale demonstration of oxy-fuel technology strongly backed by the US DOE and done in collaboration with an industrial consortium composed mostly of coal mining companies represented in the FutureGen Alliance.
- Technology readiness can be a challenge for large-scale projects. Demonstration programmes must account for the type of technology that is being demonstrated. At the time of FutureGen 2.0 project development, oxyfuel combustion was far from commercialisation at scale. US DOE concluded that the technology would add a large overhead on the electricity prices while significantly reducing the electricity produced due to parasitic load.
- Procedures to gain first-of-a-kind permits can be very time-consuming and expensive, such as the EPA Class VI injection permit[57]. In FutureGen 2.0, there was a need for a first ever EPA Class VI[58] well injection permit.

2.2.22 ROAD – Rotterdam Capture and Storage Demonstration Project [59] *(Rotterdam Opslag en Afvang Demonstratieproject)* [60, 61]

General information

ROAD is the *Rotterdam Opslag en Afvang Demonstratieproject* and it is one of the largest, integrated CCS demonstration projects in the world. It aimed to retrofit a capture plant to the coal-fired Masklike Power Plant 3 (MPP3) using on amine-based post combustion capture technology. The demonstration done with 250 MW capacity and assessed the technical and economic feasibility of a large-scale, integrated CCS chain deployed on power generation. Starting 2012, the ROAD project has slowed down due to financing gap, however it had reached key milestones for engineering, permitting, contracting). Road was a joint venture of E.ON Benelux and ENGIE Energie Nederland. The project was mainly financed by the EC and the government of Netherlands.

- **Status**: Cancelled in 2017. ROAD served as anchor project to the Rotterdam full chain CCS project.
- **Capture Capacity**: ~1.1 $MtCO_2$/year
- **CO_2 destination**: The captured CO_2 will be ttransported via pipeline for permanent storage in depleted gas fields in the North Sea.

Reason(s) for cancellation

- **Reason for cancellation:** The changing prices of EU ETS – which was the main planned revenue stream – exhausted all public funding in the construction phase. The project was not able to secure further financing for commissioning and operation.

Lessons learned and factors leading to cancellation

- Strong public funding support was in place nationally and regionally through the framework of the European Energy Programme for Recovery (EEPR). This expeditated the initial project

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[57] EPA Underground Injection Control (UIC) https://www.epa.gov/uic/class-vi-guidance-documents

[58] Class VI wells are used to inject carbon dioxide (CO_2) into deep rock formations.

[59] https://www.globalccsinstitute.com/wp-content/uploads/2019/09/ROAD-Close-Out-Report-on-Public-Engagement-final.pdf

[60] https://www.portofrotterdam.com/en/news-and-press-releases/road-project-to-be-cancelled-ccs-to-continue

[61] http://www.ccsassociation.org/files/9414/6840/6772/7._ROAD_-_Andy_Read.pdf

progress and facilitated reaching milestones of engineering, permitting and contracting. The grants amount to EUR 180 million from the EC and EUR 150 million from the government of the Netherlands. The GCCSI is a knowledge sharing partner of ROAD and has given financial support of EUR 4.1 million to the project. The Port of Rotterdam has also supported the project through investment in the CO_2 pipeline.

- Strong regulatory framework created a positive environment, this was driven by the Rotterdam Climate Initiative and the Willingness to establish Netherlands as the CCS leader to attract international clients for CO_2 storage in the North Sea. The involvement of the Ministry of Economic Affairs and its Energy Projects Agency helped ROAD in mapping the wide range of permitting authorities and adjusting its plan to the changing permitting landscape at the time.
- The ROAD project had a dedicated Stakeholder Management team focusing on communications & public engagement which was instrumental in ensuring managed expectations, getting external views on both technical and non-technical problem.
- The way the ROAD project was funded, with substantial capital grants, but a low reward for operation, created a strong incentive to minimise capital costs. This has led to a much lower focus on reliability and major key choices in design.
- The cancellation of ROAD project led to a consensus that there is need to not only focus on environmental impacts, but also on the economic benefits of CCS and local value propositions it can offer to local communities which was pivotal in the development of the Rotterdam full-chain CCS project.

2.3 Key learnings around constructability and operability aspects

Through the analysis carried out in the previous section for individual sites, key learnings attributed to constructability and operational challenges were categorised under 10 key areas spanning the project phases from planning to construction to commissioning and operation. Key decisions and choices under each of these areas can be considered as success factors that impacts the realisation of a large-scale project. These learnings are summarised in Figure 2-2. This analysis of decision areas and success factors guided the underpinning logic of decision chain presented in the following section 3.

Summary of lessons learned on the constructability and operations of large-scale CCS projects

Business & regulatory framework

The business case and regulatory framework sets the ecosystem for the realisation of a CCS project. A successful CCS project must ensure a sound business case, long-term economic viability and revenue streams, financial & regulatory support and ensure involvement of all stakeholders including local community engagement in early stage of the project.

Cross-chain coordination

Critical coordination of timelines, efforts, liabilities amongst different stakeholders across the CCS value chain. This includes capture and transport infrastructure readiness, storage sites appraisal and availability and ensuring a long-term steady demand for CO_2 are all aligned with the commencement of capture operation.

Design criteria

Design approach will be highly dictated by the type of facility; new vs. retrofit. A typical full-chain CCS project will involve four key design pieces that need to be designed carefully: access to flue gas, conditioning of CO_2, transport of CO_2 offsite and its final storage/destination. In terms of construction design, high levels of modularity and off-site fabrication will deliver minimal risk and cost.

Capture technology selection

Capture technology selection is based on the application, sector (power or industry), flue gas composition, required avoidance rate and the emissions regulations in a specific region. Testing different capture technologies prior to commercial scale on own flue-gas is a key success factor. In some industries, utilisation of an in-house capture technology can make the business case more viable.

Site location

The impacts of a specific site location must be accounted for in the construction planning, activities, transportation mode, permits, environmental assessment and personnel availability. Remote sites might be more appealing in terms of community acceptance but poses personnel availability challenges. Similarly, sites present within an industrial cluster will benefit from shared infrastructure and driving the overall project costs down.

Plant integration

Integrating capture plant with the host site will have an impact on different processes, plant efficiency and flexibility. This is a key design aspect particularly critical for power plants. Optimal integration of heat and power utilities is another important aspect. Whenever possible and technically-feasible, utilisation of existing infrastructure must be maximised.

Construction site management

Common construction best practises are applicable for CCS projects. However, extra care should be given to permitting related to the usage amine-based products and CO_2 storage at site under specific pressure conditions. Clear definition of extra security and/or HSE measures and site ownership should be communicated to all stakeholders.

Plant commissioning and start-up

The transitional phase from the completion of plant construction to commissioning and commercial operations is very critical especially for retrofitted facilities. Interruption should be minimised through intensive planning of the transition-to-operation phase. Clear procedures for normal and emergency start-up and shutdown must always be available for the operating crew.

Operation and Maintenance (O&M)

Planning and simulations should be in place whenever possible to account for all operational aspects. These include aspects related to plant efficiency, maintenance programs, personnel availability and operational capacity, monitoring sensors installation and control rooms as well as by-products and waste handling procedure.

Shutdown and decommissioning

Shut Down

Early planning for site decommissioning is key to managing liabilities, risk allocation and ownership. Detailed plans for capture site decommissioning and storage site closure should be in place and communicated during the planning phase.

Figure 2-2: Key decision areas and success factors based on lessons learned from different projects

2.4 Reasons for cancellation

Based on the analysis of the cancelled projects presented in the earlier section, there has been many reasons related to planning and construction stages, summarised as follows:

Lack of long-term economic viability can be a showstopper for any large-scale CCUS project. Ensuring long-term revenue streams while accounting for other dynamics and uncontrollable factors like Carbon prices, Oil and Gas prices, declining renewable energy costs is a critical factor in project economics. In the power sector, coal power plants have increasingly been seen as uncompetitive compared to natural gas combined cycle units. Hence, there is a need to understand the long-term competitiveness of the technology in a wider market outlook.

Over-reliance on government subsidies can be risky but also often vital. CCUS projects must ensure continuous and systematic political support over their long timelines. This challenge was observed across many regions including UK, Norway and the USA where change in political direction impacted government support and its withdrawal led to project failure. This inconsistent nature of government support has also reduced trust of private investors. In most cases, the absence of direct commercial benefits from CCUS projects makes government grants, initiatives and support programs pivotal in the long-term project success.[62]

Uncertainty around risk management and allocation. Liability has always been cited as a significant barrier to the wide scale deployment of CCUS and is instrumental to the management of operators' and regulators' risk exposure. This becomes of elevated importance for large investments required for offshore CO_2 storage. Recent studies[63] proposed putting more emphasis on the role of the private and insurance sectors as a potential solution to this problem describing it as "a commercial approach to CCUS-specific liabilities".

For CCUS full-chain projects[64], there are specific risks that can lead to project cancellation. These are related to having multiple project developers at different stages of the value chain, which entails extra coordination in the areas below:

- Cross-chain liabilities definition and default risk allocation across all stakeholders.
- Identifying clear responsibilities and ownership of obtaining permitting, operating consents and licensing across all stakeholders.
- Commercial integration of stakeholders at various phases of the chain. This becomes more critical if there is a cross-sector collaboration between power, oil and gas and chemical sectors, which is a very common case in full-chain projects.
- Coordination of the design and construction activities of the key interconnections and interfaces between capture, transport and storage infrastructure.
- And finally, the technical integration of the key components comprising the full chain.

Technical integration and compatibility when scaling up from pilot or demonstration to commercial scale. This is particularly relevant when attempting to bring together many FOAK technologies at scale. This has proven to be challenging to integrate and can result in an overall incompatible set of technologies, unaccounted for by-products and reliability issues. This can be mitigated through capture technology testing on actual flue gas and through choosing mature and tested technologies. In some cases, modelling and building simulators has proven valuable in bringing to light unknown start-up and operation problems.

Construction-related reasons and design approach

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[62] MIT Report : Lessons Learned from CCS Demonstration and Large Pilot Projects
[63] GCCSI – Lesson and perceptions: Adopting a commercial approach to CCS liability.
[64] White Rose Full-chain Lessons Learned Report

- For brownfield sites, huge cost reductions can be achieved through the re-use of existing infrastructure and optimal integration of heat and power utilities between the main and capture sites.
- While custom-made designs are necessary for refit plants, it usually requires a lot of onsite fabrication adding to the overall construction price tag. Therefore, maximum modularisation levels combined with offsite manufacturing – whenever possible – should always be adopted.
- With the rise of digitalisation and the plethora of AI and IoT applications, there is a huge potential for cost reduction in construction phase. Building 3D objects and rapid prototyping can help streamline a lot of the design stages, reduce time, effort and the need for extra personnel.

3 Decision chain

The information reported in this section is aimed at advising the development of a large-scale CCUS project. Most relevant decisions that will commonly need to be taken during the planning phase and that will influence the outcome of the project are summarised and complemented with advice based on the experience of previous large-scale CCUS projects.

The reader is guided through a list of relevant decisions. For each decision, guidance is provided on the most appropriate options for various types of CCUS projects, together with complementary information that will need to be considered during the decision process. This framework ensures that the planner:

- Is made aware of the most relevant decisions to be considered
- Can navigate through each decision step in a logical order
- Is advised on the best options for each decision, tailored to the characteristics of the project
- Is informed on additional details that will need to influence each decision

3.1 Preliminary considerations on CCUS economics

While the reliance on a robust business model is recognised to be a determinant factor for the success of a large-scale CCUS project, the available business model options are not studied in detail in this work, which focusses on constructability and operational challenges of CCUS. A more detailed analysis of industrial carbon capture business models can be found in a recent report[65] by Element Energy.

CCUS economics based on the revenue from the sale of CO_2 to EOR operations is associated with a high risk, as EOR CO_2 sale agreements often set a price for CO_2 which is tied to the price of oil. Several projects in the U.S. were recently put on hold or cancelled due to the COVID-19 emergency, as the drop in oil price resulted in a sharp loss of value of CO_2 in offtake agreements. A similar case was behind the cancellation of the Kemper CCS project: the reduction in the price of natural gas and oil due to the shale gas boom rendered the economic case for power from coal gasification less competitive.

One of the main obstacles posed to the deployment of CCUS in the U.S. has been for many years the lack of a regulatory driver, despite the availability of mature CCUS technologies. The introduction of carbon reduction goals and 45Q in the recent years have contributed to revitalizing the industry.

Due to the limited number of CCUS projects worldwide and the variety of technologies and applications available, many projects considered in this study are FOAK plants. It is expected that CCUS projects that aim to replicate technologies already implemented at other facilities will be able to take advantage of the general cost reduction to which NOAK plants are subject. This will contribute to strengthening the business case of new CCUS projects and increasing the rate of success of future CCUS projects.

