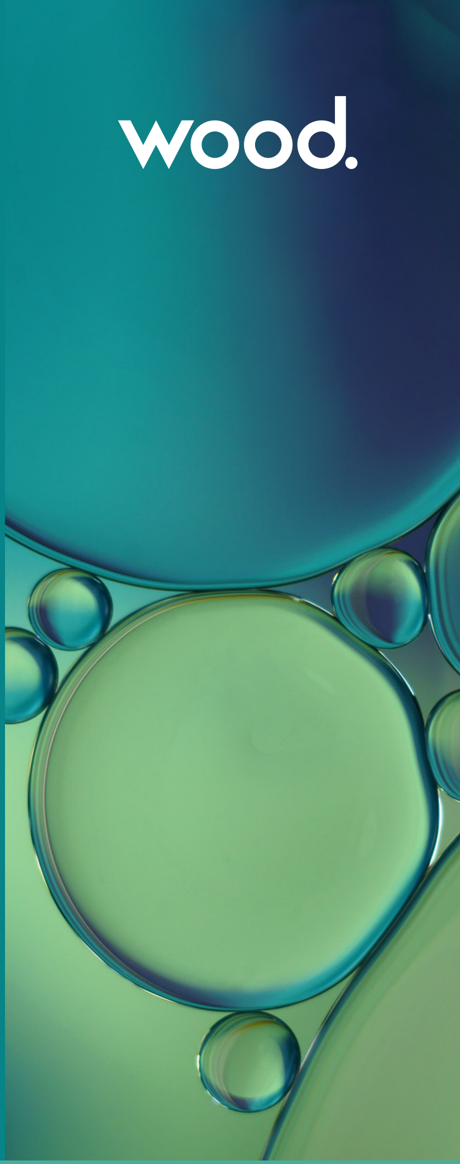
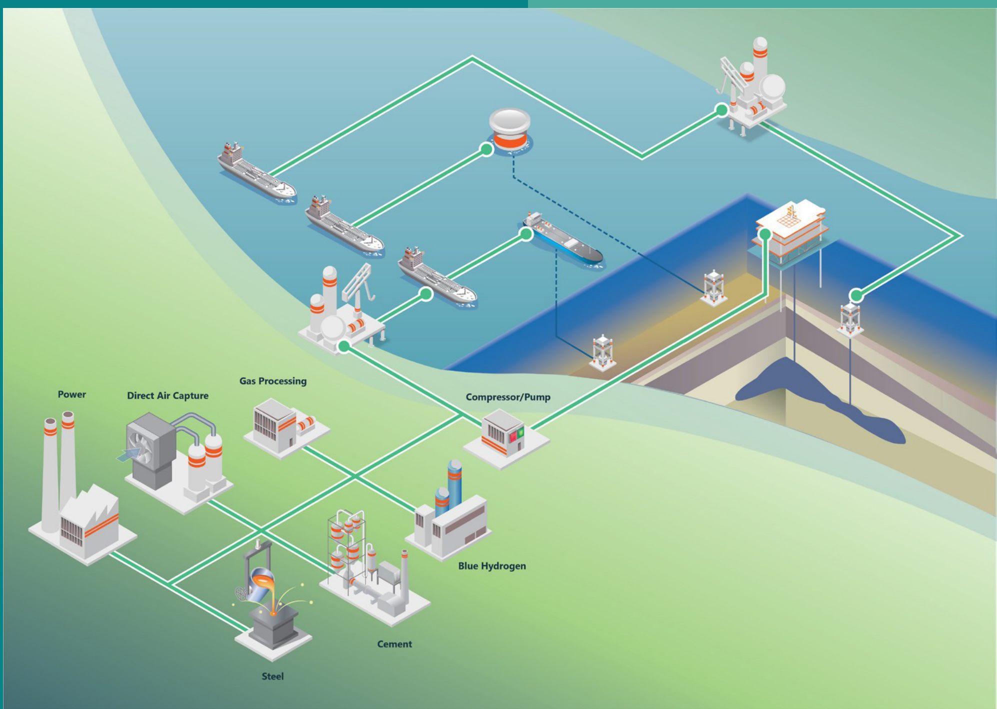
wood.

Industry Guidelines for Setting the CO_2 Specification in CCUS Chains



Introduction to the Guidelines



JIP Members

aramco
equinor
fluxys
GASSCO
Harbour Energy
OMV
MITSUBISHI HEAVY INDUSTRIES
Net Zero Technology Centre
Technology Driving Transition
PETRONAS
TotalEnergies
DNV
HERIOT WATT UNIVERSITY
IFE
NGI
NPL National Physical Laboratory
TÜV SÜD nel
wood.

September 2024

Preface

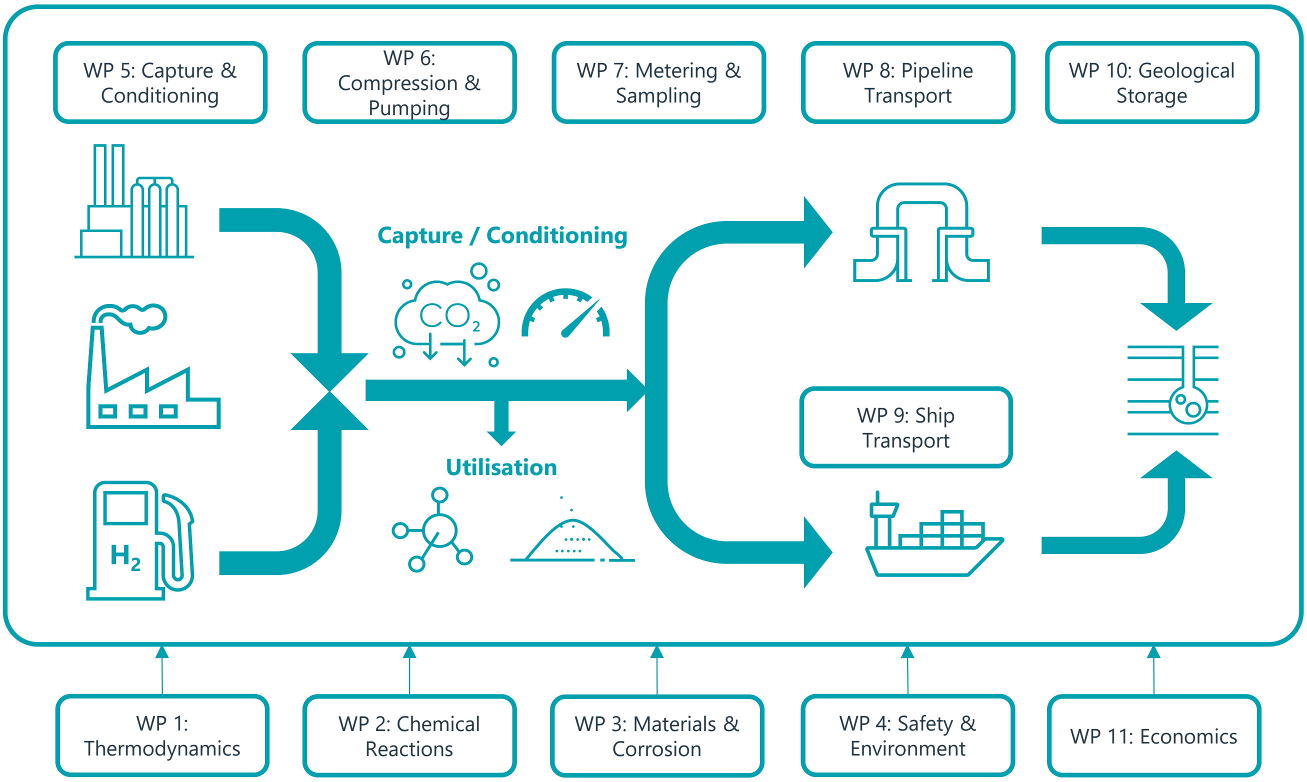
Carbon Capture, Utilisation and Storage (CCUS) is one of the key pathways towards net-zero goals and significant growth is expected in this industry to meet these demands.

The presence of impurities in captured CO_2 impacts the cost and operation of CCUS. A CO_2 Specification represents the maximum allowable level of impurities within a CO_2 stream to ensure safe and cost-effective CCUS chains from capture through to storage.

To support the successful development of CCUS, a Joint Industry Project (JIP) has been formed to provide guidance in setting CO_2 Specifications for CCUS projects.

A series of Work Packages was performed across the CCUS value chain including key areas such as thermodynamics, reaction chemistry and material corrosivity. Each Work Package produced a Guideline report providing current knowledge on the impact of impurities in CCUS.

This report is part of a suite of deliverables and should be read in conjunction with the other Guideline reports which can be downloaded from the Wood website at www.woodplc.com/insights/reports/Industry-Guidelines-for-Setting-the-CO2-Specification-in-CCUS-Chains.



Feedback on the JIP guidelines is welcomed, please get in touch via the link on the above website or directly via CO2SpecJIP@woodplc.com.

Client
CO2 Specification JIP
Document Title
Introduction to the Guidelines
Document Number
522240-WP12-REP-001

Revision	Date	Reason for Issue	Prepared	Checked	Approved
2	20/09/2024	Issued for Use	T. Evans-Gavhure	C. Phillips	C. Phillips
1	05/07/2024	Issued for Use	S. Florence	T. Evans-Gavhure	C. Phillips
0	03/06/2024	Issued for Review	R. Laing	C. Phillips	C. Phillips

Table of Contents

1.0 Introduction 7
1.1 JIP Objective 7
1.2 JIP Members 7

2.0 JIP Scope 9
2.1 JIP Work Packages 9
2.2 Introduction 10
2.3 Work Package 1: Thermodynamics [1] 10
2.4 Work Package 2: Chemical Reactions [2] 11
2.5 Work Package 3: Materials & Corrosion [3] 11
2.6 Work Package 4: Safety & Environment [4] 12
2.7 Work Package 5: Capture & Conditioning [5] 12
2.8 Work Package 6: Compression & Pumping [6] 13
2.9 Work Package 7: Metering & Sampling [7, 8] 13
2.10 Work Package 8: Pipeline Transport [9] 14
2.11 Work Package 9: Ship Transport [10] 14
2.12 Work Package 10: Geological Storage [11] 15
2.13 Work Package 11: Economics [12] 15

3.0 Setting the CO_2 Specification for a CCUS Chain 16
3.1 CO_2 Specification Workflow Diagram 16
3.2 CO_2 Specification Workflow Diagram - Worked Example 21

4.0 References 41

List of Figures

Figure 2-1: CO_2 Specification JIP Work Packages 9
Figure 3-1: Workflow diagram for setting the CO_2 Specification for a CCUS chain. 20
Figure 3-2: Project scope CCS block diagram. 21
Figure 3-3: RFCC flue gas with carbon capture & conditioning flow scheme. 36
Figure 3-4: CCGT power plant with carbon capture & conditioning flow scheme. 36
Figure 3-5: Blast furnace with carbon capture & conditioning flow scheme. 37
Figure 3-6: Direct air carbon capture & conditioning flow scheme. 37

List of Tables

Table 3-1: CO_2 Sources Raw / Flue Gas Compositions 22
Table 3-2: SPECIFICATION Iteration 0 23
Table 3-4: CO_2 Transport Limits Iteration 1 – (FOR EXAMPLE PROJECT USE ONLY) 26
Table 3-5: SPECIFICATION Iteration 1 – (FOR EXAMPLE PROJECT USE ONLY) 27
Table 3-6: Captured CO_2 Compositions from Each CO_2 Source to the T&S 29
Table 3-7: Limits for Additional Capture & Pre-Treatment Impurities – (FOR EXAMPLE PROJECT USE ONLY) .30
Table 3-8: SPECIFICATION Iteration 2 – (FOR EXAMPLE PROJECT USE ONLY) 31
Table 3-9: SPECIFICATION Iteration 2 vs CO_2 Compositions to T&S 1st Check - – (FOR EXAMPLE PROJECT USE ONLY) 32
Table 3-10: Exceeded SPECIFICATION Limits – (FOR EXAMPLE PROJECT USE ONLY) 34
Table 3-11: SPECIFICATION Iteration 3 vs Conditioned CO_2 Compositions to T&S 2nd Check – (FOR EXAMPLE PROJECT USE ONLY) 39
Table 3-12: Final Project CO_2 Specification – (FOR EXAMPLE PROJECT USE ONLY) 40