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[65] Element Energy for BEIS 2018, Industrial carbon capture business models

3.2 Decision chain logic

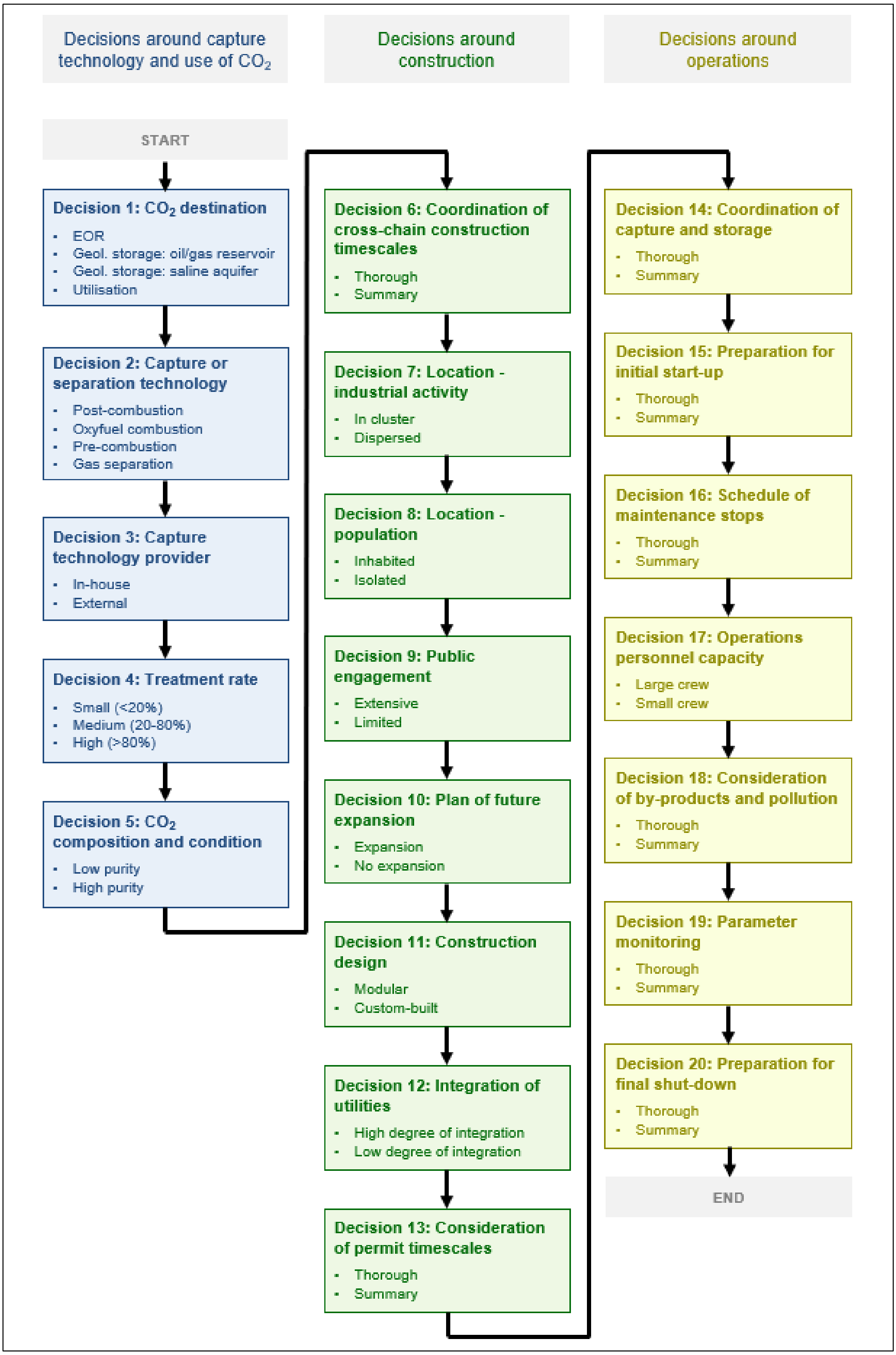
All relevant decisions are organised in the structure of a decision chain. Each block composing the decision chain focusses on one of the key decisions that will need to be evaluated during the planning phase of a project.

The logical sequence of the chain represents how some decisions at the start of the chain may pose constraints to other decisions further down the line and does not imply that each decision should necessarily be finalised before moving onto the next. In fact, when moving along the chain some decisions can be put on hold and multiple options can be explored. In some cases, previous decisions can be re-evaluated in an **iterative process**, until the project assumes the desired shape.

An overview of the decision chain logic is reported in Figure 6. Each decision step reports the name of the decision together with the available options to choose from. Additionally, note that the considered decisions are labelled according to the following categories, which are tackled in succession:

- Blue: Decisions around capture technology and use of CO_2
- Green: Decisions around construction
- Yellow: Decisions around operations

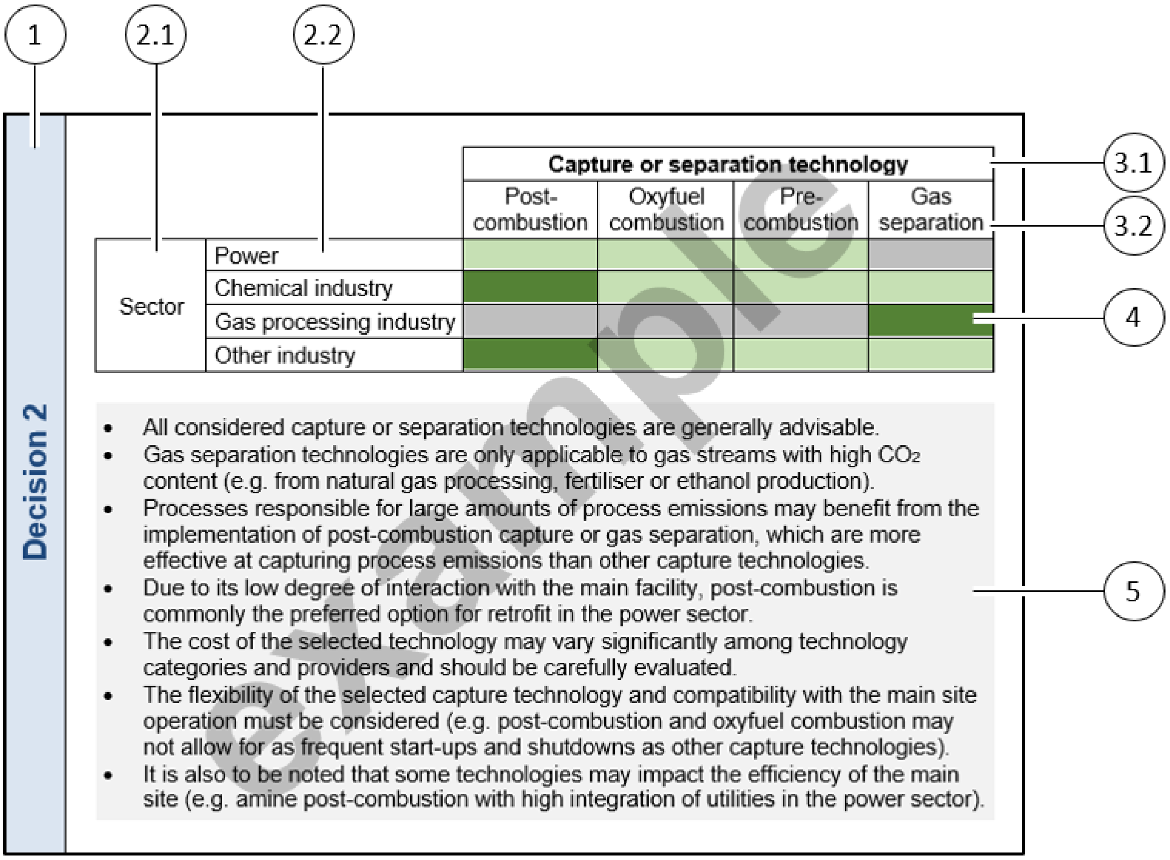
Figure 6: Overview of decision chain logic



3.3 Decision block structure and use

All information and guidance on each decision is elaborated and structured in the form of a decision block. Figure 7 shows an example of the typical decision block, together with a legend and colour key.

Figure 7: Structure of decision blocks



		Capture or separation technology			
		Post-combustion	Oxyfuel combustion	Pre-combustion	Gas separation
Sector	Power	▧	▧	▧	⬜
	Chemical industry	🟩	▧	▧	▧
	Gas processing industry	⬜	⬜	⬜	🟩
	Other industry	🟩	▧	▧	▧

- All considered capture or separation technologies are generally advisable.
- Gas separation technologies are only applicable to gas streams with high CO_2 content (e.g. from natural gas processing, fertiliser or ethanol production).
- Processes responsible for large amounts of process emissions may benefit from the implementation of post-combustion capture or gas separation, which are more effective at capturing process emissions than other capture technologies.
- Due to its low degree of interaction with the main facility, post-combustion is commonly the preferred option for retrofit in the power sector.
- The cost of the selected technology may vary significantly among technology categories and providers and should be carefully evaluated.
- The flexibility of the selected capture technology and compatibility with the main site operation must be considered (e.g. post-combustion and oxyfuel combustion may not allow for as frequent start-ups and shutdowns as other capture technologies).
- It is also to be noted that some technologies may impact the efficiency of the main site (e.g. amine post-combustion with high integration of utilities in the power sector).

Decision block legend:

1	Decision number
2.1	Constraint categories
2.2	Constraint characteristics
3.1	Decision
3.2	Decision options
4	Advice scores
5	Decision guidance

Advice score key:

🟩	Very advisable / Very applicable
▧	Advisable / Applicable
🟧	Less advisable / Low priority
⬜	Not applicable

Each decision block is composed of three main areas: a **decision number** on the left, a **decision matrix** at the top and a **guidance box** at the bottom of the block.

The decision number (label 1) is reported in an area on the left of the block which is colour-coded depending on the decision category.

The decision matrix provides an overview of the options available and of the site characteristics playing a role in the decision and presents a high-level evaluation of the suitability of each option. While the decision (label 3.1) and its available options (label 3.2) build the columns of the matrix, each row represents a constraint or site characteristic (label 2.2), grouped by categories (label 2.1). A colour-coded advice score (label 4) provides high-level ranking of the appropriateness of each decision option for each of the considered site characteristics.

At the bottom of the decision block a guidance box with grey background (label 5) illustrates the reasons behind the scores provided by the above decision matrix and provides further insight and information that will be helpful in formulating the decision most appropriate for the reader’s specific project.

Recommendations for the use of the decision blocks

The guidance provided by each decision block can be helpful in the formulation of a decision tailored to a specific site, as long as the correct approach is followed:

- A decision should not be taken only on the basis of the advice scores provided by the decision matrix, but by taking into consideration the narrative provided by the guidance box.
- Where multiple constraint categories are present, the scores provided for the options in each category should be considered independently. In fact, the colour scores are related to the constraints of one category alone, independently from the constraints of other categories.
- It is also important to follow the decision chain in the proposed logical order. In fact, the outcome of the decisions taken early on in the decision chain will later affect the constraints of subsequent decisions, as these become fixed characteristics of the site (e.g. the decision on the destination of CO_2 taken in “Decision 1” will become a constraining characteristic of the site in “Decision 5”).

3.4 Decision chain guidance tool

All decision blocks are illustrated individually in this chapter, reporting for each a decision matrix and the related guidance that should aid the reader in the formulation of the decision. To begin, we will consider decisions around capture technology and the use of CO_2, summarised in decision blocks 1 to 5.

Decision 1

		CO_2 destination			
		Enhanced oil recovery (EOR)	Geol. storage: oil/gas reservoir	Geol. storage: saline aquifer	Utilisation
Sector	Power	🟩	🟩	🟩	🟩
	Chemical industry	🟩	🟩	🟩	■
	Gas processing industry	🟩	🟩	🟩	🟩
	Other industry	■	■	■	🟩
Revenue stream	CO_2 sale	🟩	▨	▨	🟩
	CO_2 inhouse utilisation	▨	▨	▨	🟩
	Government subsidy	🟩	■	■	🟩
	Value on carbon	🟩	🟩	🟩	🟩

Depending on sector:

- All considered CO_2 destinations are advisable: enhanced oil recovery, geological storage in depleted hydrocarbon deposits or saline aquifers and utilisation.
- **Chemical industry:** sites in the chemical sector may be able to exploit synergies and in-house knowledge for CO_2 utilisation.
- **Other industry**: sites involved in the production of transportation fuels are subject to the requirements of the low-carbon fuel standard (LCFS), which favour the destination of the captured CO_2 to EOR or geological storage.

Depending on revenue stream:

- **CO_2 sale**: the destination of CO_2 for use in EOR typically provides higher revenues than for geological storage.
- **Government subsidy**: subsidies may vary by CO_2 destination. For example, the 45Q tax credit in the USA is higher for CO_2 captured and destined to geological storage than for CO_2 destined for EOR. The higher earning is intended to match the additional revenue obtained from the sale of CO_2 destined for EOR.
- **Value on carbon**: depending on the type of value on carbon scheme in place, some destinations may be more profitable.

Generally, geological storage in oil/gas reservoirs may sometimes be preferable to geological storage in saline aquifers, which require more extensive preparatory work for characterisation and testing prior to injection. However, CO_2 storage in oil fields after EOR activities may be more problematic and legally daunting. Different monitoring and verification requirements may be in place for the considered storage options, depending on the type of injection activity and on local regulations.

Notes: In this report the term “utilisation” refers to the use of CO_2 as feedstock for new products, such as chemicals, synthetic fuels or minerals. The use of CO_2 for enhanced oil recovery is labelled as “EOR”.
EOR and geological storage options were considered separately, due to their generally different life cycle of storage.

Decision 2

		Capture or separation technology			
		Post-combustion	Oxyfuel combustion	Pre-combustion	Gas separation
Sector	Power	□	□	□	▨
	Chemical industry	■	□	□	□
	Gas processing industry	▨	▨	▨	■
	Other industry	■	□	□	□

- All considered capture or separation technologies are generally advisable.
- Gas separation technologies are only applicable to gas streams with high CO_2 content (e.g. from natural gas processing, fertiliser or ethanol production).
- Processes responsible for large amounts of process emissions may benefit from the implementation of post-combustion capture or gas separation, which are more effective at capturing process emissions than other capture technologies.
- Due to its low degree of interaction with the main facility, post-combustion is commonly the preferred option for retrofit in the power sector.
- The cost of the selected technology may vary significantly among technology categories and providers and should be carefully evaluated.
- The flexibility of the selected capture technology and compatibility with the main site operation must be considered (e.g. post-combustion and oxyfuel combustion may not allow for as frequent start-ups and shutdowns as other capture technologies).
- It is also to be noted that some technologies may impact the efficiency of the main site (e.g. amine post-combustion with high integration of utilities in the power sector).

Decision 3

		Capture technology provider	
		In-house	External
Sector	Power	□	■
	Chemical industry	■	■
	Gas processing industry	■	■
	Other industry	□	■

- While most sites will require an external provider for the capture technologies, some companies in the chemical or gas processing industry may be able to utilise in-house technology, reducing costs and creating commercial advantage. In-house technology should however not be utilised if the alternatives offered by external providers are more advanced.
- When relying on a capture technology from an external provider, a range of providers should be considered, in order to create competitive advantage and keep costs low. Settling for one specific provider too soon is discouraged, as it can result in the loss of negotiation leverage and may lead to cost over-runs. A later decision on the final provider allows to drive down costs of both technology and EPC contractors, although development costs are thereby higher.

Decision 4

		Treatment rate		
		Small (<20%)	Medium (20-80%)	High (>80%)
Sector	Power	▨	▨	🟩
	Chemical industry	▨	▨	▨
	Gas processing industry	🟧	▨	🟩
	Other industry	▨	▨	▨

- A high treatment rate, corresponding to a large number of sources and/or proportion of facility emissions onsite to which carbon capture is applied, is generally advisable, as it enables the capture of a large portion of the produced CO_2. This is generally easier and more economical to implement in the power and gas processing sectors, characterised by the presence of few, large sources of CO_2.
- However, if a new capture technology is being implemented, it may be prudent to start with a relatively low treatment rate (e.g. applying carbon capture to only one of the flue stacks of a power station with multiple units) and increase the number of sources over time (see Boundary Dam with ~20% treatment rate).