Abbreviations

Term	Description
BF	Blast Furnace
BOG	Boil-Off Gas
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation & Storage
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COS	Carbonyl Sulphide
CPA	Cubic Plus Association
CRA	Corrosion Resistant Alloy
CS	Carbon Steel
DAC	Direct Air Capture
DCC	Direct Contact Cooler
EOS	Equations of State
ESP	Electro-Static Precipitator
GERG	European Gas Research Group
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulphide
H_2SO_4	Sulphuric Acid
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HF	Hydrogen Fluoride

Term	Description
HP	High Pressure
HP	High Pressure
HWPVT	Heriot-Watt University Hydrate and Phase Equilibria Software
IMO	International Maritime Organization
JIP	Joint Industrial Project
LCOA	Levelised Cost of CO_2 Abatement
LLE	Liquid-Liquid Equilibrium
LP	Low Pressure
MEA	Monoethanolamine
MMV	Measurement, Monitoring and Verification
MP	Medium Pressure
ND	Not Detected
NO	Nitric Oxide
NO_X	Nitrogen Oxides
O_2	Oxygen
OPEX	Operating Expenditure
PHAST	DNV Proprietary Dispersion Model
ppm mol	Parts per million by mole
ppmv	Parts per million volume
PR	Peng-Robinson
RFCC	Residue Fluid Catalytic Cracker
SCC	Stress Corrosion Cracking
SCR	Selective Catalytic Reduction
SIGTTO	Society of International Gas Tanker and Terminal Operators
SMR	Steam Methane Reforming
SNCR	Selective Non-Catalytic Reduction
SO_X	Sulphur Oxides
SRK	Soave-Redlich and Kwong
T&S	Transport & Storage
TCM	Technology Centre Mongstad
TOC	Total Organic Carbon
VLE	Vapour-Liquid Equilibrium
VOCs	Volatile Organic Compounds
WP	Work Package
ZEP	Zero Emissions Platform

1.0 Introduction

This report is an introduction to the "Industry Guidelines for Setting the CO_2 Specification in CCUS Chains" and includes:

- The objective of the Joint Industry Project (JIP) and list of constituent members (see Section 1.0)
- A scope summary of the JIP Work Packages (WPs) and location for downloading the guidelines plus an explanation of the accompanying Signposting Tool (see Section 2.0)
- A methodology for setting a CO_2 specification for a CCUS chain including a logic workflow diagram and a worked case study example (see Section 3.0)

1.1 JIP Objective

Carbon Capture, Utilisation and Storage (CCUS) is one of the key pathways towards net-zero goals and significant growth is expected in this industry to meet these demands.

The presence of impurities in captured CO_2 can adversely affect the material integrity, operation and injectivity in CCUS chains. Therefore impurity limits need to be set to create safe and effective CCUS chains. A CO_2 Specification represents the maximum allowable level of impurities within a CO_2 stream that emitters must meet in order to gain entry to a transportation and injection network.

Setting the CO_2 specification for a CCUS project requires an understanding of the impact of impurities across the full CCUS value chain. A JIP was therefore formed to collate current knowledge surrounding impurities and to create guidelines to support industry when setting a CO_2 specification for their CCUS projects.

These JIP guidelines have been made publicly available to support the growth of the CCUS industry by providing an understanding of the required CO_2 conditioning to meet safety, environmental, technical and operational requirements of the entire chain.

The main focus of these guidelines is to sequester CO_2 into geological storage. Whilst utilisation technologies such as mineralisation or speciality chemicals are not directly addressed within the work packages, much of the guidance will remain relevant to utilisation applications.

The guidelines shall not be considered as a substitute for regulations or legislation and it is the responsibility of the user to assess the specific risks in application of these guidelines.

Note, the guidelines are specifically focussed on the impact of impurities within CCUS as opposed to general carbon capture and storage guidance.

1.2 JIP Members

The JIP was formed between the following companies who jointly own the guidelines:

- Aramco Overseas Company B.V.
- Equinor Energy AS
- Fluxys Belgium SA
- Gassco AS
- Harbour Energy plc
- Mitsubishi Heavy Industries Ltd
- Net Zero Technology Centre Limited (NZTC)
- Shell Global Solutions International B.V.
- TotalEnergies EP Norge AS

- OMV (Norge) AS
- Petroliam Nasional Berhad
- Wood Group UK Ltd

A Steering Committee was created from representatives of the above companies (excepting NZTC) to administer the management of the JIP.

The JIP collaborated with the following research and industry experts to provide a comprehensive and holistic understanding of the impact of impurities across the CCUS chain.

- DNV Services UK Limited
- Heriot Watt University
- IFE (Institute for Energy Technology)
- NGI (Norwegian Geological Institute)
- National Physical Laboratory (NPL)
- TÜV NEL (National Engineering Laboratory)

2.0 JIP Scope

2.1 JIP Work Packages

The JIP has executed a series of Work Packages to cover the full value chain of CCUS, considering capture of CO_2 from various industrial sources and transportation via different options through to permanent sequestration in geological storage. Additional cross-chain Work Packages including Thermodynamics, Reaction Chemistry and Materials & Corrosion were created to underpin the entire CCUS chain (see Figure 2-1).

The guidelines target the cost optimisation of CCUS chains by recognising the interdependence between the various elements in a CCUS chain and performing only the CO_2 conditioning necessary to meet safety, environmental and operational robustness of the chain.

Each Work Package provides a comprehensive report where the current knowledge on the impact of impurities is given and opportunities for further research identified. As a suite of reports, these guidelines will support users in their understanding of the impact of impurities and aid in the setting of a CO_2 specification for CCUS projects.

A summary of the scope of each of the Work Packages is given in the following sections.

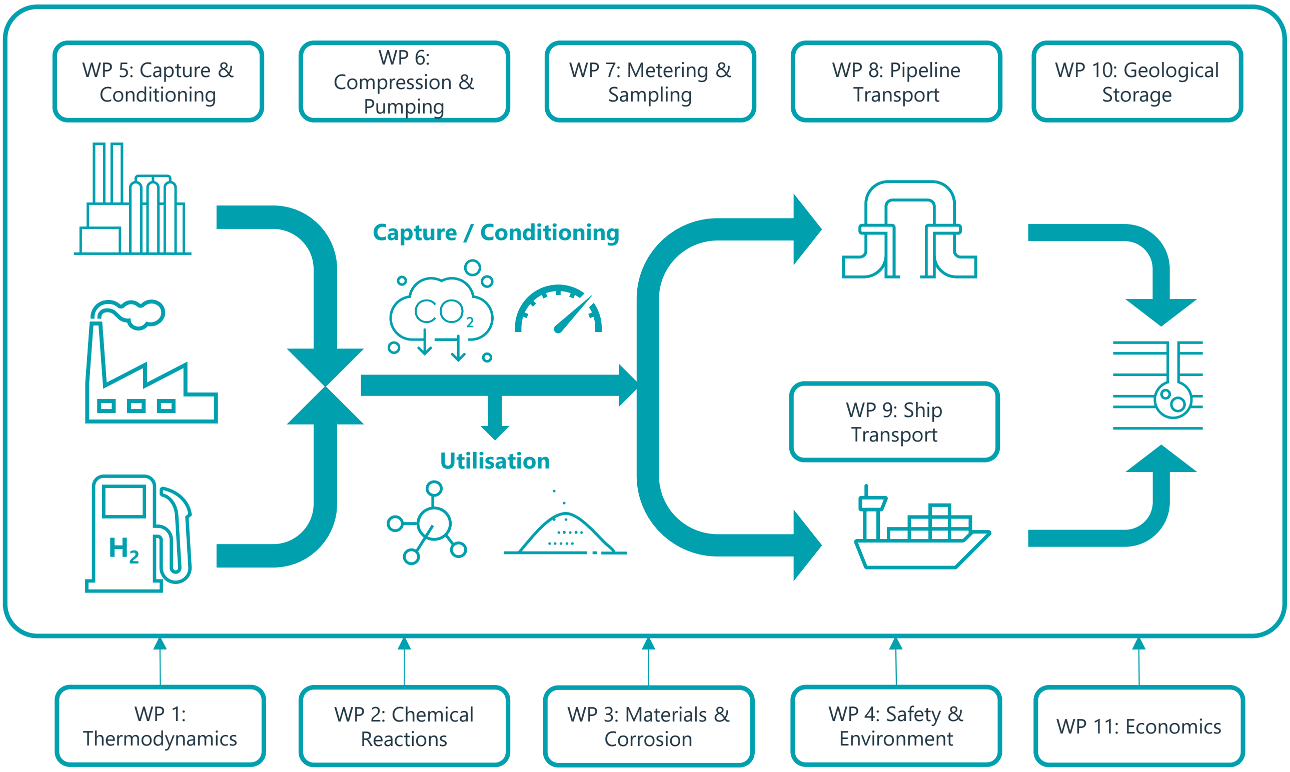


Figure 2-1: CO_2 Specification JIP Work Packages

2.1.1 Guidelines Download Location

All deliverables from the JIP can be downloaded from the Wood webpage at the link below.

https://www.woodplc.com/insights/reports/Industry-Guidelines-for-Setting-the-CO2-Specification-in-CCUS-Chains

To download, users will be asked to supply their name, email address, industry and purpose for downloading. This information will help the JIP understand how the guidelines are distributed into industry and will allow users to be advised of any future updates to the reports or future JIP phases. The user email address shall only be used for JIP related information. A facility will be provided for users to opt-out of future communications on request.

2.1.2 Guidelines Feedback

The JIP welcomes comments on the guidelines, which users can provide by clicking the Send Feedback button on the webpage. Alternatively users can provide feedback by directly emailing CO2SpecJIP@woodplc.com.

2.1.3 Guidelines Signposting Tool

A Signposting Tool accompanies the guidelines, which directs users to specific sections of the JIP guidelines that may be relevant to their CCUS chain, based on impurities present in source industries selected by the user.

This tool can be launched from the CO_2 Specification webpage via the Access Signpost Tool button located under the Work Package descriptions. The tool uses an intuitive web-based which interface allows the user to select from a broad range of industries feeding the CCUS chain, from power generation to direct air capture.

Depending on the different industries selected, the tool determines which impurities may be present and provides hyperlinks to sections of interest within the guidelines reports. On clicking these links the full work package report is opened at the relevant section.

Note: The tool assumes typical impurities from each industry which may not be representative in each case. The provided links to report sections are not exhaustive and the signposting tool should not be considered a substitute for a full review of all the guidelines.

2.2 Introduction

This Introduction to the guidelines will guide you through the suite of work packages which have been created to address the full CCUS value chain, from capture of industrial sources of CO_2 and transportation via different options through to geological storage. Additional key work packages are included which underpin the entire CCUS chain, including Thermodynamics, Reaction Chemistry and Materials & Corrosion.

Key contents of this report include:

- The objective of the JIP and introduction to the team of industry and research contributors.
- A summary of the suite of JIP Work Packages.
- A step-by-step methodology for setting a CO_2 Specification with a worked case study example.

2.3 Work Package 1: Thermodynamics [1]

The Thermodynamic Work Package provides a comprehensive and systematic analysis of the thermodynamic impact of impurities within CO_2 and offers guidelines for selecting the most appropriate equations of state and benchmark data for modelling CO_2 systems. The work package also identifies the knowledge gaps and the potential risks associated with the lack of data and inaccurate modelling.

The work package uses the models developed at Heriot Watt University in their thermodynamics tool HWPVT. These models include cubic, multiparameter, and hybrid equation-of-states, as well as models for transport properties and solid formation. These models are considered as the state-of-the art for CO_2 thermodynamics.

The work package performed a literature review of available experimental data for CO_2 binary mixtures and multicomponent mixtures, and compared them against the predictions of the HWPVT models. The results show the accuracy and limitations of different models for various properties and impurities. These results are summarised within the report and are detailed in a number of supplementary spreadsheets covering different thermodynamic, physical and transport properties. In each spreadsheet, modelling deviations are shown in tabular and graphical format across a range of temperature and pressure conditions for available binary and multicomponent mixtures. A spreadsheet is also provided for pseudo-experimental data for a range of applications across the CCUS chain to support users in checking the quality of their own models.

Key contents of the Thermodynamics Report includes:

- Generation of a representative list of impurities that can exist in CO_2 streams, categorized by their nature and behaviour
- 1.5 million experimental data points were gathered from literature for over 30 CO_2 impurities and a gap analysis was performed on the availability of experimental data
- Error margins between an advanced modelling tool and available experimental data is reported
- Data generated using the best available thermodynamic models for CCUS applications is provided for users without access to well-tuned models or large experimental data sets
- Guidelines for selecting the most appropriate modelling approach

2.4 Work Package 2: Chemical Reactions [2]

Impurities within CO_2 streams can chemically react with their environment and with each other to create products which can adversely affect CCUS design and operation. Some reactions may produce products which cause plugging and injectivity issues, whilst others may impact material integrity through corrosion and cracking.

This Chemical Reactions Report was developed with expertise from IFE and key contents include:

- Identification of the main reactions occurring within CCUS chains and categorization into acid formation, sulphur producing and solid forming reactions
- A review of solubility and precipitation of impurities and reaction products in dense and gaseous CO_2 phases, such as water, glycols, alcohols, sulphur, acids, ammonium carbamate, and salts
- A summary of published data and available reaction models
- A summary of published CO_2 specifications and recommendations comparing the maximum concentrations for various impurities, including H_2O, H_2S, CO, O_2, SO_X, NO_X, and NH_3
- Suggestions for further research to address current knowledge gaps

2.5 Work Package 3: Materials & Corrosion [3]

CO_2 streams in CCUS projects can originate from various sources, such as power plants, industrial emitters, and natural gas production and may use different capture technologies, such as pre-combustion, post-combustion, and oxyfuel. These sources and technologies can result in different types and levels of impurities in the CO_2, such as water, oxygen, nitrogen, sulphur and hydrogen compounds. These impurities can affect the phase behaviour, corrosivity, and integrity of the materials used within the CCUS chain.

The Materials & Corrosion Work Package report outlines the main challenges and recommendations for materials selection and corrosion control for each element of the CCUS chain, based on the available standards, guidelines, and research data.

This Materials & Corrosion Report was developed with expertise from Shell and key contents include:

- Impact of impurities on low temperature embrittlement and running ductile fracture in pipelines
- Selection of corrosion resistant alloys and non-metallic materials for specific conditions
- Controlling the CO_2 specification to prevent acid and sulphur drop-out
- Applying a risk-based approach and integrity operating windows for each corrosion loop, and conducting testing and monitoring of the CO_2 composition and corrosion rates
- Identification for gaps in current knowledge and guidance for future research

2.6 Work Package 4: Safety & Environment [4]

Safety and environmental management considerations are paramount throughout the CCUS chain. This work package explores the effects impurities may have on potential CO_2 releases and dispersion and to provide guidance on effective modelling and risk review.

The Safety & Environment report was developed with support from DNV and key contents include:

- A review of CO_2 exposure safety limits and threshold data applied to occupational health and safety assessment worldwide and the impact of impurities on CO_2 toxicity and safety thresholds
- A review of consequence and risk-based assessment methodologies and tools for modelling CO_2 releases, including the application use of safety distances and exclusion zones as safeguards for CCUS infrastructure
- A demonstration of the effect of impurities on CO_2 dispersion modelling using the DNV PHAST model for different environmental conditions and release scenarios

2.7 Work Package 5: Capture & Conditioning [5]

CO_2 streams from different industries have a wide variance in CO_2 concentration and can be accompanied by a range of different impurities.

The Capture & Conditioning work package provides guidance on the types of impurities expected in CO_2 streams and their impact on carbon capture technologies and presents processes typically used to remove impurities from CO_2 streams.

Key contents of the report include:

- The range of impurities which may be anticipated from different industry sources
- A review of flue gas impurity measurement methods
- A review of the main carbon capture technologies
- The impact of impurities on the performance of CO_2 capture and conditioning processes
- A review of data from test facilities such as Technology Centre Mongstad on expected impurity levels from CO_2 capture plants
- Feedback from Capture Licensors on modelling software limitations and prediction of impurities in CO_2 product streams
- A review of impurity removal technologies
- The impact of impurities on liquefaction processes
- A decision flow chart for CO_2 purification and liquefaction requirements
- A flow chart methodology for selection of capture and & conditioning processes

- Gaps in knowledge and guidance for future research

2.8 Work Package 6: Compression & Pumping [6]

Compression and pumping are essential for pressurising CO_2 for processing and transport and to meet the injection pressures required for geological storage. Compression and pumping cover a range of CO_2 phases from liquid and vapour through to supercritical conditions. Impurities can directly affect the thermodynamic and physical properties of CO_2 and can impact materials and seal selection.

The Compression & Pumping work package explores the impact of impurities on compression and pumping equipment design and operation.

Key contents of the report include:

- An introduction to the use of pumps and compressors across the CCUS chain
- A review of the non-ideal behaviour of CO_2 and the impact of impurities on the design and performance of rotating equipment
- A discussion on the factors that influence the compressor and pump design and selection, such as pressure ratio, interstage cooling, seal type, material selection and operating point
- Addition of case studies to demonstrate the impact of impurities on CO_2 pumping and compression

2.9 Work Package 7: Metering & Sampling [7, 8]

Confident measurement and control of CO_2 through the CCUS chain relies on traceably accurate and reliable metering and sampling. Impurities present in the CO_2 stream can affect this accuracy and understanding the precise composition, nature and the consequences of impurities present is important for regulatory reporting, custody transfer, commercial allocation, process control and storage measurement, monitoring and verification (MMV).

The Metering & Sampling work package provides a detailed discussion of the various available metering technologies and suitable analysis techniques (online and offline) applicable for the various impurities present in the CCUS gas streams.

The Metering report was prepared with support from TÜV SÜD National Engineering Laboratory (NEL). Key contents include:

- Flow measurement upstream of capture plant: The report describes the direct and indirect methods for measuring the mass of CO_2 entering the capture plant, and the techniques for determining the biogenic fraction of the captured CO_2
- Flow measurement downstream of capture plant: The report discusses the design considerations and the available technologies for measuring the flow of CO_2-rich streams downstream of the capture plant, and the quality assurance requirements for accurate and reliable measurement
- Flow meter calibration strategies: The report explores various calibration strategies for flow meters, such as proving using process medium, using transferrable laboratory medium, and non-flow calibration methods, and their advantages and limitations
- Standards, guidelines and regulations for CCUS measurements: The report summarises the existing standards, guidelines and regulations and identifies the gaps and challenges that need to be addressed to facilitate the development and implementation of CCUS projects

The Sampling report was prepared with support from the National Physical Laboratory (NPL). Key contents of the report include:

- Sampling locations: Identification of appropriate sampling locations across the CCUS chain including additional points that may be required for regulatory, custody transfer, or operational purposes

- Sampling methods: A review of direct and indirect sampling methods for CO_2 streams across the CCUS chain. It also provides guidance on general considerations for effective sampling
- Analysis methods: A review of techniques for online and offline analysis of CO_2 impurities, such as gas chromatography, liquid chromatography, mass spectrometry, spectroscopy, and sensors. It also recommends the suitable techniques for different impurities based on their concentration range, sensitivity, selectivity, and performance criteria

2.10 Work Package 8: Pipeline Transport [9]

The Pipeline Transport Work Package discusses how the presence of impurities can affect phase behaviour, water solubility and hydrate formation of CO_2 streams, and how these factors can influence the design and operation of CO_2 pipelines.

The report was supported technically by Fluxys and key contents include:

- A review and comparison of applicable codes and standards on CO_2 pipeline design and identification of gaps and challenges
- The impact of impurities on the pipeline operating envelope and management of two-phase CO_2 transport
- Suitability of repurposing existing pipelines and umbilicals for CO_2 transmission in the presence of different impurities
- Material selection and corrosion management: Guidance on selecting materials for CO_2 pipelines, considering the corrosion and cracking risks associated with different impurities and conditions. It also recommends corrosion monitoring and mitigation strategies for ensuring long-term integrity
- Brittle and ductile fracture propagation and arrest in CO_2 pipelines, and the effects of hydrogen impurities on the fracture toughness and fatigue performance of pipeline materials. It includes methods for fracture control assessment and material qualification
- Pre-commissioning and operation: Best practices for pre-commissioning, line-filling, venting, and managing off-specification fluid in CO_2 pipelines. It also highlights the challenges and uncertainties involved in these processes and the need for further research and development

2.11 Work Package 9: Ship Transport [10]

Impurities present in CO_2 can affect shipping operations through their impact on phase behaviour, solubility and potential for chemical reactions affecting the material integrity and solid formation.

The Ship Transport Work Package explores the current knowledge of the impact of impurities with respect to corrosion, cargo handling and management.

The report was technically supported by DNV and key contents include:

- A review of existing industry guidelines and standards for CO_2 shipping and highlights ongoing initiatives by IMO, SIGTTO, and ZEP to develop guidance for CO_2 ship and terminal operators
- A discussion of publicly available CO_2 specifications for ship-based transport
- A discussion on the current practice and specifications for ship-based transportation of liquified gases and the implications of impurities to the design and operation of CO_2 carriers
- A discussion on the considerations on shipping of CO_2 streams; including CO_2 transport conditions, material selection for CO_2 applications and the implications of impurities to the design and operation of CO_2 carriers
- The report also identifies knowledge gaps and recommends areas for further research such as impurity

solubility limits, potential chemical reactions and acid drop-out at low temperatures

2.12 Work Package 10: Geological Storage [11]

The Geological Storage work package explores the physical and chemical impacts of impurities within reservoirs, including the effects on capacity, injectivity and integrity of the storage complex.

This work package/report was supported with input from NGI and IFE and key contents include:

- Review of geological impacts from CO_2 impurities, such as enhanced mineral dissolution or precipitation, changes in CO_2 properties, interfacial tension, phase boundaries, microbial activity, storage performance and particulates. A risk impact summary table for each of the impurities is included
- Recommendations to storage asset owners to conduct a system and supply chain impurity review, a system modelling of CO_2 properties and phase behaviour, and laboratory and pilot trials of representative systems to determine the optimal CO_2 specification for their reservoirs
- A review of existing standards and guidelines for setting CO_2 composition for geological storage and identification of knowledge gaps and areas for further work research, including guidance on CO_2 contaminants, the variability of CO_2 composition along the CCUS chain, the site-specific characteristics of the reservoir and the caprock, and the long-term behaviour and interactions of CO_2 impurities in the subsurface

2.13 Work Package 11: Economics [12]

To meet a CO_2 specification for a CCUS chain may require the removal or reduction of impurities. Minimising the cost of additional conditioning is a key part of providing a safe and cost effective CCUS chain. This Economics work package provides guidelines for calculating the levelized cost of CO_2 abatement (LCOA) for different capture and impurity removal technologies and identifies several factors that can influence the LCOA of a CCUS project.

Also provided are order of magnitude costs and LCOA data for some of the main impurity removal technologies, such as dehydration, oxygen removal, cryogenic distillation, flue gas desulphurisation, selective catalytic reduction, hydrogen sulphide removal, and mercury removal. Trade-offs between the cost of impurity removal and the cost of designing the CCUS system to tolerate the impurity are also discussed.

3.0 Setting the CO_2 Specification for a CCUS Chain

A methodology for setting a CO_2 Specification for a CCUS project is presented below. This methodology has been designed to be used in conjunction with the work package guidelines to support users in developing their own CO_2 specifications.

The methodology and supporting workflow diagram provide a holistic logical approach that can be followed to determine the optimum CO_2 specification and impurity risk management strategy for the given project. The approach presented accounts for impurity impacts across the CCUS chain and directs to relevant work packages for each step in the workflow.

It is recognised that identifying all the impurities that may be present in a CCUS chain can be challenging and requires close collaboration with all stakeholders including emitters, licensors, vendors and transport and storage operators. When impurities are not identified within a CO_2 specification, it is generally acknowledged that they are not acceptable within the chain. However, should further emitters later join a CO_2 hub, or other impurities later become evident, CCUS projects may need to revise their specification accordingly.

3.1 CO_2 Specification Workflow Diagram

A workflow diagram for setting a CO_2 specification is presented in Figure 3-1. The workflow consists of several stages of Identification, Evaluation, and Selection activities, through which a specification can be iterated to achieve the most cost effective and sustainable results for a given CCUS chain. The work package guideline reports relevant for supporting each activity step are highlighted in bold.

In order to illustrate how the workflow may be used to produce a CCUS chain CO_2 specification, a worked example has been produced by applying the methodology and is presented in Section 3.2.

Key Note

The example given in this section for setting the CO2 Specification is provided to demonstrate the workflow only and the final specification produced is <u>not</u> intended as a recommendation for use by the reader.

This example is based on a fictitious project and several assumptions are made to reflect project information and decisions that are not detailed here.

Users must conduct their own due diligence and risk assessment when producing their own CO_2 specification.

With reference to Figure 3-1, each step of the workflow is described below:

PROJECT SCOPE

- Establish core scope of the CCUS chain project including CO_2 sources, transport method(s) and storage site. Establish key fixed parameters which may include project specifications such as minimum CO_2 purity, CO_2 footprint and transport rates.

IDENTIFICATION I

- Identify the CO_2 sources and their parameters.
- Emitter type: combustion type and fuel/gas type; typical impurities are indicated in **WP5: Capture and Conditioning** but should be confirmed by sampling and analysis which can be supported by **WP7: Metering and Sampling**.