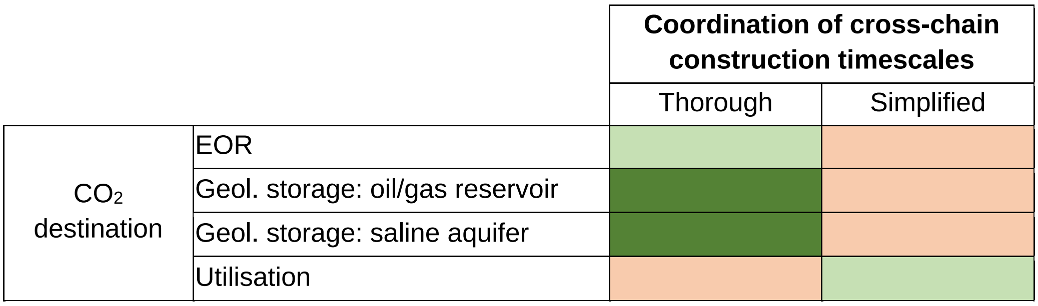
Decision 5

		CO_2 composition and condition	
		Low purity	High purity
CO_2 destination	EOR	▨	🟩
	Geol. storage: oil/gas reservoir	▨	🟩
	Geol. storage: saline aquifer	▨	🟩
	Utilisation	🟧	▨

- Note that the constraints on this decision depend on the outcome of decision 1.
- The removal of gases potentially harmful for humans and for the environment may be required prior to any type of injection, depending on local regulations. Additionally, water and other acid gasses contained in the gas stream need to be removed to prevent damage to the pipeline materials and consequent costs due to repair or replacement.
- Utilisation of CO_2 may involve stringent composition and condition requirements.

Next, we will consider the most relevant decisions around the construction of the facility, summarised in decision blocks 6 to 13.

Decision 6



		Coordination of cross-chain construction timescales	
		Thorough	Simplified
CO_2 destination	EOR	🟩	🟧
	Geol. storage: oil/gas reservoir	■	🟧
	Geol. storage: saline aquifer	■	🟧
	Utilisation	🟧	🟩

- Coordination of the timescales for construction of the capture facility and for exploration and appraisal of the geological storage site needs to be considered very carefully, as the latter can be lengthy.
- Cross-chain timescales coordination is relevant also in case of EOR. Although an EOR field may require a more modest amount of testing, the timescales required to achieve a high rate of CO_2 injection can still be significant.
- In the case of utilisation, the coordination of the construction of the capture facility and of the utilisation facility is expected to be less problematic, as these have more similar timescales.
- For retrofit projects it is advisable to coordinate the construction of the capture facility with the operation of the main facility. Interface points of the capture site should be carried out during a scheduled period of workover of the main facility, in order to minimise down time of the main facility.

Decision 7

		Location - industrial activity (can be decided only if greenfield)	
		In cluster	Dispersed
CO_2 destination	EOR	🟩	🟧
	Geol. storage: oil/gas reservoir	🟩	🟧
	Geol. storage: saline aquifer	🟩	🟧
	Utilisation	🟩	🟩
Capture or separation technology	Post-combustion	🟩	🟩
	Oxyfuel combustion	■	🟩
	Pre-combustion	■	🟩
	Gas separation	🟩	🟩

Depending on CO_2 destination:

- The location of the CCUS facility within an industrial cluster is advantageous for all CO_2 destinations, except for utilisation of CO_2, for which the location is not relevant. The inclusion in a cluster allows for the utilisation of communal CO_2 transportation infrastructure, which is not required in the case of utilisation.

Depending on capture or separation technology:

- Oxyfuel combustion may benefit from being located within a cluster. If the capture site is associated with oxygen separation units onsite, collateral gases such as nitrogen and argon could be sold to industrial clients in close proximity.
- The implementation of pre-combustion works best if hydrogen can be produced on-site or in the proximity to a facility producing hydrogen.

Decision 8

		Location - population (can be decided only if greenfield)	
		Inhabited	Isolated
Capture or separation technology	Post-combustion	🟩	■
	Oxyfuel combustion	🟩	■
	Pre-combustion	🟩	🟩
	Gas separation	🟩	🟩

- Post-combustion with amines carries the risk of pollution with amine compounds from the flue stack. Accurate testing of amine emissions must be carried out on the flue stream, especially when the plant is located within a highly populated area.
- In case of oxyfuel combustion, the Air Separation Unit required for the production of oxygen should generally be located away from densely populated areas, mainly due to the associated high risk of explosion and fire.

Decision 9

		Public engagement	
		Extensive	Limited
Project type	Greenfield	🟩	🟧
	Brownfield	▨	🟧
CO_2 destination	EOR	▨	🟧
	Geol. storage: oil/gas reservoir	▨	🟧
	Geol. storage: saline aquifer	▨	🟧
	Utilisation	▨	▨
Capture or separation technology	Post-combustion	🟩	🟧
	Oxyfuel combustion	▨	🟧
	Pre-combustion	▨	🟧
	Gas separation	▨	🟧
Location - population	Inhabited	🟩	🟧
	Isolated	▨	🟧

A high level of stakeholder engagement is always highly advised. In some cases, it is especially important for the success of the project.

Depending on project type:

- Brownfield projects are generally better received by the public than greenfield project, as they aim at solving an existing problem (emissions). Therefore, more extensive public engagement may be required by greenfield projects.

Depending on CO_2 destination:

- EOR and geological storage may pose more risk to the surrounding population than utilisation and therefore require more engagement with the public.
- Additionally, onshore storage often faces more public opposition than offshore storage and thus requires a more extensive engagement with the local population.

Depending on capture or separation technology:

- Post-combustion with amines carries the risk of pollution with amine compounds from the flue stack and therefore requires more intense engagement and transparency with local communities.

Depending on location - population:

- The implementation of CCUS in densely populated locations will require a larger effort and more extensive public engagement.

Decision 10

		Plan of future expansion	
		Expansion	No expansion
Project type	Greenfield	🟩	▨
	Brownfield	▨	▨
Location - industrial activity	In cluster	▨	▨
	Dispersed	🟩	▨

The intention to further develop the CCUS project at a later stage should be made clear early on during the initial planning phase. While expansion and upscaling of the CCUS facility is generally advisable, it might be more complex for facilities affected by space constraints.

Depending on project type:
- Space for the installation of CCUS equipment and for future CCUS expansion is easier to allocate on greenfield sites. The planning of greenfield sites should assign sufficient space for the installation of future equipment.

Depending on location - industrial activity:
- If industrial sites are located in close proximity to one another (e.g. in a cluster), there may be less space available around the site for future CCUS expansion.

Decision 11

		Construction design approach	
		Modular	Custom-built
Project type	Greenfield	🟩	▨
	Brownfield	▨	▨
Location - industrial activity	In cluster	🟩	▨
	Dispersed	▨	▨
Location - population	Inhabited	▨	▨
	Isolated	🟩	▨

A modular approach is always highly advised, to the highest extent suitable, as this is generally more conducive to driving lower costs.

Depending on project type:
- Brownfield projects may present restrictions on the maximum size of modules that can be moved around onsite.

Depending on location - industrial activity:
- Sites in dispersed locations may present restrictions on the maximum weight and size of the loads (and modules) that can be transported to the site.

Depending on location - population:
- The location in a scarcely populated area (isolated) can negatively impact the availability of skilled workforce, placing therefore more value on modularity.

Decision 12

		Integration of utilities	
		High degree of integration	Low degree of integration
Sector	Power	■	□
	Chemical industry	□	□
	Gas processing industry	□	□
	Other industry	■	□
Project type	Greenfield	■	□
	Brownfield	□	□

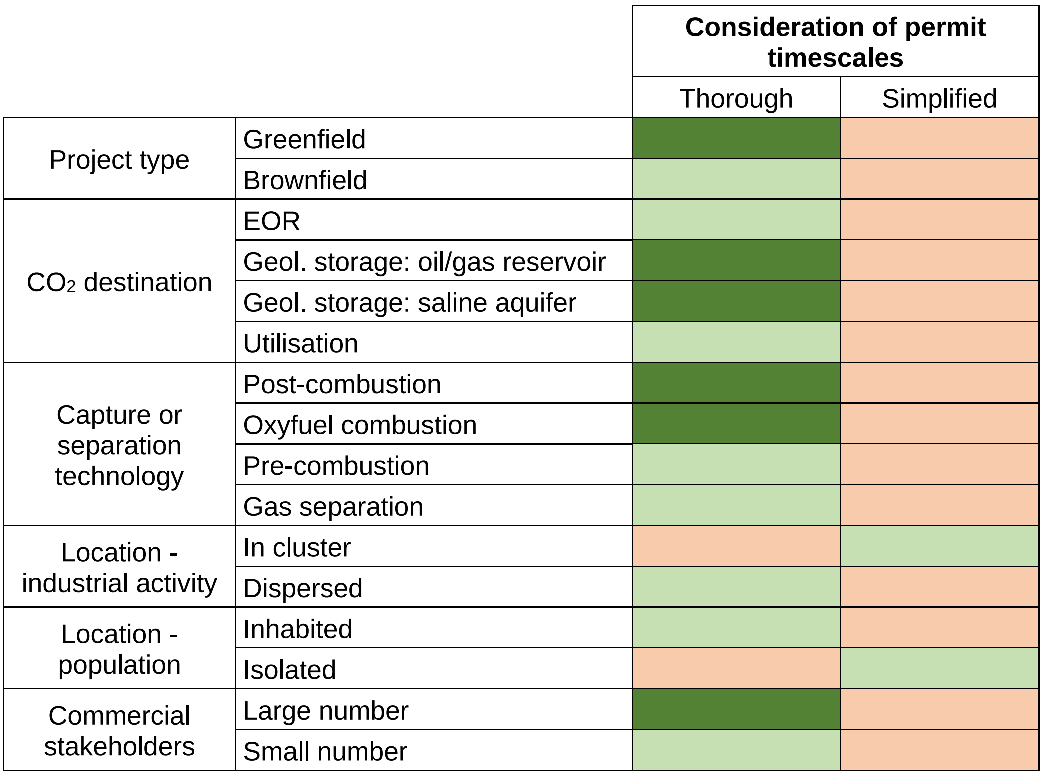
<ins>Depending on sector</ins>:

- Integration of utilities is especially advised for sites where power or heat surplus are readily available (e.g. power industry, cement, waste incineration, etc.).

<ins>Depending on project type</ins>:

- The integration of utilities is easier for greenfield projects and should be the more natural choice.

Decision 13



		Consideration of permit timescales	
		Thorough	Simplified
Project type	Greenfield	🟩	🟧
	Brownfield	▨	🟧
CO_2 destination	EOR	▨	🟧
	Geol. storage: oil/gas reservoir	🟩	🟧
	Geol. storage: saline aquifer	🟩	🟧
	Utilisation	▨	🟧
Capture or separation technology	Post-combustion	🟩	🟧
	Oxyfuel combustion	🟩	🟧
	Pre-combustion	▨	🟧
	Gas separation	▨	🟧
Location - industrial activity	In cluster	🟧	▨
	Dispersed	▨	🟧
Location - population	Inhabited	▨	🟧
	Isolated	🟧	▨
Commercial stakeholders	Large number	🟩	🟧
	Small number	▨	🟧

Consideration of timescales for permitting is extremely critical for all CCUS projects.

Depending on project type:

- As brownfield projects might be more welcome than greenfield projects, timescales of permitting for greenfield projects might be comparatively longer.

Depending on CO_2 destination:

- Timescales of permitting for geological storage are always critical, especially if geological storage is located in areas with special environmental status.

Depending on capture or separation technology:

- Capture technologies that are first of a kind (FOAK) or polluting are more likely to encounter difficulties in permitting.

Depending on location - industrial activity:

- More attention is dedicated to industrial development of clusters and a speedier permitting process is expected to also be in place for clusters, reducing permitting timescales.
- A dispersed capture site structure might encounter difficulties with permitting if located in areas with special environmental status.

Depending on location - population:

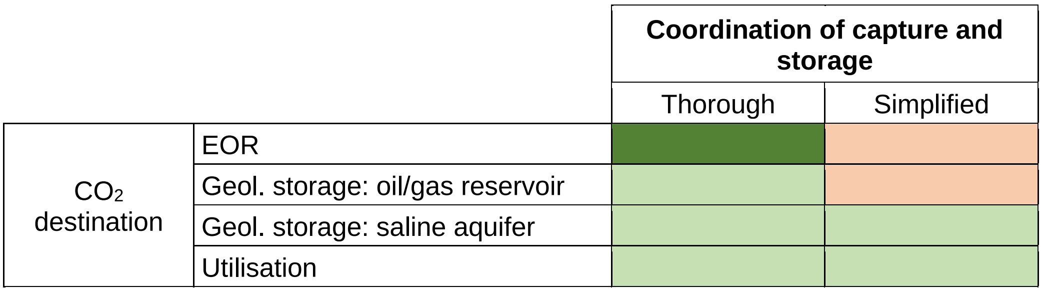
- Being located in a populated area may result in a lengthier permitting process.

Depending on commercial stakeholders:

- The involvement of a large number of commercial stakeholders is likely to increase the timescales for permitting.

Finally, questions around operation of a CCUS facility are addressed in decision blocks 14 to 20.

Decision 14



		Coordination of capture and storage	
		Thorough	Simplified
CO_2 destination	EOR	🟩	🟧
	Geol. storage: oil/gas reservoir	▨	🟧
	Geol. storage: saline aquifer	▨	▨
	Utilisation	▨	▨

- A timely and reliable supply of CO_2 to the storage or utilisation site is critical. This is especially true if CO_2 is destined to EOR, where CO_2 capture volumes and well operations must be carefully matched.

Decision 15

		Preparation for initial start-up	
		Thorough	Simplified
Sector	Power	🟩	🟧
	Chemical industry	▨	🟧
	Gas processing industry	▨	🟧
	Other industry	🟩	🟧

- Planning of the initial start-up and transition to operation is always critical. In particular for those sectors which have limited experience and competency in operating chemical industrial plants (e.g. power sector and other industries).
- Initial start-up can be delivered by an external company.
- Performing a staged start-up is also a useful strategy to reduce risk at commissioning of the facility.
- A risk prevention/mitigation plan should always be in place.

Decision 16

		Schedule of maintenance stops	
		Thorough	Simplified
Sector	Power	🟩	🟧
	Chemical industry	▩	🟧
	Gas processing industry	▩	🟧
	Other industry	🟩	🟧
Capture or separation technology	Post-combustion	🟩	🟧
	Oxyfuel combustion	🟩	🟧
	Pre-combustion	▩	🟧
	Gas separation	▩	🟧

Scheduling and coordinating maintenance stops is highly critical for processes that depend on continuous operation, especially in the power sector and some industries. Additionally, it is imperative that a separate plan for regular and emergency shutdowns is in place.

Depending on sector:

- Scheduling maintenance stops is especially critical in the power sector, where the load factor of the site is particularly relevant in the business model of the project.

Depending on capture or separation technology:

- Start-ups and shutdowns might be complex for some technologies (such as post-combustion and oxyfuel combustion) and must therefore be carefully planned.

Decision 17

		Operations personnel capacity	
		Large crew	Small crew
Sector	Power	🟩	▩
	Chemical industry	▩	▩
	Gas processing industry	▩	▩
	Other industry	🟩	▩
Location vs. Population	Inhabited	▩	🟧
	Isolated	🟧	▩

There is no optimal number of personnel required to operate a capture site and this will depend on the technology and on strategic decisions of the operating company.

Depending on sector:

- For FOAK technologies or sectors with little experience in running a chemical plant, a larger number of operators is advised, in order to mitigate risks.

Depending on location - population:

- Sites located in isolated areas should be able to design the capture site to be operated by a smaller workforce, in order to reduce operational costs.

Decision 18

		Consideration of by-products and pollution	
		Thorough	Simplified
Capture or separation technology	Post-combustion	■	🟧
	Oxyfuel combustion	🟩	🟩
	Pre-combustion	🟩	🟩
	Gas separation	🟩	🟩

- Extensive planning of the handling of by-products may be required for some capture technologies, such as post-combustion technologies utilising amines. "Exhaust" amines will need to be regularly replaced and transported to a treatment facility.
- Potential environmental pollution deriving from some capture technologies should be carefully considered, also in accordance with national and local regulations. For example, there is a significant risk of amine compounds utilised in post-combustion to escape the flue stack and contaminate the surrounding area. Risk mitigation practices and extensive parameter monitoring may be required.

Decision 19

		Parameter monitoring	
		Thorough	Simplified
Capture or separation technology	Post-combustion	■	🟧
	Oxyfuel combustion	🟩	🟧
	Pre-combustion	🟩	🟧
	Gas separation	🟩	🟧

- The flue gas stream composition should be monitored before and after capture, due to health and safety requirements and for controlling technical specifications. This is especially the case when utilising amine technologies, the degradation of which can be greatly impacted by potential flue gas contaminants.

Decision 20

		Preparation for final shut-down	
		Thorough	Simplified
CO_2 destination	EOR	🟩	🟧
	Geol. storage: oil/gas reservoir	🟩	🟧
	Geol. storage: saline aquifer	🟩	🟧
	Utilisation	🟧	🟢
Capture or separation technology	Post-combustion	🟢	🟧
	Oxyfuel combustion	🟢	🟢
	Pre-combustion	🟢	🟢
	Gas separation	🟢	🟢

- Both capture site decommissioning and storage site closure need to be organised in the planning phase of the project. This is particularly relevant for capture plants with larger environmental footprint and for sites injecting CO_2 in geological storage or for EOR.

4 Conclusions

4.1 Key messages and learnings

- **CCS remains an important technology for wide-scale decarbonisation of utility and industrial facilities.** Several sectors – like cement, steel, and waste-to-energy – as investigated by this study are now starting FOAK capture plants. This has resulted in new technologies, increased knowledge, cost reduction and the uptake of CCS across wider industrial sectors.
- **Some key decisions in the panning of a CCS project are highly intertwined with others and may need to be evaluated in an iterative process.** While some early decisions may pose constraints to others further down the line, some decisions can be put on hold and multiple options can be explored. In some cases, previous decisions can be re-evaluated until the project assumes the desired shape.
- **Financing remains a key hurdle for CCS developers.** The fluctuation of governmental support levels in several regions around the world has shaken the trust of private investors, leaving large-scale projects highly reliant on public funds. Long-term economic viability and sustainable revenue streams can help alleviate this problem, given the right regulatory framework is in place.
- Although CCS is key to decarbonisation and combating climate change, **there remains a considerable amount of public opposition facing large-scale CCS projects.** This can emerge from disapproval of laying onshore CO_2 pipelines, fear of CO_2 leakage and pressurised storage, or concerns about amine-based pollutants and waste handling. The importance of local community engagement was emphasised in every analysed site in this study. Regular communication, local community awareness and inclusion in the overall benefits from the site development is crucial to realising CCS benefits in several regions.
- **Testing capture technology in a pilot scale on own flue gas has been the common success factor across all the projects.** This provides confidence that the technology works as intended in terms of capture rate, safety, solvent degradation and emissions which – in some regions – can be a regulatory requirement for a project to progress.
- **Site location is one of the key decision factors.** It impacts almost every aspect of the project: construction plans, costs, personnel availability, and transport, permitting process complexity and ease of access to permanent storage sites and/or potential CO_2 buyers.
- The design criteria or approach will rely highly on the industry and application of the capture plant. However, **modularisation and off-site manufacturing should always be maximised** whenever adequate for the site. Modular units will achieve fewer risks in plant integration and commissioning.
- **The transitional phase from the completion of plant construction to commissioning and commercial operations is very critical**, particularly for retrofitted facilities. Phased or staged approaches have been very successful in achieving minimal interruption for the host facility. This can be of economic impact on the overall project in the case of production plants.
- **The operational capacity of the crew running the capture plant should not be overlooked.** Capture facilities are relatively new systems with scarce availability of experienced personnel, particularly in industry. Clear procedures for normal and emergency start-up and shutdown must be available for the operating crew at all time.
- **Planning and simulations should be in place** whenever possible to account for all operational aspects. These include aspects related to plant efficiency, maintenance programs, personnel availability and operational capacity, monitoring sensors installation and control rooms as well as by-products and waste handling procedure.
- **Decommissioning and capture site closure should be a part of the planning stage.** Large-scale CCS projects should demonstrate early enough the plans for making adequate provision for the complete and safe decommissioning of all facilities that fall within the scope of a certain

project. These plans need to be communicated and agreed on by all the stakeholders involved in the project including the local community that will be highly impacted with these decommissioning activities.

4.2 Suggestions for further work

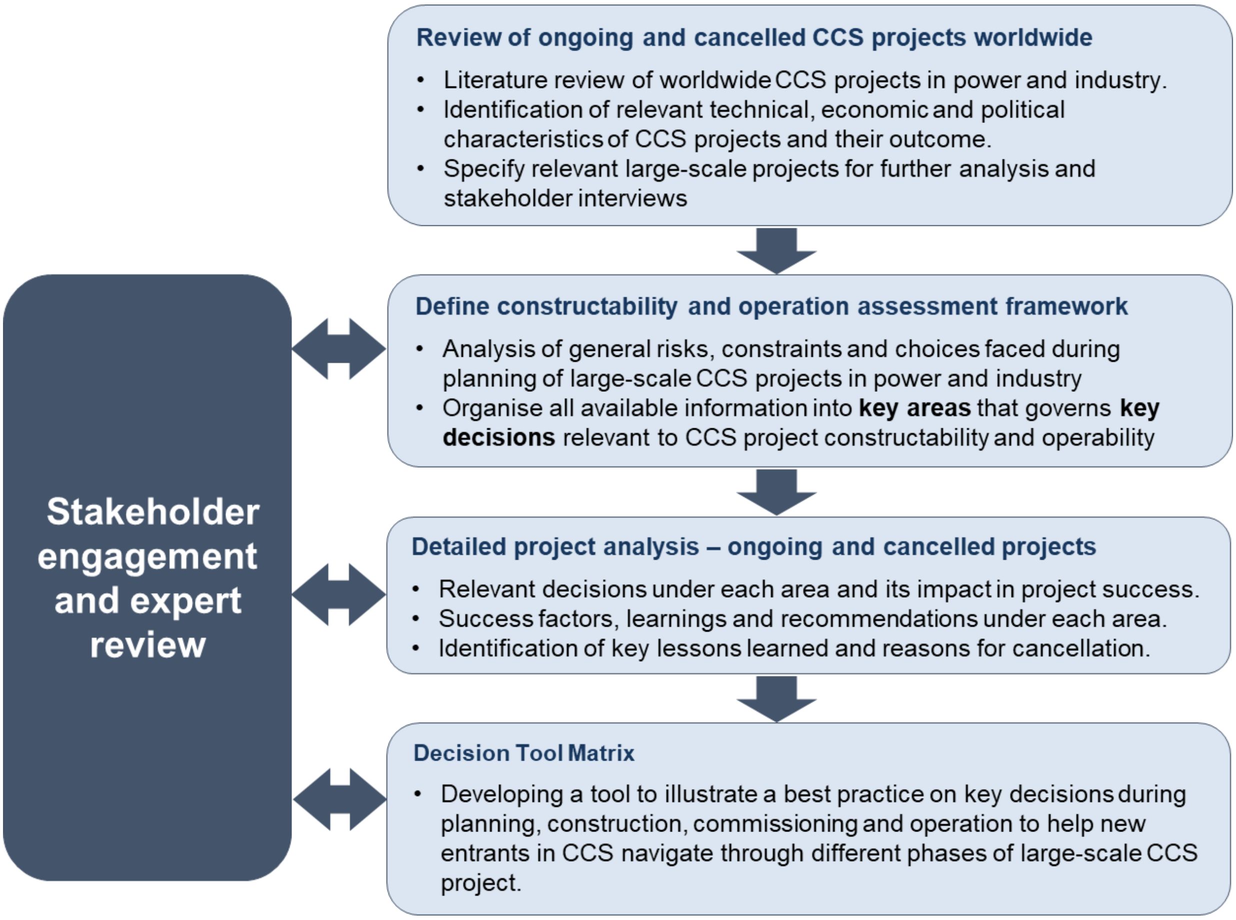
This study has provided a high-level assessment of the constructability and operation challenges experienced by some of the large-scale CCS projects around the world. Although this study has highlighted the key decision areas and success factors for the capture side of the CCS chain, T&S and full-chain integration has been repeatedly cited as an essential part of the planning and failing to achieve optimal interfacing between capture and T&S has been a reason for cancelling several potential projects. Many countries like Norway, Netherlands and the UK are developing full chain CCS projects, industrial hubs and clusters to deliver its system-wide decarbonisation targets. Hence, the need to analyse constructability, operation and integration challenges faced by this kind of wide-scale projects can’t be overstated.

5 Appendix

5.1 Methodology

This chapter details the methodology of the analysis carried out in this study. Each section will include the specific steps performed and resources consulted to achieve the overarching study objective and key deliverables discussed in the previous chapter

5.1.1 Overarching study approach



Review of ongoing and cancelled CCS projects worldwide

- Literature review of worldwide CCS projects in power and industry.
- Identification of relevant technical, economic and political characteristics of CCS projects and their outcome.
- Specify relevant large-scale projects for further analysis and stakeholder interviews

Define constructability and operation assessment framework

- Analysis of general risks, constraints and choices faced during planning of large-scale CCS projects in power and industry
- Organise all available information into **key areas** that governs **key decisions** relevant to CCS project constructability and operability

Detailed project analysis – ongoing and cancelled projects

- Relevant decisions under each area and its impact in project success.
- Success factors, learnings and recommendations under each area.
- Identification of key lessons learned and reasons for cancellation.

Decision Tool Matrix

- Developing a tool to illustrate a best practice on key decisions during planning, construction, commissioning and operation to help new entrants in CCS navigate through different phases of large-scale CCS project.

Figure 5-1: Overarching study approach

5.1.2 Literature review

An extensive literature review for the best-available sources was carried out. Detailed information was gathered on worldwide CCS projects in the power and industry sectors. Data collection was performed on the basis of the most up-to-date CCS project databases, such as GCCSI, SCCS, NETL, MIT, and also publicly available reports and relevant documentation. Key database resources consulted in the literature review step and their relevance for the study are listed in Table 5-1.

Table 5-1: List of key database resources and their relevance for the study

CCS projects databases	Status	Relevance for this study
GCCSI	Up to date and data easily accessible. Does not report cancelled projects.	Main source for operating/ongoing projects
SCCS	Up to date but data not easily accessible. We obtained data for cancelled projects through direct contact with SCCS	Main source for cancelled projects
MIT	Not up to date – Discontinued in 2016	Secondary source for cross-checking and data validation
NETL	Not up to date	Secondary source for cross-checking and data validation
ZEROCO$_2$	Last updated in 2017. It contains lots of useful information about countries funding and CCS initiatives, key project players and contacts	Secondary source for cross-checking and identification of key organisations and contacts for stakeholder engagement

5.1.3 Constructability and operability assessment framework

This step is focused on the constructability and operability aspects of a CCS project. Through a detailed assessment of large-scale operating CCS projects around the world, a list of parameters and constraints impacting CCS project planning and construction, as well as obstacles and challenges to commissioning and operation, was created. The detailed list of parameters is shown in Appendix 5.2 and was used as a guideline for detailed project analysis and to guide the stakeholder interview process.

5.1.4 Stakeholder engagement

The stakeholder engagement process was based on targeted interviews with key persons from significant projects, as identified during the literature review phase. It was performed in parallel with the other tasks.

During the interviews, key findings and lessons learned from the most relevant large-scale CCS projects were discussed with stakeholders involved in the construction and commissioning of their projects. This informed the synthesised summary of constructability and barriers to commissioning for large-scale CCS projects and fed directly into building the decision tool matrix. A list of interviewed site and persons is included in Appendix 5.3.

5.1.5 Expert review

During this study and at its different steps, expert review was carried out to inform and validate the findings. In this project, Element Energy has partnered with GCCSI and Air Products US for this purpose.