- Suitable thermodynamic package identification allows modelling of CO_2 with impurities and ensures accurate assessments can be made, **WP1: Thermodynamics** can support this identification, this should also consider potential reactions and expected operating conditions.
- Reactions between impurities and or with CO_2 can introduce further impurities and will depend on the impurity concentrations present as well as the expected operating conditions, **WP2: Reaction Chemistry** can support this identification.
- Consider if the CO_2 is collected from a single or multiple sources, multi-source needs to consider interaction of impurities between sources when the streams are mixed.
- All components present in source emissions have potential to reach the CO_2, even if at extremely low levels, and thus all these components should be identified and receive a specified limit within the specification.

IDENTIFICATION II

- Identify the CO_2 permanent storage(s) and their parameters, this can be supported by **WP10: Geological Storage**.
- Storage type: saline aquifer or depleted hydrocarbon reservoir.
- Rock geology and reservoir chemistry: formation rock mineralogy, reservoir fluids, site geology, cap rock porosity, etc.
- Reaction chemistry impact on reservoir and well performance, including injectivity, formation of solids, biological growth, corrosion of well materials, potential hydrate formation when injecting into gas depleted reservoirs etc.
- Consider impact of any new impurities such as chemicals for well performance / operation.
- Location: Onshore or offshore, depth, existing wells infrastructure & locations.

For the purposes of this example, it is assumed that the project has performed the necessary analysis to address the impact of impurities on the wells and reservoir and no changes to specification are required.

IDENTIFICATION III

- Identify the CO_2 transport method(s) and their parameters.
- Transport methods: gas pipeline, dense phase pipeline, shipping (LP, MP or HP regimes), rail, road tanker or combination of these. Pipeline development and shipping development can be supported by **WP8: Pipeline Transport** and **WP9: Ship Transport** respectively.
- Locations & distance: identify locations of CO_2 sources and storage, identify access to shipping and existing pipelines, rail and roads, identify travel distances and potential routes for transport methods.
- Safety: toxicity should be maintained no worse than for CO_2, flammability is generally not an issue, **WP4: Safety and Environment** can support safety assessments.
- Metering & sampling: **WP7** can support identification of suitable metering and sampling of CO_2, limits should be measurable else the CO_2 quality cannot be assured.
- Compression equipment: impurities can impact the power and size of equipment but are not likely to dictate removal requirements, **WP6: Compression and Pumping** can support identification of compression equipment and key considerations.
- Liquefaction: required for batch transport methods such as shipping, rail and road tanker transport, managing boil off gas will be a key consideration with impurities, **WP5** can support identification of liquefaction schemes and key considerations.
- Materials of Construction: different materials have different tolerances to impurities, with higher tolerance materials generally being more expensive, carbon steel vs stainless steel for example. As a

starting point, projects may wish to consider the most economic material selection first and iterate up to more expensive materials as part of the iterative evaluation. **WP3: Materials and Corrosion** can support material selection.

- Re-Use: projects may identify infrastructure for re-use within the CCUS chain, this will have existing materials which should be identified and thus provide some applicable limits to allow its safe re-use.

IDENTIFICATION IV

- As per IDENTIFICATION I, but additionally considering impurities removed and added by the CO_2 capture type(s).
- Capture chemicals and degradation products have potential to reach the CO_2, even if at extremely low levels, and thus all these components should be identified and receive a specified limit within the specification.
- Introduction of additional components may introduce new and different reactions, changes to operating conditions may also impact these.
- A different thermodynamic package may be required to consider these extra components and any additional operating conditions.
- A baseline composition to Transport and Storage (T&S) should be identified, this will be further iterated with the specification.

IDENTIFICATION V

- Identify the exceeded specification(s) and which requirement(s) are producing the limit, this will allow assessment if there is potential to change the limit or if the impurity must be removed.
- Identify the full additional conditioning requirements to meet the specification. **WP5** can support this activity.
- Identify the changes to T&S infrastructure required to raise the specification limit(s) to avoid additional conditioning requirements. **WP3**, **WP4**, **WP5, WP8**, **WP9** & **WP10** can support this activity.
- Identify any trade-off points where some additional conditioning and some infrastructure changes may result in a more optimum solution.

EVALUATE I

- Based on the identified geology and reservoir chemistry of the storage evaluate how the expected impurities will impact the storage site's integrity, capacity and injectivity, and then from this establish suitable impurity limits as applicable. **WP10** can support this activity. These limits also apply to the well design and completion materials which may require more onerous limits than the reservoir itself.
- Based on identified transport infrastructure of the transport methods evaluate how the expected impurities will impact the transports' integrity, capacity, flow assurance, and safety. From this establish suitable impurity limits as applicable. **WP3**, **WP4**, **WP5, WP6**, **WP7**, **WP8** & **WP9** can support this activity.
- Impurities can impact the CO_2 capture performance and make some technologies more suitable than others. Evaluate how the expected impurities will impact capture, what type(s) will be optimal and what if any pre-treatment(s) will be required to optimise the capture process. WP5 can support this activity.

EVALUATE II

- Evaluate the impact of additional CO_2 conditioning to meet the specification, this includes both technical and economic impacts i.e. additional chemical and energy requirements, pressure drop, removal efficiency, any new impurities introduced, waste disposal, CAPEX & OPEX. **WP5** and **WP11: Economics** can support this activity.
- Evaluate the impact of increasing the tolerance of the T&S infrastructure to the impurities above specification, this includes both technical and economic impacts i.e. higher tolerance materials, impacts on boil-off gas management, ensuring integrity and capacity, ensuring flow assurance, changes to compression/metering, toxicity and other safety impacts, CAPEX & OPEX. **WP3**, **WP4**, **WP5, WP6**, **WP7**, **WP8**, **WP9**, **WP10** & **WP11** can support this activity.
- Evaluate any potential optimal combinations of the above. As well as technical feasibility and economics, the solutions should consider the sustainability and environmental impact on the full chain. **WP3**, **WP4**, **WP5**, **WP6**, **WP7**, **WP8**, **WP9**, **WP10** & **WP11** can support this activity.

SELECT I

- Based on the evaluation outcomes select the most appropriate capture and pre-treatment technologies for each capture source to optimise the design technically, economically, and sustainably.
- The selection procedure is intended to be an iterative process.

SELECT II

- Based on the evaluation outcomes select the most appropriate conditioning technologies and T&S infrastructure to optimise the design technically, economically, and sustainably.
- The selection procedure is intended to be an iterative process.

SPECIFICATION

- The CO_2 specification for the project scope is iterated by following the workflow until an optimum for the chain is reached with all components within specified limits.
- Limits should be realistically achievable, measurable, account for all potential impurities from the chain and consider the key areas listed. As well as technical feasibility and economics, the limits should consider the sustainability and environmental impact of the full chain.
- Ultimately CCUS chain projects must satisfy themselves that the selected specifications reduce the project risk to sufficiently low levels through appropriate risk assessment activities.

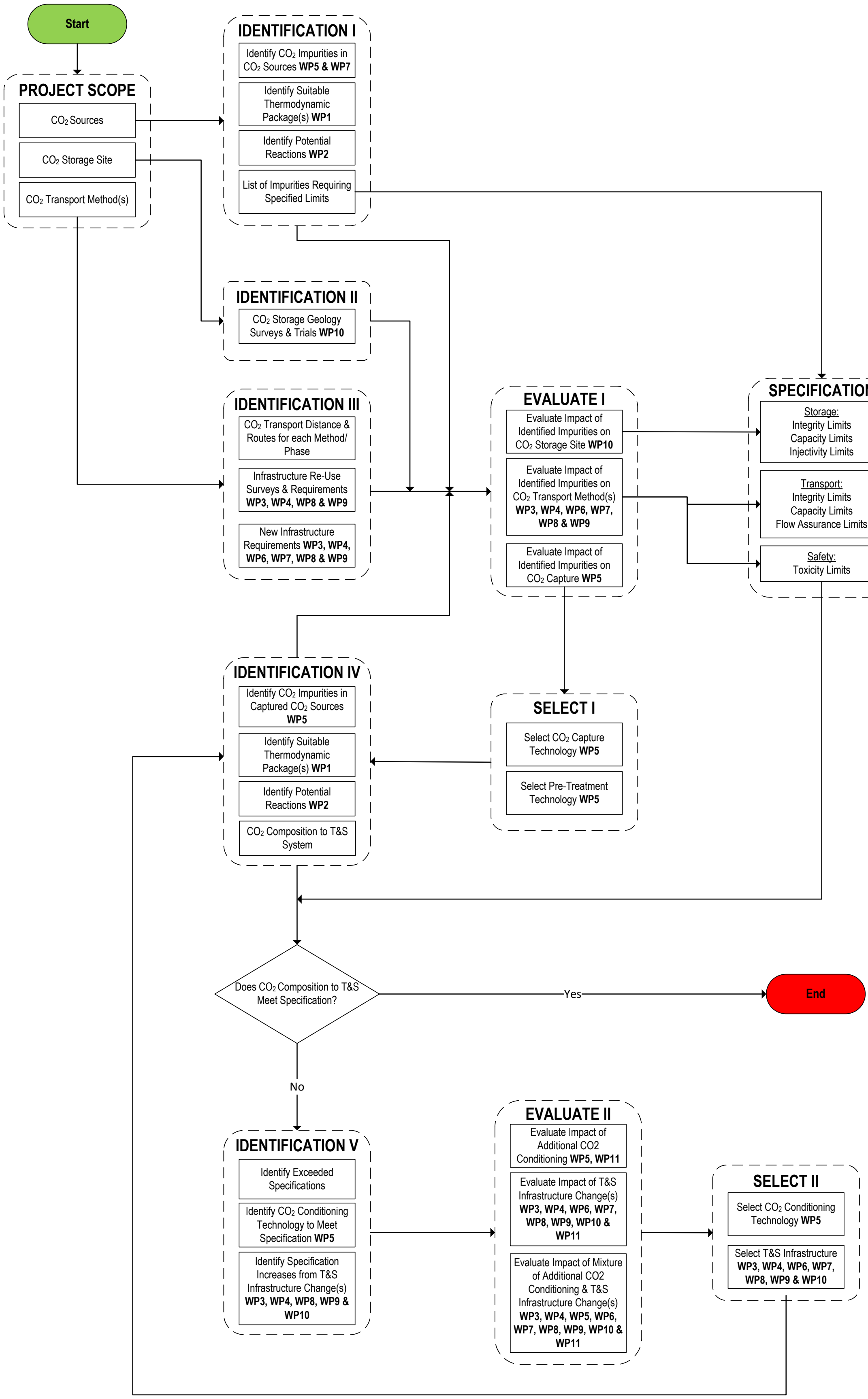


Figure 3-1: Workflow diagram for setting the CO_2 Specification for a CCUS chain.

3.2 CO_2 Specification Workflow Diagram - Worked Example

Using the methodology described in Section 3.0 and the workflow diagram from Figure 3-1, a worked example has been prepared and is presented in this section.

Key Note

The example given in this section for setting the CO2 Specification is provided to demonstrate the workflow only and the final specification produced is not intended as a recommendation for use by the reader.

This example is based on a fictitious project and several assumptions are made to reflect project information and decisions that are not detailed here.

Users must conduct their own due diligence and risk assessment when producing their own CO_2 specification.

PROJECT SCOPE

The example project assumes the following information:

- CO_2 Sources = Various local industrial emitters
- CO_2 Storage Site = Large offshore storage facility with some existing infrastructure to be assessed for re-use for CCS.
- CO_2 Transport Method(s) = Core transportation will be shipping based, taking CO_2 from the various emitter locations to a central hub located in proximity to the offshore storage site, with final transportation by pipeline to the injection wells.
- CO2 minimum purity in specification is assumed for the example project to be 95% minimum. However, given that shipping will form part of the transport chain, it shall be set as the "balance" between 100% and the maximum level of impurities as set by the CO_2 specification.

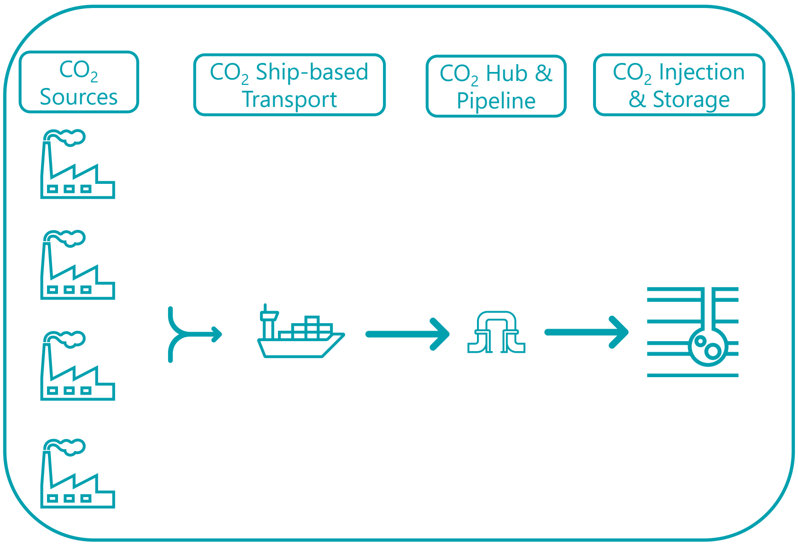


Figure 3-2: Project scope CCS block diagram.

IDENTIFICATION I

A number of emitter sites from across industry in the local region are identified as potential CO_2 sources for the project. After negotiations with the various operators, agreements are reached for four emitter sites to supply the CCUS chain. These consist of CO_2 captured from each of the following: Refinery RFCC, CCGT Power Plant, Steel Plant Blast Furnace, and a Direct Air Capture Plant.

Following guidance in WP5 each of the emitters are classified by combustion type and fuel/gas type:

- Refinery RFCC – post-combustion, coal & oil
- CCGT Power Plant – post-combustion, clean gas
- Steel Plant Blast Furnace (BF) – post-combustion, coal & oil and process CO_2
- Direct Air Capture (DAC) Plant – no combustion, air

Based on the emitter type classifications an initial list of possible impurities expected is shown in Table 3-1 (taken from WP5 Table A.1 [5]).

Sampling and analysis of each of the raw/flue gases is also performed with reference to guidance in WP7 [7, 8] to further confirm the impurities present and provide inlet compositions for the capture of the gases' CO_2. The following compositions are identified:

Table 3-1: CO_2 Sources Raw / Flue Gas Compositions

Component	Units	RFCC	CCGT	BF	DAC[1]
CO_2	mol%	13.0 to 14.5[1]	3.5 to 3.9	24.4[1]	0.035
H_2O	mol%	Saturated	7.1 to 7.5	Saturated	0 to 4
N_2	mol%	73 to 79	74.9 to 75.0	47.1[1]	78.1
O_2	mol%	3 to 8	12.8 to 13.5	0.0	20.9
Ar	mol%	-	0.9	0.6	0.9
NO_X	ppm mol	100	26 to 29	-	-
SO_X	ppm mol	<5	1.4	0.2	-
CO	ppm mol	<10	0 to 87	23.5 mol%[1]	-
NH_3	ppm mol	<1	-	0.2	-
H_2	ppm mol	-	-	4.3 mol%[1]	-
CH_4	ppm mol	-	-	238	-
H_2S	ppm mol	-	-	10	-
COS	ppm mol	-	-	32	-
HCl	ppm mol	-	-	0.2	-
HCN	ppm mol	-	-	0.1	-
Other Noble Gases	ppm mol	-	-	-	<25
Other Non-Noble Gases	ppm mol	-	-	-	<3
Particulates	μm	$0.8x10^6$ parts/cm^3	0 mg/Nm^3	1 to 10 mg/Nm^3	Unknown

Notes:

1. Reported on dry basis

With reference to the impurities present in the compositions an assessment of potential reactions is performed referring to guidance in Section 7.0 WP2 [2]. This identifies that water, O_2, NO_X, SO_X, NH_3, H_2S, COS, HCl and HCN are present as potential reactants. Therefore, formation of acids, such as sulphuric, nitric and hydrochloric, may be a concern for corrosion. Additionally, there is potential for solids production in the form of sulphur and ammonium salts. The production of these acids and salts would need to be controlled to sufficient levels to limit formation, therefore specification limits will be applied to the reactants to minimise reaction and thus no limits need applied to the reaction products.

A suitable thermodynamic package is then identified for the components, reactions, and conditions possibly present with reference to guidance in WP1 [1]. This identifies:

- Polar components (H_2O, alcohols, glycols) - CPA for VLE/LLE and hydrates
- Non-condensables, traces and hydrocarbons (including aldehydes and ketones) - Cubic EOS (PR/SRK) for VLE/LLE
- Density, speed of sound, heat capacity and Joule-Thomson coefficient - Extended GERG EOS
- Viscosity - Lennard-Jones model
- Dry ice – Any EOS/Model from above

All the components identified require a limit within the SPECIFICATION and thus may be updated to a list of these components as follows:

Table 3-2: SPECIFICATION Iteration 0

Component	Units	Limit
CO_2	mol%	Note 1
H_2O	ppm mol	?
N_2	ppm mol	?
O_2	ppm mol	?
Ar	ppm mol	?
NO_X	ppm mol	?
SO_X	ppm mol	?
CO	ppm mol	?
NH_3	ppm mol	?
H_2	ppm mol	?
CH_4	ppm mol	?
H_2S	ppm mol	?
COS	ppm mol	?
HCl	ppm mol	?
HCN	ppm mol	?
Other Noble Gases	ppm mol	?
Other Non-Noble Gases	ppm mol	?
Particulates	μm	?

Notes

1. Whilst the CO_2 minimum purity is set by the shipping element as "Balance"(i.e. the limit between 100% pure CO_2 and the level of dissolved impurities), the minimum purity of CO_2 from the capture stage is assumed as 95% minimum.

IDENTIFICATION II

In this project example, the CO_2 storage site is identified as a depleted hydrocarbon reservoir 80 km offshore and at a depth of 3 km. It is assumed geological surveys are available from previous use as a hydrocarbon reservoir, and that further surveys and trials have been conducted to further identify the mineralogy and current reservoir fluids as necessary per guidance in WP10. Existing wells are also identified to allow evaluation for use for CO_2 injection.

IDENTIFICATION III

In this project example, the emitters selected as CO_2 sources for the CCUS chain have been partly selected due to their proximity to marine access for shipping, as such minimal onshore pipeline transport is required from the emitter to the marine loading facilities. The project example assumes medium pressure level shipping will be employed which shall provide the bulk of the transport from each emitter site to the central transport hub. Final transportation from the hub to the injection wells will be provided by a subsea pipeline. Shipping requires that the CO_2 is liquified prior to loading, as such liquefaction is required at each emitter site. The unloaded liquid CO_2 will then be pumped to dense phase through the subsea pipeline and injected into the wells. An existing subsea pipeline has been identified for possible re-qualification for CO_2 transport. New pumping, metering, and sampling facilities will be required along the transport chain.

The transport concept is developed with reference to the relevant WPs; pipelines WP8, shipping WP9, compression and pumping WP6, liquefaction WP5, materials WP3, safety WP4, metering & sampling WP7.

The key elements of the CCUS chain identified from IDENTIFICATION I through III are:

- CO_2 emitters/sources
- CO_2 capture & conditioning at each emitter/source
- CO_2 sampling & metering at each emitter/source, post-capture, post-compression/liquefaction, post-transportation, and injection wellheads, as well as at custody transfer locations along the chain
- CO_2 liquefaction at each emitter/source
- CO_2 onshore buffer storage at each emitter/source
- CO_2 shipping from at each emitter/source to central hub
- CO_2 onshore buffer storage at central hub
- CO_2 buffer storage boil-off gas management
- CO_2 compression to dense phase at central hub
- CO_2 dense phase subsea pipeline from central hub to injection wells at permanent storage site, with potential re-use of existing pipeline
- CO_2 injection wells and geological storage site, with potential re-use of injection wells and infrastructure

EVALUATE I

In this example, it is assumed that the project performed an evaluation of the mineralogy and reservoir properties identified in IDENTIFICATION II against the list of possible impurities identified in IDENTIFICATION I. A discussion of such an evaluation process is given in Work Package 10 – Geological Storage regarding a review of the system chain requirements, reservoir modelling and laboratory and pilot trials (see Sections 8.1, 8.2, 8.3 and Table 8-1 in WP10 [11]). This review assumed to have taken place in this project example would have assessed the impact of impurities on integrity, capacity, plume dispersion and injectivity of the storage as well as include laboratory analysis. In addition the assessment would have included the impurity impact on the Joule-Thomspon low temperature effect when injecting into a gas depleted reservoir and any impact on well materials and well cements. With reference to the above the following limits for the reservoir were assumed:

Table 3-3: CO_2 Storage Limits Iteration 1 – (FOR EXAMPLE PROJECT USE ONLY)

Component	Units	Storage Limit
CO_2	mol%	Balance
H_2O	ppm mol	≤50
N_2	ppm mol	≤ 40,000 (as part of total non-condensables
O_2	ppm mol	≤10
Ar	ppm mol	(see N_2 for total non-condensables)
NO_X	ppm mol	≤ 100
SO_X	ppm mol	≤ 50
CO	ppm mol	(see N_2 for total non-condensables)
NH_3	ppm mol	?
H_2	ppm mol	≤ 10,000 (see N_2 for total non-condensables)
CH_4	ppm mol	≤10,000 (see N_2 for total non-condensables)
H_2S	ppm mol	≤ 10
COS	ppm mol	?
HCl	ppm mol	?
HCN	ppm mol	?
Other Noble Gases	ppm mol	Total Non-condensables <40,000
Other Non-Noble Gases	ppm mol	
Particulates	µm	≤1 to 7

The transport infrastructure identified in IDENTIFICATION III are evaluated against the list of possible impurities identified in IDENTIFICATION I with reference to guidance in WP3, WP4, WP5, WP6, WP7, WP8, and WP9. Impurity limits are developed to protect the mains areas of impact: integrity, capacity and flow assurance of the transportation and to ensure operational safety. Transport limits identified were as follows:

Table 3-4: CO_2 Transport Limits Iteration 1 – (FOR EXAMPLE PROJECT USE ONLY)

Component	Units	Pipeline Limit[1]	Liquid / Shipping Limit[2]	Safety Toxicity Limit[3]	CS Materials Limit[4]
CO_2	mol%	>95	Balance	-	Balance
H_2O	ppm mol	≤50	≤20	-	≤50
N_2	ppm mol	Total N_2, Ar, H_2, CH_4, CO ≤40,000	Total N_2, Ar, H_2, CH_4 ≤2,000	-	-
O_2	ppm mol	≤10	≤10	-	≤10
Ar	ppm mol	See N_2	See N_2	-	?
NO_X	ppm mol	≤2.5	≤1.5	≤50	≤2.5
SO_X	ppm mol	≤4[4]	≤10	≤50	≤4[4]
CO	ppm mol	≤1,000 (see N_2)	≤100	≤2,000	≤1,000
NH_3	ppm mol	?	≤10	≤1,500	?
H_2	ppm mol	≤10,000 (see N_2)	500 (see N_2)	-	≤10,000
CH_4	ppm mol	See N_2	See N_2	-	?
H_2S	ppm mol	≤4[4]	≤5	≤300	≤4[4]
COS	ppm mol	H_2S + SO_2 + COS ≤20	≤5	≤300	H_2S + SO_2 + COS ≤20
HCl	ppm mol	?	Acid Forming Compounds (Cl_2, HF, HCl, HCN) <100 mg/Nm^3	≤150 mg/Nm^3	?
HCN	ppm mol	?		≤150 mg/Nm^3	?
Other Noble Gases	ppm mol	Total Non-condensables ≤40,000	See N_2	-	-
Other Non-Noble Gases	ppm mol			-	-
Particulates	µm	?	≤1	-	-

Notes:

1. Pipeline Limit from WP8 Pipeline Transport Appendix A3 Table A-3 [9].
2. Liquid / Shipping Limit from WP5 Capture and Conditioning Table 9-15 [5].
3. Safety Toxicity Limit from WP4 Safety and Environment Table 4-8 [4] (ppmv assumed equivalent to ppm-mol).
4. CS Materials Limit from Table 3-2 and Appendix C Table C-1 WP3 Materials and Corrosion provide suggested limits for pipeline transportation [3]. Note a maximum total limit of H_2S + SO_X of 4 ppm-mol is also given. For the purposes of this example project it is assumed that the total H_2S + SO_X limit will always be met at the blended CO_2 flowrates.

These impurity limits can be combined to provide the first full iteration of the SPECIFICATION. At this point it is possible some components may still not have a limit determined. Further surveys, trials, and assessments as necessary should be performed to establish suitable criteria for these.