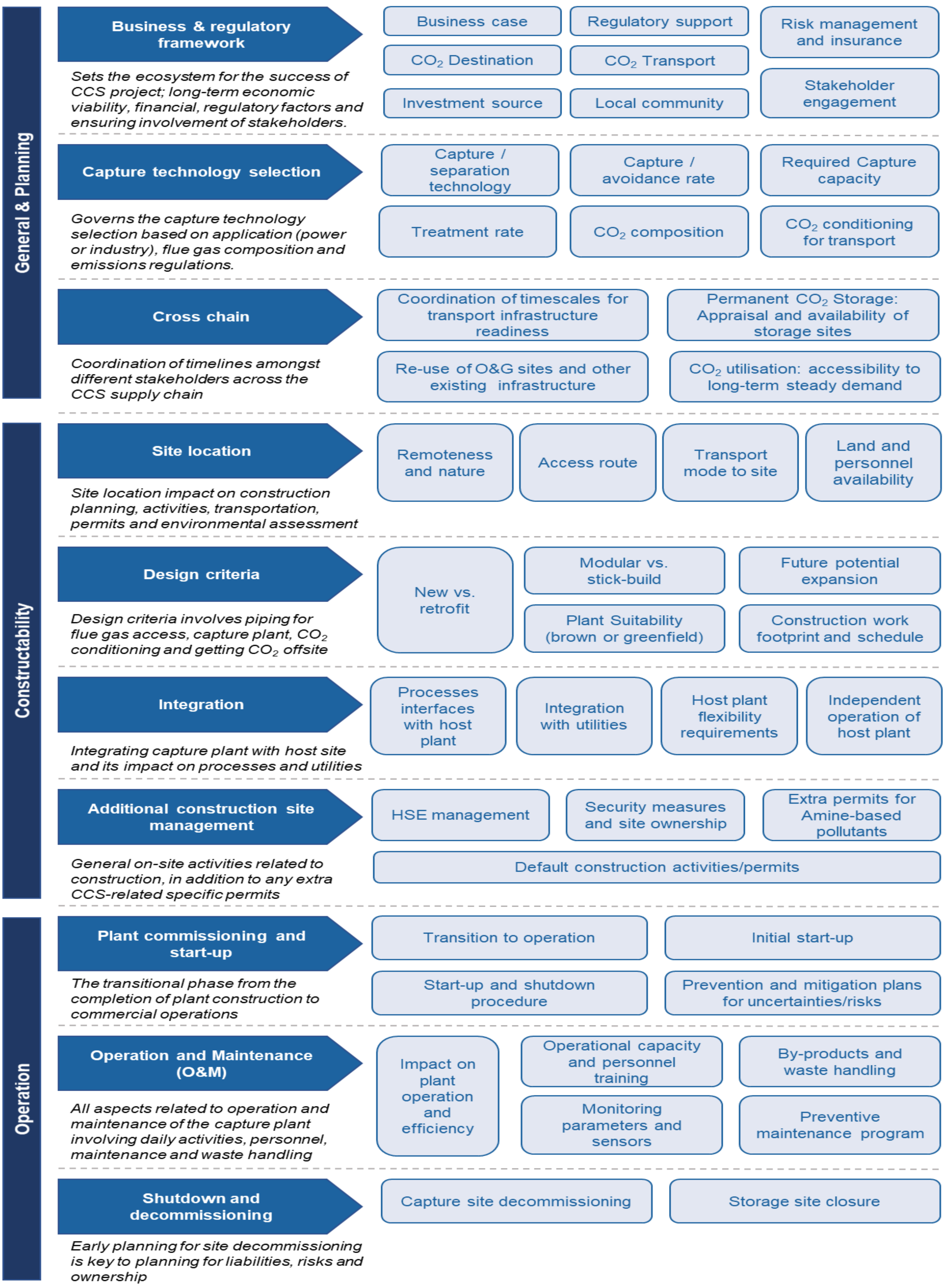
Global CCS Institute

The GCCSI is an international organisation with diverse international membership, including governments, global corporations, private companies, and project developers. Our key CCS expert Angus Gillespie was Vice President CO_2 for Shell where he shaped many of the organisation's CO_2 related activities, including Shell's CCS projects. He will bring invaluable knowledge and practical learnings from the Peterhead (UK), Quest (Canada), and Zerogen (Australia) projects.

Air Products

Air Products is a world-leading Industrial Gases company in operation for over 75 years. Air Products will bring valuable learnings and insights on refineries, Steam Methane Reformers and CCUS based on Air Products global operations and specifically from their SMR CCS project in the US. Air Products retrofitted each of its two steam methane reformers SMRs, located within an existing refinery at Port Arthur, Texas, to separate CO_2 from the process gas stream. The capture capacity is at around 1 $MtCO_2$/yr and more than 3 million tonnes of CO_2 have been captured since the facilities became operational.

5.2 Assessment framework used for stakeholder interviews



CCS constructability and operation assessment framework – Key decision areas and success factors

General & Planning

Business & regulatory framework

Sets the ecosystem for the success of CCS project; long-term economic viability, financial, regulatory factors and ensuring involvement of stakeholders.

- Business case
- Regulatory support
- Risk management and insurance
- CO_2 Destination
- CO_2 Transport
- Investment source
- Local community
- Stakeholder engagement

Capture technology selection

Governs the capture technology selection based on application (power or industry), flue gas composition and emissions regulations.

- Capture / separation technology
- Capture / avoidance rate
- Required Capture capacity
- Treatment rate
- CO_2 composition
- CO_2 conditioning for transport

Cross chain

Coordination of timelines amongst different stakeholders across the CCS supply chain

- Coordination of timescales for transport infrastructure readiness
- Permanent CO_2 Storage: Appraisal and availability of storage sites
- Re-use of O&G sites and other existing infrastructure
- CO_2 utilisation: accessibility to long-term steady demand

Constructability

Site location

Site location impact on construction planning, activities, transportation, permits and environmental assessment

- Remoteness and nature
- Access route
- Transport mode to site
- Land and personnel availability

Design criteria

Design criteria involves piping for flue gas access, capture plant, CO_2 conditioning and getting CO_2 offsite

- New vs. retrofit
- Modular vs. stick-build
- Future potential expansion
- Plant Suitability (brown or greenfield)
- Construction work footprint and schedule

Integration

Integrating capture plant with host site and its impact on processes and utilities

- Processes interfaces with host plant
- Integration with utilities
- Host plant flexibility requirements
- Independent operation of host plant

Additional construction site management

General on-site activities related to construction, in addition to any extra CCS-related specific permits

- HSE management
- Security measures and site ownership
- Extra permits for Amine-based pollutants
- Default construction activities/permits

Operation

Plant commissioning and start-up

The transitional phase from the completion of plant construction to commercial operations

- Transition to operation
- Initial start-up
- Start-up and shutdown procedure
- Prevention and mitigation plans for uncertainties/risks

Operation and Maintenance (O&M)

All aspects related to operation and maintenance of the capture plant involving daily activities, personnel, maintenance and waste handling

- Impact on plant operation and efficiency
- Operational capacity and personnel training
- By-products and waste handling
- Monitoring parameters and sensors
- Preventive maintenance program

Shutdown and decommissioning

Early planning for site decommissioning is key to planning for liabilities, risks and ownership

- Capture site decommissioning
- Storage site closure

5.3 Stakeholder Engagement – List of sites and interviewees

#	Project	Country	Interviewee	Organisation	Sector
1	Boundary Dam Carbon Capture Project – SaskPower	Canada	Corwyn Bruce Yuewu Feng	International CCS Knowledge Centre	Power generation (Coal)
2	Quest carbon capture and storage project	Canada	Tim Wiwchar Nicole Ternes	Shell	Hydrogen production
3	Port Arthur CCS Project	USA	Michael Lynch, Julie O'Brien Sarah G. Farnand	Air Products - US	Hydrogen production
4	Petra Nova CCUS Project	USA	Jim Tharp (*Potential*)	NRG	Power generation (Coal)
5	Gorgon Carbon Dioxide Injection Project	Australia	John Torkington	Chevron Australia	Natural gas processing
6	NET Power Clean Energy Demonstration Plant	USA	Bill Brown, Damian Beauchamp	8 Rivers Capital	Power generation (Gas)
7	NET Power Clean Energy Demonstration Plant	USA	Charlie Bowser, Brandon Heffinger	NET Power	Power generation (Gas)
8	Illinois Basin-Decatur Project (IBDP)	USA	Sallie Greenberg, Ray McKaskle	Trimeric Corporation	Ethanol production
9	Port of Rotterdam CCUS Backbone Initiative (Porthos)	Netherlands	Ian J Brass Vince White	Air Products - UK	Various industries
10	Fortum Oslo Varme Capture Plant	Norway	Jannicke Bjerkås, Ole Martin Moe Jørgen Thomassen	Fortum Oslo Varme	Waste-to-energy
11	Norcem Brevik Capture Plant	Norway	Per Brevik	HeidelbergCement	Cement
12	Peterhead CCS Project	UK	Bill Spence	Shell	Power generation (Gas)

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User guide on constructability and operability of large-scale CCUS

A guide for

IEAGHG

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Disclaimer

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Acronyms

AI	Artificial Intelligence
CCUS	Carbon capture utilisation and storage
CO_2	Carbon dioxide
EOR	Enhanced oil recovery
ETS	Emissions trading system
FEED	Front End Engineering Design
FOAK	First of a kind
GCCSI	Global CCS Institute
GHG	Greenhouse Gas
HSE	Health, Safety and Environment
IoT	Internet of Things
SMR	Steam Methane Reformation

Glossary

Capture rate: Is here defined as the portion of CO_2 that is extracted from the general gas stream (whether well production, flue gas or even atmospheric) to which carbon capture is applied. This value varies significantly depending on the selected technology.

Cross chain coordination: Coordination among the various stages of the CCUS supply chain, including capture, treatment, transportation and storage or utilisation.

Oxyfuel combustion: Carbon capture technology based on the combustion of fuels with a mix of oxygen and CO_2 instead of air, thus releasing pure CO_2 and water vapour as products of combustion.

Post-combustion: Range of carbon capture technologies relying on the capture of CO_2 from a gas stream with varying concentration of CO_2, originated from fuel combustion or industrial process emissions.

Pre-combustion: Process utilising a low-carbon fuel (typically hydrogen) previously generated from a fossil fuel while capturing the CO_2 emitted in the reformation process.

Treatment rate: Is here defined as the portion of sources of CO_2 to which carbon capture is applied. For example, in a power station with 4 units of equal capacity (in MW capacity) and utilising the same type of fuel, the application of carbon capture to one of the units results in a treatment rate of 25%.

Table of contents

1 Introduction

1.1 Purpose and target audience

The target audience of this guide is large-scale CCUS developers. The document aims to advise the reader on the decisions that need to be made during the planning phase of a large-scale CCUS facility and that are most crucial to ensure its successful construction, commissioning and operations.

1.2 Scope of the guide

A careful review of a range of large-scale CCUS projects worldwide as well as extensive consultation with stakeholders involved in their planning, construction and operation were carried out. All learnings gathered around the key factors that were determinant in the success or that contributed to the cancellation of the projects are combined in this guide.

The provided information aims to make the reader aware of the type of decisions that must be most carefully considered in the planning phase of a large-scale CCUS project. For each decision, the reader is guided towards the options that are most appropriate for a specific project. Finally, the guide provides an overview of the key success factors and of the reasons for cancellation of past projects worldwide.

Further information on the considered CCUS projects is reported in section 1.4, on page 4.

1.3 Structure of the guide

This guide is composed of three main tools:

- **Decision chain** (Chapter 2, from page 6): This tool guides the reader in the decision process and provides information on each of the key decisions, tailored to a variety of needs and constraints of typical CCUS projects.
- **Key success factors** (Chapter 3, from page 23): This tool provides a summary of the key factors that contributed to the success of previous large-scale CCUS projects.
- **Reasons for cancellation** (Chapter 4, from page 24) : This tool presents an overview of the reasons that led to the cancellation of previous large-scale projects that were terminated.

1.4 Overview of considered large-scale CCUS projects

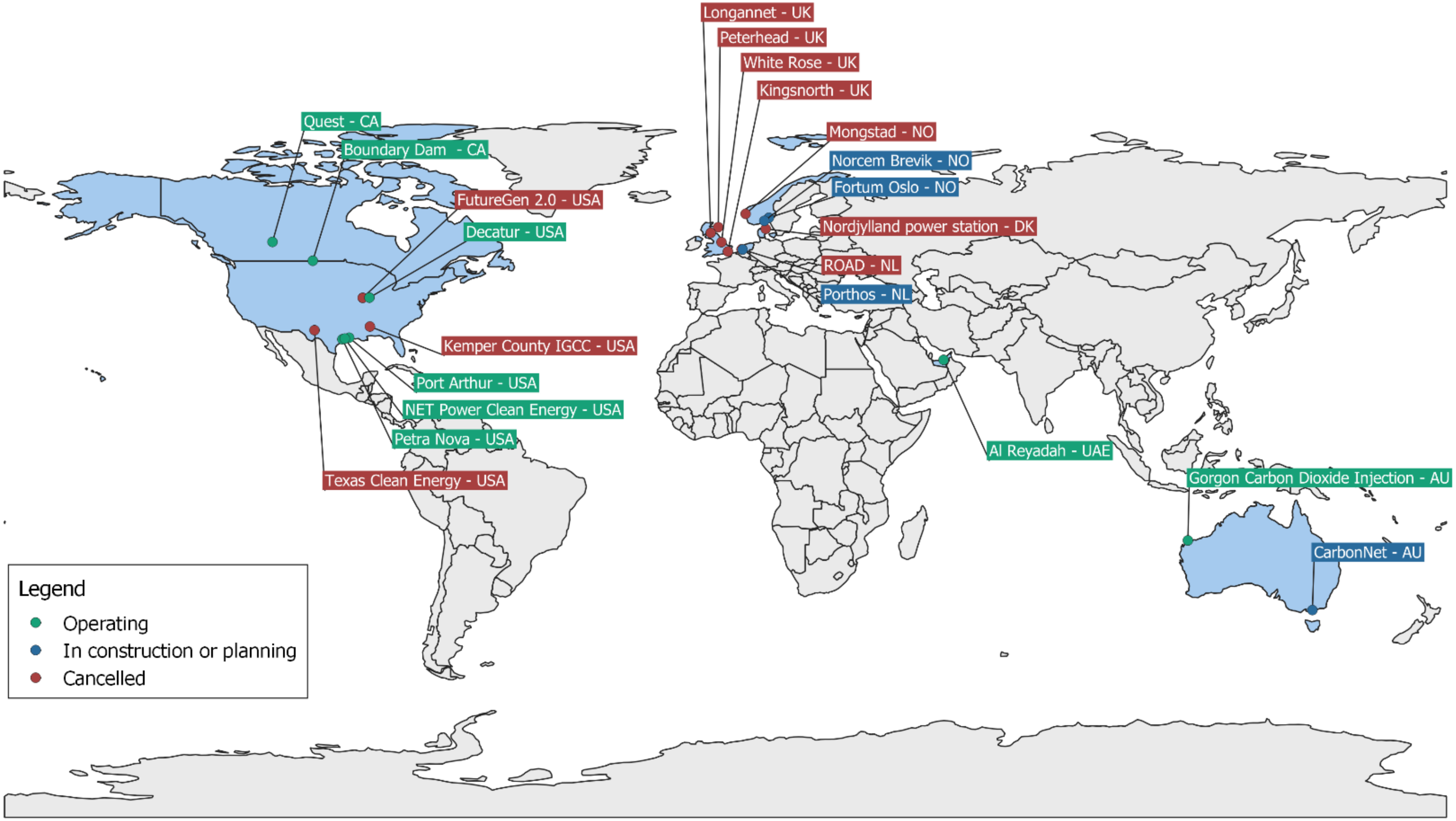
The guidance provided in this guide is based on the learnings gathered from the most relevant large-scale CCUS projects worldwide. Note that only a limited selection of facilities in the gas processing industry were selected, as this sector is considered to be less affected by implementation risk.

A complete list of the considered CCUS projects is reported in Table 1. Additionally, a map with the location of the considered large-scale CCUS sites is shown in Figure 1. The map reports operating sites in green, sites in planning or construction in blue and cancelled projects in red.

Table 1: List of large-scale CCUS projects considered in the formulation of the advice

	Project	Country	Sector
Operating	Al Reyadah CCUS Project	UAE	Iron and steel
	Boundary Dam Carbon Capture Project	Canada	Power generation (Coal)
	Quest Carbon Capture and Storage Project	Canada	Hydrogen production
	Port Arthur CCS Project	USA	Hydrogen production
	Petra Nova CCUS Project	USA	Power generation (Coal)
	Gorgon Carbon Dioxide Injection Project	Australia	Natural gas processing
	NET Power Clean Energy Demonstration Plant	USA	Power generation (Gas)
	Illinois Basin-Decatur Project (IBDP)	USA	Ethanol production
In construction or advanced development	The CarbonNet Project	Australia	Power and H_2 from coal
	Port of Rotterdam CCUS Initiative (Porthos)	Netherlands	Various industries
	Fortum Oslo Varme Capture Plant	Norway	Waste-to-energy
	Norcem Brevik Capture Plant	Norway	Cement
Cancelled	Peterhead CCS Project	UK	Power generation (Gas)
	White Rose CCS Project	UK	Power generation (Gas)
	Longannet CCS Project	UK	Power generation (Coal)
	Kingsnorth CCS Project	UK	Power generation (Coal)
	The Kemper County CCS Project	USA	Power generation (Coal)
	Full-scale CCS at Mongstad Project	Norway	Power generation (Gas)
	Texas Clean Energy Project (TCEP)	USA	Power generation (Coal)
	Vattenfall Nordjyllandsværket CCS Project	Denmark	Power generation (Coal)
	FutureGen 2.0	USA	Power generation (Coal)
	ROAD – Rotterdam Capture and Storage Demonstration Project	Netherlands	Power generation (Coal)

Figure 1: Location of investigated large-scale CCUS sites



2 Decision chain

The information reported in this section is aimed at advising the development of a large-scale CCUS project. Most relevant decisions that will commonly need to be taken during the planning phase and that will influence the outcome of the project are summarised and complemented with advice based on the experience of previous large-scale CCUS projects.

The reader is guided through a list of relevant decisions. For each decision, guidance is provided on the most appropriate options for various types of CCUS projects, together with complementary information that will need to be considered during the decision process. This framework ensures that the planner:

- Is made aware of the most relevant decisions to be considered
- Is advised on the best options for each decision, tailored to the characteristics of the project
- Is informed on additional details that will need to influence each decision

2.1 Preliminary considerations on CCUS economics

While the reliance on a robust business model is recognised to be a determinant factor for the success of a large-scale CCUS project, the available business model options are not studied in detail in this work, which focusses on constructability and operational challenges of CCUS. A more detailed analysis of industrial carbon capture business models can be found in a recent report[1] by Element Energy.

CCUS economics based on the revenue from the sale of CO_2 to EOR operations is associated with a high risk, as EOR CO_2 sale agreements often set a price for CO_2 which is tied to the price of oil. Several projects in the U.S. were recently put on hold or cancelled due to the COVID-19 emergency, as the drop in oil price resulted in a sharp loss of value of CO_2 in offtake agreements. A similar case was behind the cancellation of the Kemper CCS project: the reduction in the price of natural gas and oil due to the shale gas boom rendered the economic case for power from coal gasification less competitive.

One of the main obstacles posed to the deployment of CCUS in the U.S. has been for many years the lack of a regulatory driver, despite the availability of mature CCUS technologies. The introduction of carbon reduction goals and 45Q in the recent years have contributed to revitalizing the industry.

Due to the limited number of CCUS projects worldwide and the variety of technologies and applications available, many projects considered in this study are FOAK plants. It is expected that CCUS projects that aim to replicate technologies already implemented at other facilities will be able to take advantage of the general cost reduction to which NOAK plants are subject. This will contribute to strengthening the business case of new CCUS projects and increasing the rate of success of future CCUS projects.

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[1] Element Energy for BEIS 2018, Industrial carbon capture business models

2.2 Decision chain logic

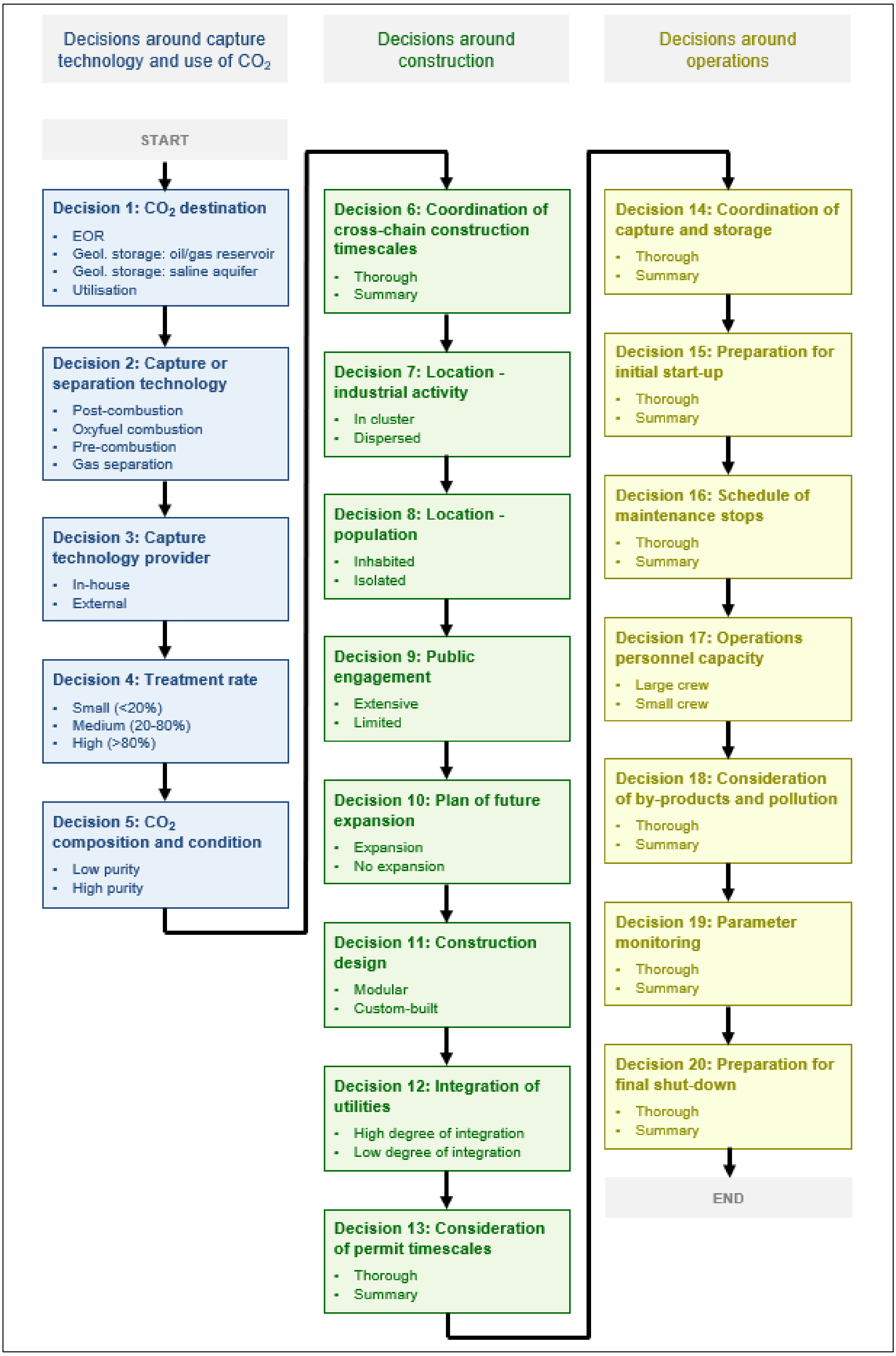
All relevant decisions are organised in the structure of a decision chain. Each block composing the decision chain focusses on one of the key decisions that will need to be evaluated during the planning phase of a project.

The logical sequence of the chain represents how some decisions at the start of the chain may pose constraints to other decisions further down the line and does not imply that each decision should necessarily be finalised before moving onto the next. In fact, when moving along the chain some decisions can be put on hold and multiple options can be explored. In some cases, previous decisions can be re-evaluated in an **iterative process**, until the project assumes the desired shape.

An overview of the decision chain logic is reported in Figure 2. Each decision step reports the name of the decision together with the available options to choose from. Additionally, note that the considered decisions are labelled according to the following categories, which are tackled in succession:

- Blue: Decisions around capture technology and use of CO_2
- Green: Decisions around construction
- Yellow: Decisions around operations

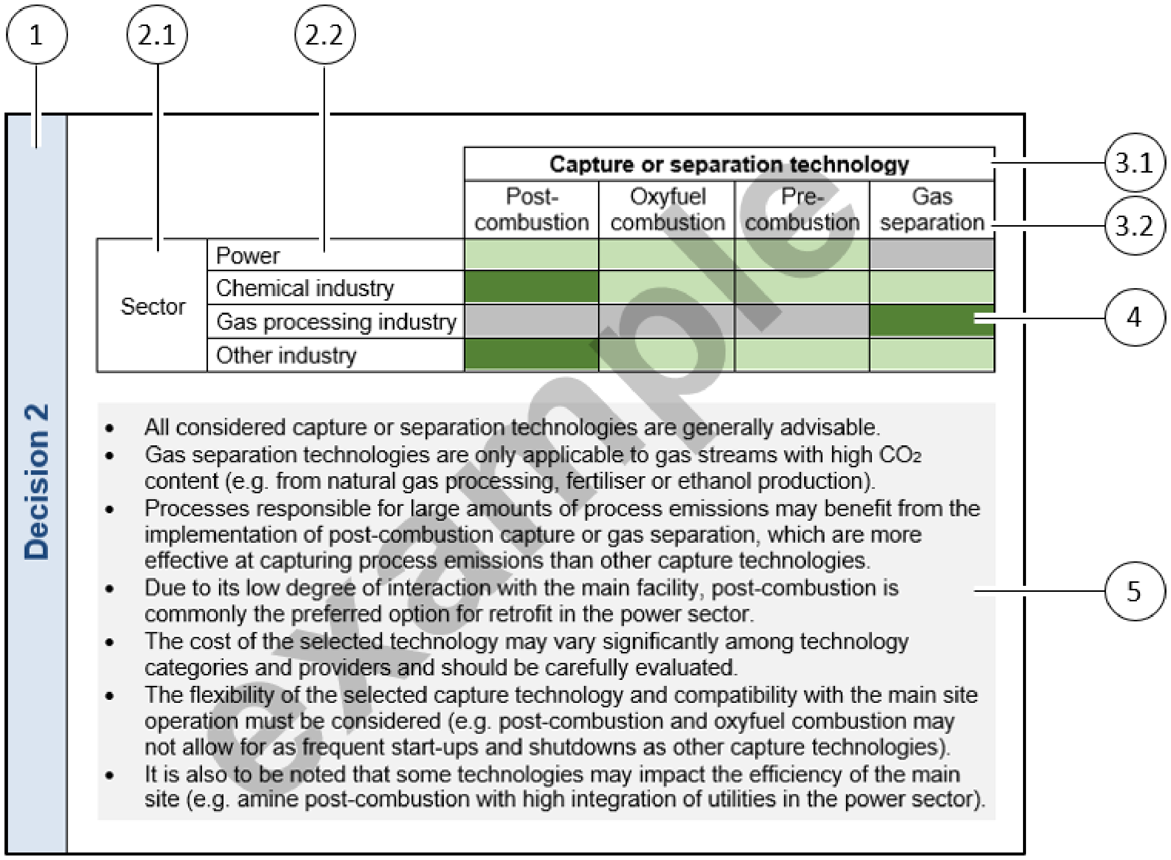
Figure 2: Overview of decision chain logic



2.3 Decision block structure and use

All information and guidance on each decision is elaborated and structured in the form of a decision block. Figure 3 shows an example of the typical decision block, together with a legend and colour key.

Figure 3: Structure of decision blocks



		Capture or separation technology			
		Post-combustion	Oxyfuel combustion	Pre-combustion	Gas separation
Sector	Power	▩	▩	▩	▨
	Chemical industry	🟩	▩	▩	▩
	Gas processing industry	▨	▨	▨	🟩
	Other industry	🟩	▩	▩	▩

- All considered capture or separation technologies are generally advisable.
- Gas separation technologies are only applicable to gas streams with high CO_2 content (e.g. from natural gas processing, fertiliser or ethanol production).
- Processes responsible for large amounts of process emissions may benefit from the implementation of post-combustion capture or gas separation, which are more effective at capturing process emissions than other capture technologies.
- Due to its low degree of interaction with the main facility, post-combustion is commonly the preferred option for retrofit in the power sector.
- The cost of the selected technology may vary significantly among technology categories and providers and should be carefully evaluated.
- The flexibility of the selected capture technology and compatibility with the main site operation must be considered (e.g. post-combustion and oxyfuel combustion may not allow for as frequent start-ups and shutdowns as other capture technologies).
- It is also to be noted that some technologies may impact the efficiency of the main site (e.g. amine post-combustion with high integration of utilities in the power sector).

Decision block legend:

1	Decision number
2.1	Constraint categories
2.2	Constraint characteristics
3.1	Decision
3.2	Decision options
4	Advice scores
5	Decision guidance

Advice score key:

🟩	Very advisable / Very applicable
▩	Advisable / Applicable
🟧	Less advisable / Low priority
▨	Not applicable

Each decision block is composed of three main areas: a **decision number** on the left, a **decision matrix** at the top and a **guidance box** at the bottom of the block.