Table 3-5: SPECIFICATION Iteration 1 – (FOR EXAMPLE PROJECT USE ONLY)

Component	Units	Limit	From
CO_2	mol%	95[1]	Capture[1]
H_2O	ppm mol	≤20	Liquid/Shipping
N_2	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
O_2	ppm mol	≤10	Chain
Ar	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
NO_X	ppm mol	≤1.5	Liquid/Shipping
SO_X	ppm mol	≤4	Pipeline, CS Materials
CO	ppm mol	≤100	Liquid/Shipping
NH_3	ppm mol	≤10	Liquid/Shipping
H_2	ppm mol	500 Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
CH_4	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
H_2S	ppm mol	≤4	Pipeline, CS Materials
COS	ppm mol	≤5	Liquid/Shipping
HCl	ppm mol	≤100 mg/Nm^3	Liquid/Shipping
HCN	ppm mol		
Other Noble Gases	ppm mol	See N_2 above	Liquid/Shipping
Other Non-Noble Gases	ppm mol		
Particulates	μm	≤1	Liquid/Shipping

Notes

1. Whilst the CO_2 minimum purity is set by the shipping element as "Balance"(i.e. the limit between 100% pure CO_2 and the level of dissolved impurities), the minimum purity of CO_2 from the capture stage is assumed as 95% minimum.

Based upon the raw/flue gas compositions identified in IDENTIFICATION I evaluation of suitable capture technologies and necessary pre-treatment conditioning can be performed with reference to guidance in WP5. This work considers the suitability based on inlet CO_2 concentration and operating conditions of the raw/flue gas, the quantity of CO_2 to capture and the presence of different impurities, as well as other techno-economic factors:

- **Refinery RFCC**
  - Low CO_2 concentration
  - SOx and particulates impurities present
  - High flow and temperature
  - Low pressure, and little pressure drop available
- **CCGT Power Plant**
  - Very low CO_2 concentration
  - NO_X impurities present
  - High flow and temperature
  - Very low pressure, and little pressure drop available

- **Steel Plant Blast Furnace (BF)**
  - High CO_2 concentration
  - High in CO and H_2
  - H_2S, SOx, COS, acid and particulates impurities present
  - High flow and temperature
  - Higher pressure and some pressure drop available
- **Direct Air Capture (DAC) Plant**
  - Extremely low CO_2 concentration
  - Air impurities only
  - Lower flow and ambient temperature
  - Atmospheric pressure, no pressure drop available

SELECT I

Based upon the evaluation findings in EVALUATE I the capture and pre-treatment technology for each CO_2 source is selected.

- **Refinery RFCC**
  - Pre-Treatment: Electrostatic Precipitator (ESP) to remove particulates
  - Capture: MEA Chemical Absorption suitable for high volume low CO_2 concentration, SOx within tolerable limits
- **CCGT Power Plant**
  - Pre-Treatment: Selective Catalytic Reduction (SCR) to reduce NO_X
  - Capture: Proprietary Amine Chemical Absorption suitable for high volume very low CO_2 concentration
- **Steel Plant Blast Furnace (BF)**
  - Pre-Treatment: Electrostatic Precipitator (ESP) to remove particulates
  - Capture: Sorbent Adsorption with high CO_2 selectivity versus CO and H_2, as well as tolerance to H_2S, SOx, COS, and acids
- **Direct Air Capture (DAC) Plant**
  - Pre-Treatment: None required
  - Capture: Potassium Salt Chemical Absorption & Calcium Chemical Looping bespoke for direct air capture application

IDENTIFICATION IV

From the capture and pre-treatment technologies selected the composition of the captured CO_2 can now be identified. Based on the emitter and capture type classifications an initial list of possible impurities expected in the captured CO_2 can be produced using WP5. Sampling and analysis of each captured CO_2 from pilots can also be performed with reference to guidance in WP7 to further confirm the impurities present. Captured CO_2 compositions will otherwise be provided by the capture licensor based on their technology expertise.

The following captured CO_2 compositions are identified, these constitute the first iteration of CO_2 compositions to the T&S system (from Table B.1 and Table 10-5 in WP5 [5]):

Table 3-6: Captured CO_2 Compositions from Each CO_2 Source to the T&S

<table>
<tr><th>Component</th><th>Units</th><th>RFCC</th><th>CCGT</th><th>BF</th><th>DAC</th></tr>
<tr><td>CO_2</td><td>mol%</td><td>≥99.9[a]</td><td>98.1</td><td>83[a]</td><td>95.8</td></tr>
<tr><td>H_2O</td><td>ppm mol</td><td>Saturated (~2 mol%)</td><td>1.9 mol%</td><td>Saturated (~2 mol%)</td><td>0.02 mol%</td></tr>
<tr><td>N_2</td><td>ppm mol</td><td>220 to 370</td><td>60</td><td>10.6 mol%[a]</td><td>2.34 mol%</td></tr>
<tr><td>O_2</td><td>ppm mol</td><td rowspan="2">17 to 36</td><td>19</td><td>0.0 mol%</td><td>1.84 mol%</td></tr>
<tr><td>Ar</td><td>ppm mol</td><td>ND</td><td>0.0 mol%</td><td>ND</td></tr>
<tr><td>NO_X</td><td>ppm mol</td><td>ND to ≤0.5</td><td>ND</td><td>-</td><td>-</td></tr>
<tr><td>SO_X</td><td>ppm mol</td><td>ND</td><td>ND</td><td>1.1</td><td>-</td></tr>
<tr><td>CO</td><td>ppm mol</td><td>ND</td><td>ND</td><td>5.3 mol%[a]</td><td>-</td></tr>
<tr><td>NH_3</td><td>ppm mol</td><td><10 to 60 (depending on degradation state of solvent)</td><td><0.1</td><td>0.05</td><td>-</td></tr>
<tr><td>H_2</td><td>ppm mol</td><td>ND</td><td>-</td><td>1.0 mol%[a]</td><td>-</td></tr>
<tr><td>CH_4</td><td>ppm mol</td><td>ND</td><td>-</td><td>ND</td><td>-</td></tr>
<tr><td>H_2S</td><td>ppm mol</td><td>-</td><td>-</td><td>50.8</td><td>-</td></tr>
<tr><td>COS</td><td>ppm mol</td><td>-</td><td>-</td><td>163</td><td>-</td></tr>
<tr><td>HCl</td><td>ppm mol</td><td>-</td><td>-</td><td>0.04</td><td>-</td></tr>
<tr><td>HCN</td><td>ppm mol</td><td>-</td><td>-</td><td>0.02</td><td>-</td></tr>
<tr><td>Other Noble Gases</td><td>ppm mol</td><td>-</td><td>-</td><td>-</td><td>ND</td></tr>
<tr><td>Other Non-Noble Gases</td><td>ppm mol</td><td>-</td><td>-</td><td>-</td><td>ND</td></tr>
<tr><td>Particulates</td><td>µm</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td></tr>
<tr><td>Acetaldehyde</td><td>ppm mol</td><td><10 to 25 (depending on degradation state of solvent)</td><td rowspan="7">Proprietary amine and degradation products are commercially sensitive (<10 for illustrative purposes)</td><td>-</td><td>-</td></tr>
<tr><td>Formaldehyde</td><td>ppm mol</td><td><1</td><td>-</td><td>-</td></tr>
<tr><td>MEA</td><td>ppm mol</td><td>ND</td><td>-</td><td>-</td></tr>
<tr><td>Amines</td><td>ppm mol</td><td>ND</td><td>-</td><td>-</td></tr>
<tr><td>Methanol</td><td>ppm mol</td><td>ND to 0.2</td><td>-</td><td>-</td></tr>
<tr><td>Ethanol</td><td>ppm mol</td><td>0.3 to 1.9</td><td>-</td><td>-</td></tr>
<tr><td>Other Alcohols</td><td>ppm mol</td><td>ND to 0.5</td><td>-</td><td>-</td></tr>
<tr><td>TOC</td><td>ppm mol</td><td>9.3 to 22</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>C6+</td><td>ppm mol</td><td>1.5 to 3.5</td><td>-</td><td>-</td><td>-</td></tr>
</table>

[a] Reported on dry basis

With reference to the impurities present in the compositions, an updated assessment of potential reactions is performed referring to guidance in WP2, noting components from capture and pre-treatment are now also present. This identifies that amines/MEA may present as reactants to form ammonium salts with CO_2, and that alcohols may help induce formation of an aqueous phase. The production of salts and aqueous drop out would need to be controlled by limiting these components to sufficient levels, therefore specification limits will be applied to the reactants to minimise reaction and thus no limits need applied to the reaction products.

Similarly, suitability of the thermodynamic package is re-assessed for the latest components, reactions, and conditions possibly present with reference to guidance in WP1. The previous identified packages are found to still be applicable.

EVALUATE I

All the components identified in the captured CO_2 require a limit within the specification. Note that newly introduced components from capture and pre-treatment do not yet have a limit evaluated in the specification. Therefore, it is necessary for the next step to iterate back to EVALUATE I to assess the impact of these impurities and establish limits for the T&S for these newly identified impurities. With reference to guidance in WP3, WP4, WP5, WP6, WP7, WP8, WP9 and WP10 [3, 4, 5, 6, 7, 8, 9, 10, 11] updated limits are evaluated.

Table 3-7: Limits for Additional Capture & Pre-Treatment Impurities – (FOR EXAMPLE PROJECT USE ONLY)

Component	Units	Storage Limit[1]	Pipeline Limit[2]	Liquid/Shipping Limit[3]	Safety Toxicity Limit[4]	CS Materials Limit[5]
Acetaldehyde	ppm mol	?	?	≤20	2,000 mg/Nm^3	?
Formaldehyde	ppm mol	?	?	≤20	150 mg/Nm^3	?
MEA	ppm mol	?	See Amines	See Amines	Nitramines/ nitrosamines 3 $\mu g/Nm^3$	?
Amines	ppm mol	?	1	≤10		
Methanol	ppm mol	≤30 to 620	≤600	≤30	?	≤500
Ethanol	ppm mol	≤20	≤20	≤20	?	≤20
Other Alcohols	ppm mol	?	?	?	?	?
TOC	ppm mol	?	?	VOC ≤10	?	?
C6+	ppm mol	?	?	C3+ ≤1,100	?	?

<u>Notes</u>:

1. Storage Limit from WP10 Geological Storage Table 8-1 [11].
2. Pipeline Limit from WP8 Pipeline Transport Appendix A3 Table A-3 [9].
3. Liquid / Shipping Limit from WP5 Capture and Conditioning Table 9-15 [5].
4. Safety Toxicity Limit from WP4 Safety and Environment Table 4-8 [4].
5. CS Materials Limit for pipeline transportation from Appendix C Table C-1 WP3 Materials and Corrosion [3].

The SPECIFICATION is then updated as follows in a second iteration:

Table 3-8: SPECIFICATION Iteration 2 – (FOR EXAMPLE PROJECT USE ONLY)

Component	Units	Limit	From
CO_2	mol%	95[1]	Capture
H_2O	ppm mol	≤20	Liquid/Shipping
N_2	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
O_2	ppm mol	≤10	Chain
Ar	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
NO_X	ppm mol	≤1.5	Liquid/Shipping
SO_X	ppm mol	≤4	CS Materials
CO	ppm mol	≤100	Liquid/Shipping
NH_3	ppm mol	≤10	Liquid/Shipping
H_2	ppm mol	500 Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
CH_4	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
H_2S	ppm mol	≤4	Pipeline, CS Materials
COS	ppm mol	≤5	Liquid/Shipping
HCl	ppm mol	≤100 mg/Nm^3	Liquid/Shipping
HCN	ppm mol		
Other Noble Gases	ppm mol	See N_2 above	Liquid/Shipping
Other Non-Noble Gases	ppm mol		
Particulates	µm	≤1	Liquid/Shipping
Acetaldehyde	ppm mol	≤20	Liquid/Shipping
Formaldehyde	ppm mol	≤20	Liquid/Shipping
MEA	ppm mol	≤1	Pipeline
Amines	ppm mol		
Methanol	ppm mol	≤30	Liquid/Shipping, Storage
Ethanol	ppm mol	≤20	Chain
Other Alcohols	ppm mol	≤50	Chain
TOC/VOC	ppm mol	≤10	Liquid/Shipping
C3+	ppm mol	≤1,100	Liquid/Shipping

Notes

1. Whilst the CO_2 minimum purity is set by the shipping element as "Balance"(i.e. the limit between 100% pure CO_2 and the level of dissolved impurities), the minimum purity of CO_2 from the capture stage is assumed as 95% minimum.