The decision number (label 1) is reported in an area on the left of the block which is colour-coded depending on the decision category.

The decision matrix provides an overview of the options available and of the site characteristics playing a role in the decision and presents a high-level evaluation of the suitability of each option. While the decision (label 3.1) and its available options (label 3.2) build the columns of the matrix, each row represents a constraint or site characteristic (label 2.2), grouped by categories (label 2.1). A colour-coded advice score (label 4) provides high-level ranking of the appropriateness of each decision option for each of the considered site characteristics.

At the bottom of the decision block a guidance box with grey background (label 5) illustrates the reasons behind the scores provided by the above decision matrix and provides further insight and information that will be helpful in formulating the decision most appropriate for the reader's specific project.

Recommendations for the use of the decision blocks

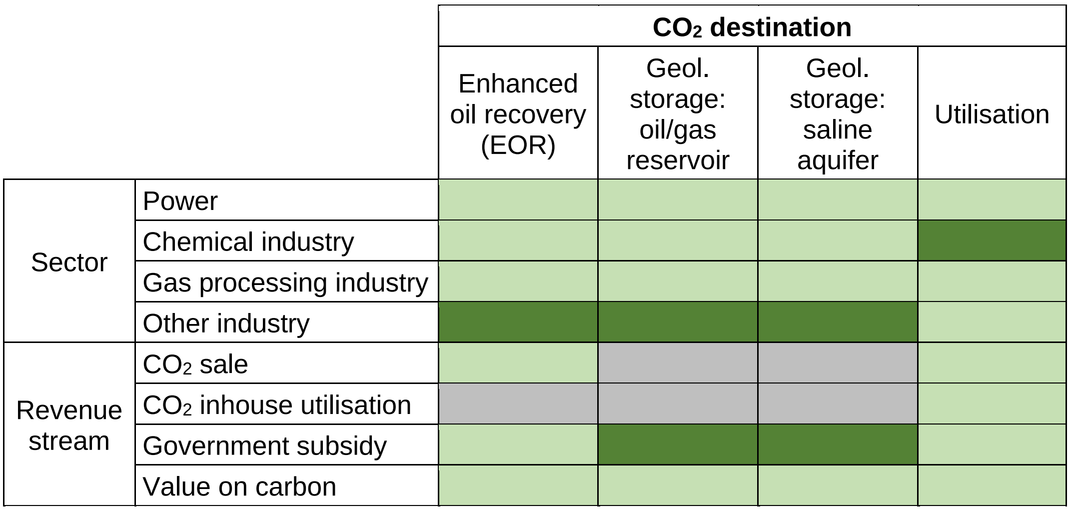
The guidance provided by each decision block can be helpful in the formulation of a decision tailored to a specific site, as long as the correct approach is followed:

- A decision should not be taken only on the basis of the advice scores provided by the decision matrix, but by taking into consideration the narrative provided by the guidance box.
- Where multiple constraint categories are present, the scores provided for the options in each category should be considered independently. In fact, the colour scores are related to the constraints of one category alone, independently from the constraints of other categories.
- It is also important to follow the decision chain in the proposed logical order. In fact, the outcome of the decisions taken early on in the decision chain will later affect the constraints of subsequent decisions, as these become fixed characteristics of the site (e.g. the decision on the destination of CO_2 taken in "Decision 1" will become a constraining characteristic of the site in "Decision 5").

2.4 Decision chain guidance tool

All decision blocks are illustrated individually in this chapter, reporting for each a decision matrix and the related guidance that should aid the reader in the formulation of the decision. To begin, we will consider decisions around capture technology and the use of CO_2, summarised in decision blocks 1 to 5.

Decision 1



		CO_2 destination			
		Enhanced oil recovery (EOR)	Geol. storage: oil/gas reservoir	Geol. storage: saline aquifer	Utilisation
Sector	Power	🟩	🟩	🟩	🟩
	Chemical industry	🟩	🟩	🟩	■
	Gas processing industry	🟩	🟩	🟩	🟩
	Other industry	■	■	■	🟩
Revenue stream	CO_2 sale	🟩	▨	▨	🟩
	CO_2 inhouse utilisation	▨	▨	▨	🟩
	Government subsidy	🟩	■	■	🟩
	Value on carbon	🟩	🟩	🟩	🟩

<u>Depending on sector</u>:

- All considered CO_2 destinations are advisable: enhanced oil recovery, geological storage in depleted hydrocarbon deposits or saline aquifers and utilisation.
- **Chemical industry:** sites in the chemical sector may be able to exploit synergies and in-house knowledge for CO_2 utilisation.
- **Other industry**: sites involved in the production of transportation fuels are subject to the requirements of the low-carbon fuel standard (LCFS), which favour the destination of the captured CO_2 to EOR or geological storage.

<u>Depending on revenue stream</u>:

- **CO_2 sale**: the destination of CO_2 for use in EOR typically provides higher revenues than for geological storage.
- **Government subsidy**: subsidies may vary by CO_2 destination. For example, the 45Q tax credit in the USA is higher for CO_2 captured and destined to geological storage than for CO_2 destined for EOR. The higher earning is intended to match the additional revenue obtained from the sale of CO_2 destined for EOR.
- **Value on carbon**: depending on the type of value on carbon scheme in place, some destinations may be more profitable.

Generally, geological storage in oil/gas reservoirs may sometimes be preferable to geological storage in saline aquifers, which require more extensive preparatory work for characterisation and testing prior to injection. However, CO_2 storage in oil fields after EOR activities may be more problematic and legally daunting. Different monitoring and verification requirements may be in place for the considered storage options, depending on the type of injection activity and on local regulations.

Notes: In this report the term “utilisation” refers to the use of CO_2 as feedstock for new products, such as chemicals, synthetic fuels or minerals. The use of CO_2 for enhanced oil recovery is labelled as “EOR”.
EOR and geological storage options were considered separately, due to their generally different life cycle of storage.

Decision 2

		Capture or separation technology			
		Post-combustion	Oxyfuel combustion	Pre-combustion	Gas separation
Sector	Power	□	□	□	▨
	Chemical industry	■	□	□	□
	Gas processing industry	▨	▨	▨	■
	Other industry	■	□	□	□

- All considered capture or separation technologies are generally advisable.
- Gas separation technologies are only applicable to gas streams with high CO_2 content (e.g. from natural gas processing, fertiliser or ethanol production).
- Processes responsible for large amounts of process emissions may benefit from the implementation of post-combustion capture or gas separation, which are more effective at capturing process emissions than other capture technologies.
- Due to its low degree of interaction with the main facility, post-combustion is commonly the preferred option for retrofit in the power sector.
- The cost of the selected technology may vary significantly among technology categories and providers and should be carefully evaluated.
- The flexibility of the selected capture technology and compatibility with the main site operation must be considered (e.g. post-combustion and oxyfuel combustion may not allow for as frequent start-ups and shutdowns as other capture technologies).
- It is also to be noted that some technologies may impact the efficiency of the main site (e.g. amine post-combustion with high integration of utilities in the power sector).

Decision 3

		Capture technology provider	
		In-house	External
Sector	Power	□	■
	Chemical industry	■	■
	Gas processing industry	■	■
	Other industry	□	■

- While most sites will require an external provider for the capture technologies, some companies in the chemical or gas processing industry may be able to utilise in-house technology, reducing costs and creating commercial advantage. In-house technology should however not be utilised if the alternatives offered by external providers are more advanced.
- When relying on a capture technology from an external provider, a range of providers should be considered, in order to create competitive advantage and keep costs low. Settling for one specific provider too soon is discouraged, as it can result in the loss of negotiation leverage and may lead to cost over-runs. A later decision on the final provider allows to drive down costs of both technology and EPC contractors, although development costs are thereby higher.

Decision 4

		Treatment rate		
		Small (<20%)	Medium (20-80%)	High (>80%)
Sector	Power	▨	▨	🟩
	Chemical industry	▨	▨	▨
	Gas processing industry	🟧	▨	🟩
	Other industry	▨	▨	▨

- A high treatment rate, corresponding to a large number of sources and/or proportion of facility emissions onsite to which carbon capture is applied, is generally advisable, as it enables the capture of a large portion of the produced CO_2. This is generally easier and more economical to implement in the power and gas processing sectors, characterised by the presence of few, large sources of CO_2.
- However, if a new capture technology is being implemented, it may be prudent to start with a relatively low treatment rate (e.g. applying carbon capture to only one of the flue stacks of a power station with multiple units) and increase the number of sources over time (see Boundary Dam with ~20% treatment rate).

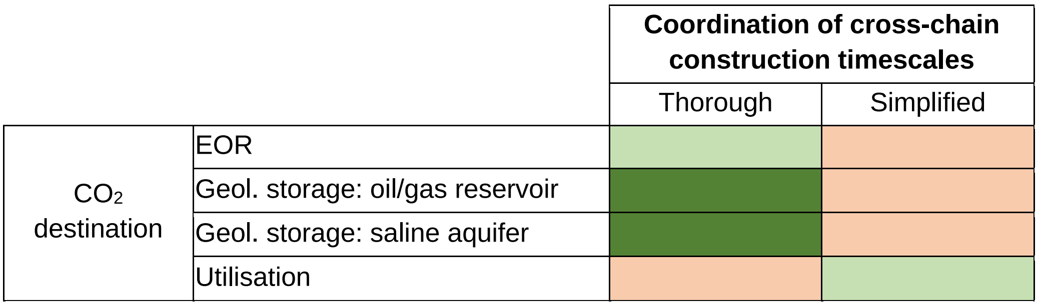
Decision 5

		CO_2 composition and condition	
		Low purity	High purity
CO_2 destination	EOR	▨	🟩
	Geol. storage: oil/gas reservoir	▨	🟩
	Geol. storage: saline aquifer	▨	🟩
	Utilisation	🟧	▨

- Note that the constraints on this decision depend on the outcome of decision 1.
- The removal of gases potentially harmful for humans and for the environment may be required prior to any type of injection, depending on local regulations. Additionally, water and other acid gasses contained in the gas stream need to be removed to prevent damage to the pipeline materials and consequent costs due to repair or replacement.
- Utilisation of CO_2 may involve stringent composition and condition requirements.

Next, we will consider the most relevant decisions around the construction of the facility, summarised in decision blocks 6 to 13.

Decision 6



		Coordination of cross-chain construction timescales	
		Thorough	Simplified
CO_2 destination	EOR	🟩	🟧
	Geol. storage: oil/gas reservoir	🟩	🟧
	Geol. storage: saline aquifer	🟩	🟧
	Utilisation	🟧	🟩

- Coordination of the timescales for construction of the capture facility and for exploration and appraisal of the geological storage site needs to be considered very carefully, as the latter can be lengthy.
- Cross-chain timescales coordination is relevant also in case of EOR. Although an EOR field may require a more modest amount of testing, the timescales required to achieve a high rate of CO_2 injection can still be significant.
- In the case of utilisation, the coordination of the construction of the capture facility and of the utilisation facility is expected to be less problematic, as these have more similar timescales.
- For retrofit projects it is advisable to coordinate the construction of the capture facility with the operation of the main facility. Interface points of the capture site should be carried out during a scheduled period of workover of the main facility, in order to minimise down time of the main facility.

Decision 7

		Location - industrial activity (can be decided only if greenfield)	
		In cluster	Dispersed
CO_2 destination	EOR	🟩	🟧
	Geol. storage: oil/gas reservoir	🟩	🟧
	Geol. storage: saline aquifer	🟩	🟧
	Utilisation	🟩	🟩
Capture or separation technology	Post-combustion	🟩	🟩
	Oxyfuel combustion	■	🟩
	Pre-combustion	■	🟩
	Gas separation	🟩	🟩

Depending on CO_2 destination:

- The location of the CCUS facility within an industrial cluster is advantageous for all CO_2 destinations, except for utilisation of CO_2, for which the location is not relevant. The inclusion in a cluster allows for the utilisation of communal CO_2 transportation infrastructure, which is not required in the case of utilisation.

Depending on capture or separation technology:

- Oxyfuel combustion may benefit from being located within a cluster. If the capture site is associated with oxygen separation units onsite, collateral gases such as nitrogen and argon could be sold to industrial clients in close proximity.
- The implementation of pre-combustion works best if hydrogen can be produced on-site or in the proximity to a facility producing hydrogen.

Decision 8

		Location - population (can be decided only if greenfield)	
		Inhabited	Isolated
Capture or separation technology	Post-combustion	🟩	■
	Oxyfuel combustion	🟩	■
	Pre-combustion	🟩	🟩
	Gas separation	🟩	🟩

- Post-combustion with amines carries the risk of pollution with amine compounds from the flue stack. Accurate testing of amine emissions must be carried out on the flue stream, especially when the plant is located within a highly populated area.
- In case of oxyfuel combustion, the Air Separation Unit required for the production of oxygen should generally be located away from densely populated areas, mainly due to the associated high risk of explosion and fire.

Decision 9

		Public engagement	
		Extensive	Limited
Project type	Greenfield	🟩	🟧
	Brownfield	▩	🟧
CO_2 destination	EOR	▩	🟧
	Geol. storage: oil/gas reservoir	▩	🟧
	Geol. storage: saline aquifer	▩	🟧
	Utilisation	▩	▩
Capture or separation technology	Post-combustion	🟩	🟧
	Oxyfuel combustion	▩	🟧
	Pre-combustion	▩	🟧
	Gas separation	▩	🟧
Location - population	Inhabited	🟩	🟧
	Isolated	▩	🟧

A high level of stakeholder engagement is always highly advised. In some cases, it is especially important for the success of the project.

Depending on project type:

- Brownfield projects are generally better received by the public than greenfield project, as they aim at solving an existing problem (emissions). Therefore, more extensive public engagement may be required by greenfield projects.

Depending on CO_2 destination:

- EOR and geological storage may pose more risk to the surrounding population than utilisation and therefore require more engagement with the public.
- Additionally, onshore storage often faces more public opposition than offshore storage and thus requires a more extensive engagement with the local population.

Depending on capture or separation technology:

- Post-combustion with amines carries the risk of pollution with amine compounds from the flue stack and therefore requires more intense engagement and transparency with local communities.

Depending on location - population:

- The implementation of CCUS in densely populated locations will require a larger effort and more extensive public engagement.