With a second iteration of the SPECIFICATION produced this can be compared against the CO_2 compositions to the T&S (from Table B.1 and Table 10-5 in WP5 [5]):

Table 3-9: SPECIFICATION Iteration 2 vs CO_2 Compositions to T&S 1st Check - – (FOR EXAMPLE PROJECT USE ONLY)

Component	Units	SPECIFICATION Limit	RFCC	CCGT	BF	DAC
CO_2	mol%	>95[1]	≥99.9[a]	98.1	**83[a]**	95.8
H_2O	ppm mol	≤20	**Saturated (~2 mol%)**	**1.9 mol%**	**Saturated (~2 mol%)**	**0.02 mol%**
N_2	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	220 to 370	60	**10.6 mol%[a]**	**2.34 mol%**
O_2	ppm mol	≤10	**17 to 36**	**19**	0.0 mol%	**1.84 mol%**
Ar	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000		ND	0.0 mol%	ND
NO_X	ppm mol	≤1.5	ND to ≤0.5	ND	-	-
SO_X	ppm mol	≤4	ND	ND	1.1	-
CO	ppm mol	≤100	ND	ND	**5.3 mol%[a]**	-
NH_3	ppm mol	≤10	**<10 to 60 (depending on degradation state of solvent)**	<0.1	0.05	-
H_2	ppm mol	500 Total N_2, Ar, H_2, CH_4 ≤2,000	ND	-	**1.0 mol%[a]**	-
CH_4	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	ND	-	ND	-
H_2S	ppm mol	≤4	-	-	**50.8**	-
COS	ppm mol	≤5	-	-	**163**	-
HCl	ppm mol	≤100 mg/Nm^3	-	-	0.04	-
HCN	ppm mol		-	-	0.02	-
Other Noble Gases	ppm mol	See above	-	-	-	ND
Other Non-Noble Gases	ppm mol		-	-	-	ND
Particulates	µm	≤1	ND	ND	ND	ND
Acetaldehyde	ppm mol	≤20	**<10 to 25 (depending on degradation state of solvent)**	**Proprietary amine and degradation products are commercially sensitive (<10 for illustrative purposes)**	-	-
Formaldehyde	ppm mol	≤20	<1		-	-
MEA	ppm mol	≤1	ND		-	-
Amines	ppm mol		ND		-	-
Methanol	ppm mol	≤30	ND to 0.2		-	-
Ethanol	ppm mol	≤20	0.3 to 1.9		-	-
Other Alcohols	ppm mol	≤50	ND to 0.5		-	-
TOC/VOC	ppm mol	≤10	**TOC 9.3 to 22**	-	-	-
C3+	ppm mol	≤1,100	C6+ 1.5 to 3.5	-	-	-

Notes

1. Whilst the CO_2 minimum purity is set by the shipping element as "Balance"(i.e. the limit between 100% pure CO_2 and

the level of dissolved impurities), the minimum purity of CO_2 from the capture stage is assumed as 95% minimum.

IDENTIFICATION V

The comparison reveals a number of impurities that are above limits, these are identified and highlighted in red bold text in the above table, and thus the specification is not met by any of the captured CO_2 sources.

The identified impurities that are exceeding the specification limits must be dealt with by either removing them from the CO_2 through conditioning, or by improving the tolerance of the T&S system to justifiably raise the impurity specification limit above the expected concentration.

An exercise is performed to identify the conditioning technologies capable of removing the impurities exceeding their limits with reference to guidance in WP5.

- **Refinery RFCC**
  - H_2O – conditioning options include compression & cooling, liquid desiccants, mole sieves, silica gels, and activated alumina.
  - O_2 – conditioning options include catalytic oxidation, solid scavenger adsorption, and cryogenic distillation.
  - NH_3 - conditioning options include water or acid washing.
  - Acetaldehydes - conditioning options include water or acid washing.
  - TOC/VOC - conditioning options include activated carbon, mole sieves, catalytic oxidation & adsorption, and thermal oxidation.
- **CCGT Power Plant**
  - H_2O – conditioning options include compression & cooling, liquid desiccants, mole sieves, silica gels, and activated alumina.
  - O_2 – conditioning options include catalytic oxidation, solid scavenger adsorption, and cryogenic distillation.
  - Proprietary Amine & Degradation Products - conditioning options include water or acid washing.
- **Steel Plant Blast Furnace (BF)**
  - Low CO_2 – resolved by reducing impurities.
  - H_2O – conditioning options include compression & cooling, liquid desiccants, mole sieves, silica gels, and activated alumina.
  - N_2 – conditioning options include cryogenic distillation and separation membranes.
  - CO – conditioning options include catalytic oxidation, cryogenic distillation, and separation membranes.
  - H_2 – conditioning options include catalytic oxidation, cryogenic distillation, and separation membranes.
  - H_2S – conditioning options include caustic direct contact cooler (DCC), catalytic oxidation & adsorption/absorption, scavengers, redox conversion/Thiopaq™, and Amine & Claus process.
  - COS – conditioning options include catalytic oxidation & adsorption/absorption, and scavenger with catalytic hydrolysis.

- **Direct Air Capture (DAC) Plant**
  - H_2O – conditioning options include compression & cooling, liquid desiccants, mole sieves, silica gels, and activated alumina.
  - N_2 – conditioning options include cryogenic distillation and separation membranes.
  - O_2 – conditioning options include catalytic oxidation, solid scavenger adsorption, and cryogenic distillation.

An exercise is performed to identify potential changes to T&S infrastructure to increase the tolerance for the impurities exceeding their limits with reference to guidance in WP3, WP4, WP5, WP6, WP7, WP8, WP9, and WP10. The limits for the exceeding components are majoritatively the result of the liquid/shipping imposed limits, as can be seen below. An alternative pipeline-based transport system would therefore likely be more tolerable to many of the impurities. Other limits are present from across the T&S chain, thus any adjustment will need to consider all the sections.

Table 3-10: Exceeded SPECIFICATION Limits – (FOR EXAMPLE PROJECT USE ONLY)

Component	Units	Limit	From
CO_2	mol%	>95[1]	Capture[1]
H_2O	ppm mol	≤20	Liquid/Shipping
N_2	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
O_2	ppm mol	≤10	Chain
Ar	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
CO	ppm mol	≤100	Liquid/Shipping
NH_3	ppm mol	≤10	Liquid/Shipping
H_2	ppm mol	500 Total N_2, Ar, H_2, CH_4 ≤2,000	Liquid/Shipping
H_2S	ppm mol	≤4	Pipeline, CS Materials
COS	ppm mol	≤5	Liquid/Shipping
Acetaldehyde	ppm mol	≤20	Liquid/Shipping
Formaldehyde	ppm mol	≤20	Liquid/Shipping
MEA	ppm mol	≤1	Liquid/Shipping
Amines	ppm mol		
Methanol	ppm mol	≤30	Liquid/Shipping, Storage
Ethanol	ppm mol	≤20	Chain
Other Alcohols	ppm mol	≤50	Chain
TOC/VOC	ppm mol	≤10	Liquid/Shipping

Notes

1. Whilst the CO_2 minimum purity is set by the shipping element as "Balance"(i.e. the limit between 100% pure CO_2 and the level of dissolved impurities), the minimum purity of CO_2 from the capture stage is assumed as 95% minimum.

A number of the limits are significantly exceeded, in these cases it is very likely that at least some degree of conditioning is required. Limits that are exceeded but close to the boundary are more likely to offer potential areas for optimisation by increased tolerance. A summary of the exceedances and potential tolerability is provided below:

- **Refinery RFCC**
  - H_2O – very significantly exceeded, dehydration conditioning will still be required.
  - O_2 – exceeded but on the same order of magnitude, potential for increased tolerance to avoid addition of conditioning.
  - NH_3 – exceeded but on the same order of magnitude, potential for increased tolerance to avoid addition of conditioning; combination with stricter solvent degradation monitoring will be of benefit.
  - Acetaldehyde – small exceedance and on the same order of magnitude, potential for increased tolerance to avoid addition of conditioning.
  - TOC/VOC – small exceedance and on the same order of magnitude, potential for increased tolerance to avoid addition of conditioning.

- **CCGT Power Plant**
  - H_2O – very significantly exceeded, dehydration conditioning will still be required.
  - O_2 – exceeded but on the same order of magnitude, potential for increased tolerance to avoid addition of conditioning.
  - Proprietary Amine & Degradation Products – definition of components is poor in the composition and thus a small same order of magnitude exceedance for amines is possible but not confirmed. Potential for increased tolerance to avoid addition of conditioning but a clearer definition to be sought from licensor to confirm against limits specified.

- **Steel Plant Blast Furnace (BF)**
  - Low CO_2 – resolved by reducing impurities present.
  - H_2O – very significantly exceeded, dehydration conditioning will still be required.
  - N_2 – very significantly exceeded, conditioning will still be required.
  - CO – very significantly exceeded, conditioning will still be required.
  - H_2 – very significantly exceeded, conditioning will still be required.
  - H_2S – significantly exceeded by an order of magnitude, conditioning likely still required.
  - COS – significantly exceeded by an order of magnitude, conditioning likely still required.

- **Direct Air Capture (DAC) Plant**
  - H_2O – very significantly exceeded, dehydration conditioning will still be required.
  - N_2 – very significantly exceeded, conditioning will still be required.
  - O_2 – very significantly exceeded, conditioning will still be required.

The impurities for main consideration are therefore O_2, NH_3, acetaldehyde, TOC/VOC, amines. Changes to T&S infrastructure to improve tolerance of these species are identified, including changes to materials of pipelines, equipment, ships, and storage tanks, increased inspection and maintenance, impacts on liquefaction, compression and BOG management performance.

EVALUATE II

The conditioning options identified in IDENTIFICATION V to meet the specification are evaluated for their impact. Both technical and economic impacts are considered i.e. additional chemical and energy requirements, pressure drop, removal efficiency, any new impurities introduced, waste disposal, CAPEX & OPEX. Reference is made to guidance in WP5 and WP11 [12] to support the evaluation. The following capture and conditioning schemes were developed and summarise the conditioning required:

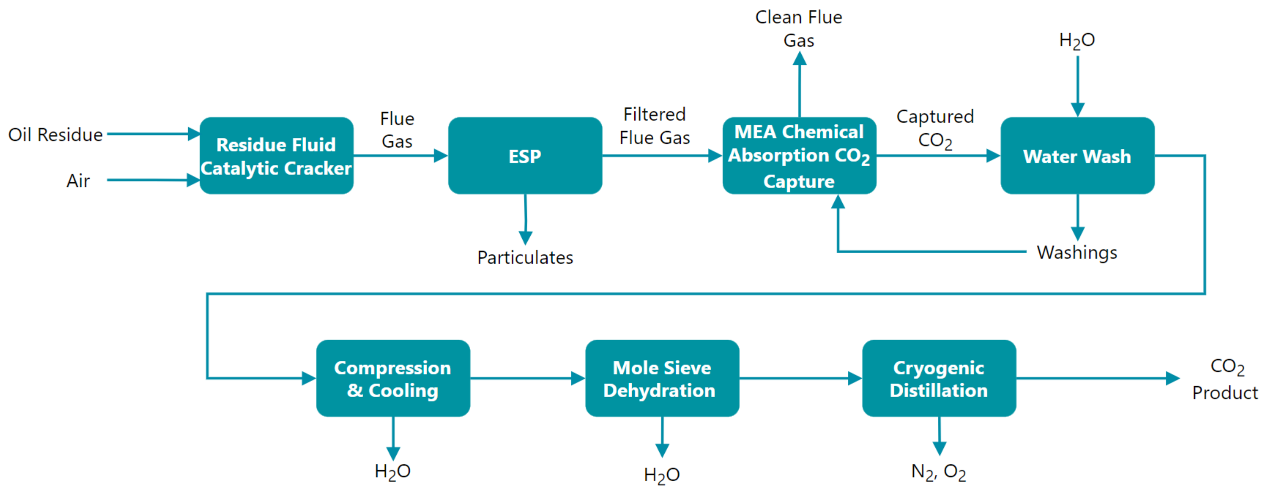


Figure 3-3: RFCC flue gas with carbon capture & conditioning flow scheme.