Decision 10

		Plan of future expansion	
		Expansion	No expansion
Project type	Greenfield	■	□
	Brownfield	□	□
Location - industrial activity	In cluster	□	□
	Dispersed	■	□

The intention to further develop the CCUS project at a later stage should be made clear early on during the initial planning phase. While expansion and upscaling of the CCUS facility is generally advisable, it might be more complex for facilities affected by space constraints.

Depending on project type:

- Space for the installation of CCUS equipment and for future CCUS expansion is easier to allocate on greenfield sites. The planning of greenfield sites should assign sufficient space for the installation of future equipment.

Depending on location - industrial activity:

- If industrial sites are located in close proximity to one another (e.g. in a cluster), there may be less space available around the site for future CCUS expansion.

Decision 11

		Construction design approach	
		Modular	Custom-built
Project type	Greenfield	■	□
	Brownfield	□	□
Location - industrial activity	In cluster	■	□
	Dispersed	□	□
Location - population	Inhabited	□	□
	Isolated	■	□

A modular approach is always highly advised, to the highest extent suitable, as this is generally more conducive to driving lower costs.

Depending on project type:

- Brownfield projects may present restrictions on the maximum size of modules that can be moved around onsite.

Depending on location - industrial activity:

- Sites in dispersed locations may present restrictions on the maximum weight and size of the loads (and modules) that can be transported to the site.

Depending on location - population:

- The location in a scarcely populated area (isolated) can negatively impact the availability of skilled workforce, placing therefore more value on modularity.

Decision 12

		Integration of utilities	
		High degree of integration	Low degree of integration
Sector	Power	■	▨
	Chemical industry	▨	▨
	Gas processing industry	▨	▨
	Other industry	■	▨
Project type	Greenfield	■	▨
	Brownfield	▨	▨

Depending on sector:
- Integration of utilities is especially advised for sites where power or heat surplus are readily available (e.g. power industry, cement, waste incineration, etc.).

Depending on project type:
- The integration of utilities is easier for greenfield projects and should be the more natural choice.

Decision 13

		Consideration of permit timescales	
		Thorough	Simplified
Project type	Greenfield	🟩	🟧
	Brownfield	🟢	🟧
CO_2 destination	EOR	🟢	🟧
	Geol. storage: oil/gas reservoir	🟩	🟧
	Geol. storage: saline aquifer	🟩	🟧
	Utilisation	🟢	🟧
Capture or separation technology	Post-combustion	🟩	🟧
	Oxyfuel combustion	🟩	🟧
	Pre-combustion	🟢	🟧
	Gas separation	🟢	🟧
Location - industrial activity	In cluster	🟧	🟢
	Dispersed	🟢	🟧
Location - population	Inhabited	🟢	🟧
	Isolated	🟧	🟢
Commercial stakeholders	Large number	🟩	🟧
	Small number	🟢	🟧

Consideration of timescales for permitting is extremely critical for all CCUS projects.

Depending on project type:

- As brownfield projects might be more welcome than greenfield projects, timescales of permitting for greenfield projects might be comparatively longer.

Depending on CO_2 destination:

- Timescales of permitting for geological storage are always critical, especially if geological storage is located in areas with special environmental status.

Depending on capture or separation technology:

- Capture technologies that are first of a kind (FOAK) or polluting are more likely to encounter difficulties in permitting.

Depending on location - industrial activity:

- More attention is dedicated to industrial development of clusters and a speedier permitting process is expected to also be in place for clusters, reducing permitting timescales.
- A dispersed capture site structure might encounter difficulties with permitting if located in areas with special environmental status.

Depending on location - population:

- Being located in a populated area may result in a lengthier permitting process.

Depending on commercial stakeholders:

- The involvement of a large number of commercial stakeholders is likely to increase the timescales for permitting.

Finally, questions around operation of a CCUS facility are addressed in decision blocks 14 to 20.

Decision 14

		Coordination of capture and storage	
		Thorough	Simplified
CO_2 destination	EOR	🟩	🟧
	Geol. storage: oil/gas reservoir	▨	🟧
	Geol. storage: saline aquifer	▨	▨
	Utilisation	▨	▨

- A timely and reliable supply of CO_2 to the storage or utilisation site is critical. This is especially true if CO_2 is destined to EOR, where CO_2 capture volumes and well operations must be carefully matched.

Decision 15

		Preparation for initial start-up	
		Thorough	Simplified
Sector	Power	🟩	🟧
	Chemical industry	▨	🟧
	Gas processing industry	▨	🟧
	Other industry	🟩	🟧

- Planning of the initial start-up and transition to operation is always critical. In particular for those sectors which have limited experience and competency in operating chemical industrial plants (e.g. power sector and other industries).
- Initial start-up can be delivered by an external company.
- Performing a staged start-up is also a useful strategy to reduce risk at commissioning of the facility.
- A risk prevention/mitigation plan should always be in place.

Decision 16

		Schedule of maintenance stops	
		Thorough	Simplified
Sector	Power	🟩	🟧
	Chemical industry	▨	🟧
	Gas processing industry	▨	🟧
	Other industry	🟩	🟧
Capture or separation technology	Post-combustion	🟩	🟧
	Oxyfuel combustion	🟩	🟧
	Pre-combustion	▨	🟧
	Gas separation	▨	🟧

Scheduling and coordinating maintenance stops is highly critical for processes that depend on continuous operation, especially in the power sector and some industries. Additionally, it is imperative that a separate plan for regular and emergency shutdowns is in place.

<u>Depending on sector</u>:

- Scheduling maintenance stops is especially critical in the power sector, where the load factor of the site is particularly relevant in the business model of the project.

<u>Depending on capture or separation technology</u>:

- Start-ups and shutdowns might be complex for some technologies (such as post-combustion and oxyfuel combustion) and must therefore be carefully planned.

Decision 17

		Operations personnel capacity	
		Large crew	Small crew
Sector	Power	🟩	▨
	Chemical industry	▨	▨
	Gas processing industry	▨	▨
	Other industry	🟩	▨
Location vs. Population	Inhabited	▨	🟧
	Isolated	🟧	▨

There is no optimal number of personnel required to operate a capture site and this will depend on the technology and on strategic decisions of the operating company.

<u>Depending on sector</u>:

- For FOAK technologies or sectors with little experience in running a chemical plant, a larger number of operators is advised, in order to mitigate risks.

<u>Depending on location - population</u>:

- Sites located in isolated areas should be able to design the capture site to be operated by a smaller workforce, in order to reduce operational costs.

Decision 18

		Consideration of by-products and pollution	
		Thorough	Simplified
Capture or separation technology	Post-combustion	🟩	🟧
	Oxyfuel combustion	▨	▨
	Pre-combustion	▨	▨
	Gas separation	▨	▨

- Extensive planning of the handling of by-products may be required for some capture technologies, such as post-combustion technologies utilising amines. "Exhaust" amines will need to be regularly replaced and transported to a treatment facility.
- Potential environmental pollution deriving from some capture technologies should be carefully considered, also in accordance with national and local regulations. For example, there is a significant risk of amine compounds utilised in post-combustion to escape the flue stack and contaminate the surrounding area. Risk mitigation practices and extensive parameter monitoring may be required.

Decision 19

		Parameter monitoring	
		Thorough	Simplified
Capture or separation technology	Post-combustion	🟩	🟧
	Oxyfuel combustion	▨	🟧
	Pre-combustion	▨	🟧
	Gas separation	▨	🟧

- The flue gas stream composition should be monitored before and after capture, due to health and safety requirements and for controlling technical specifications. This is especially the case when utilising amine technologies, the degradation of which can be greatly impacted by potential flue gas contaminants.

Decision 20

		Preparation for final shut-down	
		Thorough	Simplified
CO_2 destination	EOR	🟩	🟧
	Geol. storage: oil/gas reservoir	🟩	🟧
	Geol. storage: saline aquifer	🟩	🟧
	Utilisation	🟧	▩
Capture or separation technology	Post-combustion	▩	🟧
	Oxyfuel combustion	▩	▩
	Pre-combustion	▩	▩
	Gas separation	▩	▩

- Both capture site decommissioning and storage site closure need to be organised in the planning phase of the project. This is particularly relevant for capture plants with larger environmental footprint and for sites injecting CO_2 in geological storage or for EOR.

3 Key success factors

An overview of the lessons learned and of the best practices for construction, commissioning and operation of large-scale CCUS is reported in the summary below. All information was gathered from consultation with stakeholders involved in the construction and operation of successful CCUS projects and from publicly available sources.

Summary of lessons learned on the constructability and operations of large-scale CCS projects

Business & regulatory framework

The business case and regulatory framework sets the ecosystem for the realisation of a CCS project. A successful CCS project must ensure a sound business case, long-term economic viability and revenue streams, financial & regulatory support and ensure involvement of all stakeholders including local community engagement in early stage of the project.

Capture technology selection

Capture technology selection is based on the application, sector (power or industry), flue gas composition, required avoidance rate and the emissions regulations in a specific region. Testing different capture technologies prior to commercial scale on own flue-gas is a key success factor. In some industries, utilisation of an in-house capture technology can make the business case more viable.

Cross-chain coordination

Critical coordination of timelines, efforts, liabilities amongst different stakeholders across the CCS value chain. This includes capture and transport infrastructure readiness, storage sites appraisal and availability and ensuring a long-term steady demand for CO_2 are all aligned with the commencement of capture operation.

Site location

The impacts of a specific site location must be accounted for in the construction planning, activities, transportation mode, permits, environmental assessment and personnel availability. Remote sites might be more appealing in terms of community acceptance but poses personnel availability challenges. Similarly, sites present within an industrial cluster will benefit from shared infrastructure and driving the overall project costs down.

Design criteria

Design approach will be highly dictated by the type of facility; new vs. retrofit. A typical full-chain CCS project will involve four key design pieces that need to be designed carefully: access to flue gas, conditioning of CO_2, transport of CO_2 offsite and its final storage/destination. In terms of construction design, high levels of modularity and off-site fabrication will deliver minimal risk and cost.

Construction site management

Common construction best practises are applicable for CCS projects. However, extra care should be given to permitting related to the usage amine-based products and CO_2 storage at site under specific pressure conditions. Clear definition of extra security and/or HSE measures and site ownership should be communicated to all stakeholders.

Operation and Maintenance (O&M)

Planning and simulations should be in place whenever possible to account for all operational aspects. These include aspects related to plant efficiency, maintenance programs, personnel availability and operational capacity, monitoring sensors installation and control rooms as well as by-products and waste handling procedure.

Plant integration

Integrating capture plant with the host site will have an impact on different processes, plant efficiency and flexibility. This is a key design aspect particularly critical for power plants. Optimal integration of heat and power utilities is another important aspect. Whenever possible and technically-feasible, utilisation of existing infrastructure must be maximised.

Plant commissioning and start-up

The transitional phase from the completion of plant construction to commissioning and commercial operations is very critical especially for retrofitted facilities. Interruption should be minimised through intensive planning of the transition-to-operation phase. Clear procedures for normal and emergency start-up and shutdown must always be available for the operating crew.

Shutdown and decommissioning

Early planning for site decommissioning is key to managing liabilities, risk allocation and ownership. Detailed plans for capture site decommissioning and storage site closure should be in place and communicated during the planning phase.

4 Reasons for cancellation

The main reasons behind the cancellation of unsuccessful large-scale CCS projects are reported in this chapter and can be summarised in the below categories.

Lack of long-term economic viability can be a showstopper for any large-scale CCUS project. Ensuring long-term revenue streams while accounting for other dynamics and uncontrollable factors like Carbon prices, Oil and Gas prices, declining renewable energy costs is a critical factor in project economics. In the power sector, coal power plants have increasingly been seen as uncompetitive compared to natural gas combined cycle units. Hence, there is a need to understand the long-term competitiveness of the technology in a wider market outlook.

Over-reliance on government subsidies can be risky but also often vital. CCUS projects must ensure continuous and systematic political support over their long timelines. This challenge was observed across many regions including UK, Norway and the USA where change in political direction impacted government support and its withdrawal led to project failure. This inconsistent nature of government support has also reduced trust of private investors. In most cases, the absence of direct commercial benefits from CCUS projects makes government grants, initiatives and support programs pivotal in the long-term project success.[2]

Uncertainty around risk management and allocation. Liability has always been cited as a significant barrier to the wide scale deployment of CCUS and is instrumental to the management of operators' and regulators' risk exposure. This becomes of elevated importance for large investments required for offshore CO_2 storage. Recent studies[3] proposed putting more emphasis on the role of the private and insurance sectors as a potential solution to this problem describing it as "a commercial approach to CCUS-specific liabilities".

For CCUS full-chain projects[4], there are specific risks that can lead to project cancellation. These are related to having multiple project developers at different stages of the value chain, which entails extra coordination in the areas below:

- Cross-chain liabilities definition and default risk allocation across all stakeholders.
- Identifying clear responsibilities and ownership of obtaining permitting, operating consents and licensing across all stakeholders.
- Commercial integration of stakeholders at various phases of the chain. This becomes more critical if there is a cross-sector collaboration between power, oil and gas and chemical sectors, which is a very common case in full-chain projects.
- Coordination of the design and construction activities of the key interconnections and interfaces between capture, transport and storage infrastructure.
- And finally, the technical integration of the key components comprising the full chain.

Technical integration and compatibility when scaling up from pilot or demonstration to commercial scale. This is particularly relevant when attempting to bring together many FOAK technologies at scale. This has proven to be challenging to integrate and can result in an overall incompatible set of technologies, unaccounted for by-products and reliability issues. This can be mitigated through capture technology testing on actual flue gas and through choosing mature and tested technologies. In some cases, modelling and building simulators has proven valuable in bringing to light unknown start-up and operation problems.

Construction-related reasons and design approach

- A lack of experience with building FOAK facilities and even NOAK plants is an issue with the capital risk of deployment.
- For brownfield sites, huge cost reductions can be achieved through the re-use of existing infrastructure and optimal integration of heat and power utilities between the main and capture sites.
- While custom-made designs are necessary for retrofit plants, they usually requires a lot of onsite fabrication adding to the overall construction price tag. Therefore, maximum modularisation levels combined with offsite manufacturing – whenever possible – should always be adopted.
- With the rise of digitalisation and the plethora of AI and IoT applications, there is a huge potential for cost reduction in construction phase. Building 3D objects and rapid prototyping can help streamline a lot of the design stages, reduce time, effort and the need for extra personnel.

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[2] MIT Report : Lessons Learned from CCS Demonstration and Large Pilot Projects
[3] GCCSI – Lesson and perceptions: Adopting a commercial approach to CCS liability.
[4] White Rose Full-chain Lessons Learned Report

Evaluating technology options to mitigate greenhouse gas emissions

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