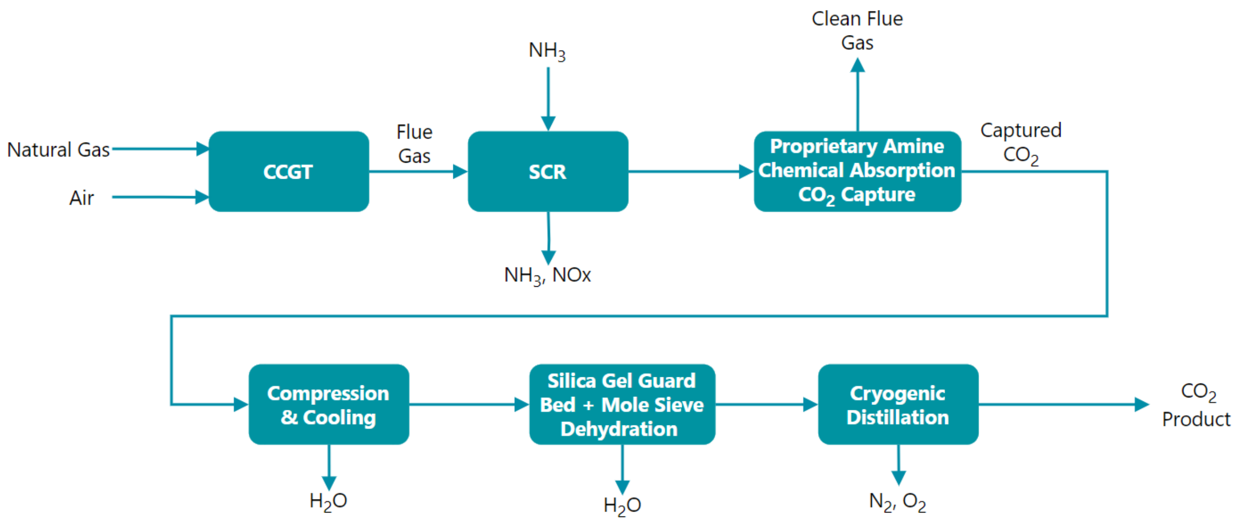


Figure 3-4: CCGT power plant with carbon capture & conditioning flow scheme.

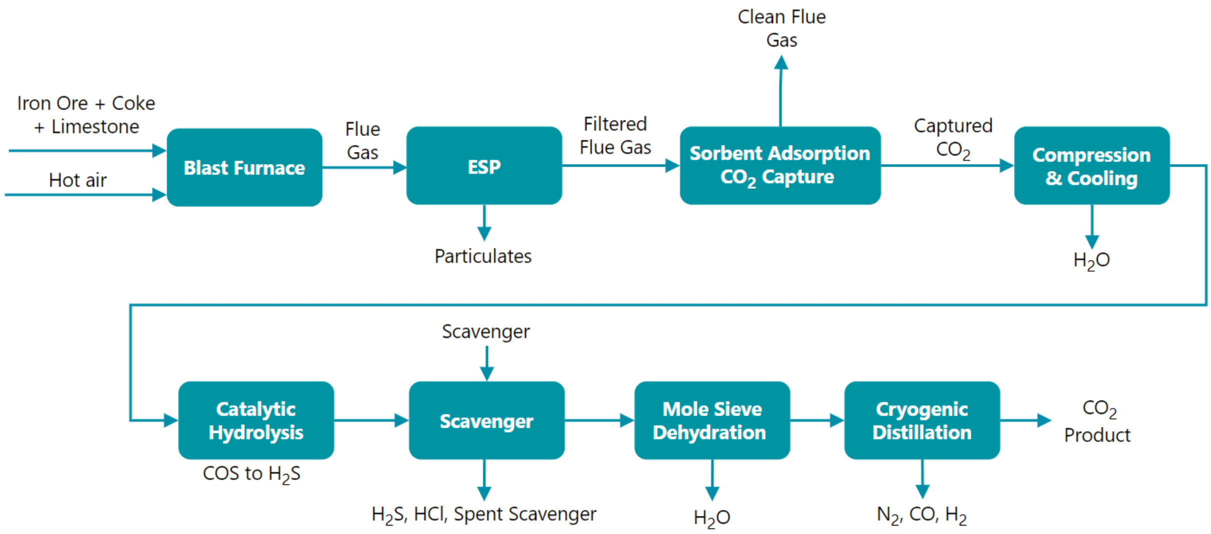


Figure 3-5: Blast furnace with carbon capture & conditioning flow scheme.

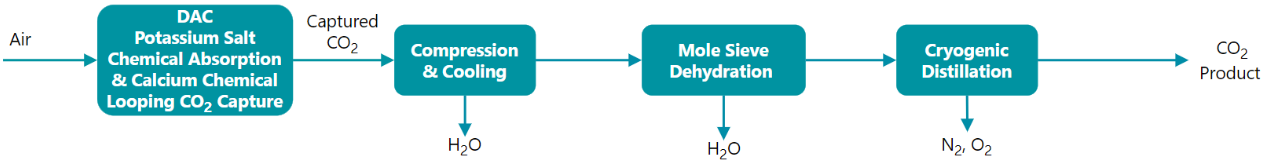


Figure 3-6: Direct air carbon capture & conditioning flow scheme.

The T&S infrastructure changes identified in IDENTIFICATION V to allow increased tolerance of the specification are evaluated for their impact. Both technical and economic impacts are considered i.e. higher tolerance materials, impacts on boil-off gas management systems, ensuring integrity and capacity, ensuring flow assurance, changes to liquefaction/compression/metering, toxicity and other safety impacts, CAPEX & OPEX. Reference is made to guidance in WP3, WP4, WP6, WP7, WP8, WP9, WP10 & WP11 to support the evaluation. A summary of the key findings is shown below:

- O_2 – increasing the tolerance would require changes from carbon steel to more expensive stainless steel and alternative materials at various points in the T&S chain, re-qualification of the existing subsea pipeline is likely not possible and a new pipeline would be required, further work on the impact to reactions is also required.
- NH_3 – is a concern for liquefaction, potential ammonium salt formation with CO_2, and induction of aqueous phase formation. Evaluation with current information assesses that the risk from an increase is unacceptable to the project and thus no changes are suggested.
- Acetaldehyde – is a concern for liquefaction, and induction of aqueous phase formation. Evaluation with current information assesses that the risk from an increase is unacceptable to the project and thus no changes are suggested.
- TOC/VOC – increasing the tolerance is assessed to be possible within the current design with an increase to inspection and maintenance frequency to remove potential fouling build-up in the liquefaction.
- Amines – primarily an increase is a concern for inducing formation of an aqueous phase, it is assessed that some tolerance increase is possible within the current design due to the low water specification.

Further with confirmation from the licensor of the amines and degradation products speciation the system is deemed sufficient to tolerate expected concentrations of amines.

It is further evaluated if any optimal solutions are present through a combination of conditioning and T&S infrastructure changes. The costs of all the different options are then developed to sufficient level to enable design selection to optimise the CCUS chain.

SELECTION II

Based upon the evaluation findings in EVALUATE II the CO_2 conditioning and T&S infrastructure is selected.

In this project example it is assumed that the project performed a cost benefit analysis for removing impurities versus designing for them and that it was found that the cost of the materials changes in the T&S system to tolerate higher O_2 were well in excess of the cost of the conditioning to remove it. This was due in many cases to the same conditioning, cryogenic distillation, still being required for other impurities present, but also for the ability to re-qualify the existing subsea pipeline and avoid installation of a new pipeline in more expensive material.

Similarly in this project example it is assumed that conditioning to remove NH_3 and acetaldehyde was required due to a lack of alternative options. As this conditioning also assists amine removal and the speciation assumed confirmed by the licensor was closer to the limit than the worst case considered, no tolerance increase was required for these impurities.

In the project example, it was assumed that an increase in TOC/VOC would be possible within the current design and that increased inspections would allow to raise the specification limit slightly. This could also allow possible future expansions to other CO_2 sources.

The conditioning stages for each CO_2 source were therefore selected as presented in the schematics shown in EVALUATE II.

IDENTIFICATION IV

With the selected CO_2 conditioning from SELECTION II in place the anticipated CO_2 composition to the T&S system is once again identified, with particular attention made to any new components introduced from conditioning processes. WP5 can support identifying the expected impurities from conditioning while sampling and analysis from pilots can also be performed with reference to guidance in WP7 to further confirm the impurities present. Conditioned CO_2 compositions will otherwise be informed by the conditioning performance specifications based on their technology vendor expertise.

For the selected conditioning the potential chemicals added consist mainly of attrited solids from either catalyst, mole sieve, or scavenger. For these cases, this is managed within the conditioning units themselves by solids filtration systems designed to at least the SPECIFICATION particulate limit where necessary. Thus, no new impurities are expected in the CO_2 to the T&S than previously identified.

Note that where pre-treatment conditioning stages are added this will impact the CO_2 capture and the resulting composition from the capture unit(s). In this case no changes have been made and thus there is no impact.

With reference to the impurities present in the compositions an updated assessment of potential reactions is performed referring to guidance in WP2, noting components from conditioning are now also present. As no new impurities are identified there is no change to the assessment.

Similarly, suitability of the thermodynamic package is re-assessed for the latest components, reactions and conditions possibly present with reference to guidance in WP1. Again, as no new impurities are identified there is no change to the assessment.

All the components identified in the conditioned CO_2 require a limit within the specification and thus the specification may be updated for the newly identified components. Again, as no new impurities are identified there is no change to the assessment.

EVALUATE I

With the selected T&S infrastructure from SELECTION II in place the SPECIFICATION for the latest list of impurities from IDENTIFICATION IV can be evaluated to establish the updated set of limits. With this done a third iteration of the SPECIFICATION is produced and can be compared against the conditioned CO_2 compositions to the T&S (from Table B.1 and Table 10-5 in WP5 [5]):

Table 3-11: SPECIFICATION Iteration 3 vs Conditioned CO_2 Compositions to T&S 2^{nd} Check – (FOR EXAMPLE PROJECT USE ONLY)

<table>
<tr><th>Component</th><th>Units</th><th>SPECIFICATION Limit</th><th>RFCC</th><th>CCGT</th><th>BF</th><th>DAC</th></tr>
<tr><td>CO_2</td><td>mol%</td><td>>95[1]</td><td>≥99.9</td><td>>98.1</td><td>>95</td><td>>95.8</td></tr>
<tr><td>H_2O</td><td>ppm mol</td><td>≤20</td><td>≤1</td><td>≤1</td><td>≤1</td><td>≤1</td></tr>
<tr><td>N_2</td><td>ppm mol</td><td>Total N_2, Ar, H_2, CH_4 ≤2,000</td><td>≤100</td><td>≤60</td><td>≤1,000</td><td>≤1,500</td></tr>
<tr><td>O_2</td><td>ppm mol</td><td>≤10</td><td rowspan="2">≤8</td><td>≤8</td><td>0.0 mol%</td><td>≤8</td></tr>
<tr><td>Ar</td><td>ppm mol</td><td>Total N_2, Ar, H_2, CH_4 ≤2,000</td><td>ND</td><td>0.0 mol%</td><td>ND</td></tr>
<tr><td>NO_X</td><td>ppm mol</td><td>≤1.5</td><td>ND to ≤0.5</td><td>ND</td><td>-</td><td>-</td></tr>
<tr><td>SO_X</td><td>ppm mol</td><td>≤4</td><td>ND</td><td>ND</td><td>≤1.1[2]</td><td>-</td></tr>
<tr><td>CO</td><td>ppm mol</td><td>≤100</td><td>ND</td><td>ND</td><td>≤100</td><td>-</td></tr>
<tr><td>NH_3</td><td>ppm mol</td><td>≤10</td><td>≤8</td><td><0.1</td><td>≤0.05</td><td>-</td></tr>
<tr><td>H_2</td><td>ppm mol</td><td>500
Total N_2, Ar, H_2, CH_4 ≤2,000</td><td>ND</td><td>-</td><td>≤500</td><td>-</td></tr>
<tr><td>CH_4</td><td>ppm mol</td><td>Total N_2, Ar, H_2, CH_4 ≤2,000</td><td>ND</td><td>-</td><td>ND</td><td>-</td></tr>
<tr><td>H_2S</td><td>ppm mol</td><td>≤4</td><td>-</td><td>-</td><td>≤4[2]</td><td>-</td></tr>
<tr><td>COS</td><td>ppm mol</td><td>≤5</td><td>-</td><td>-</td><td>≤4</td><td>-</td></tr>
<tr><td>HCl</td><td>ppm mol</td><td rowspan="2">≤100 mg/Nm^3</td><td>-</td><td>-</td><td>≤0.04</td><td>-</td></tr>
<tr><td>HCN</td><td>ppm mol</td><td>-</td><td>-</td><td>≤0.02</td><td>-</td></tr>
<tr><td>Other Noble Gases</td><td>ppm mol</td><td rowspan="2">See above</td><td>-</td><td>-</td><td>-</td><td>ND</td></tr>
<tr><td>Other Non-Noble Gases</td><td>ppm mol</td><td>-</td><td>-</td><td>-</td><td>ND</td></tr>
<tr><td>Particulates</td><td>µm</td><td>≤1</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td></tr>
<tr><td>Acetaldehyde</td><td>ppm mol</td><td>≤20</td><td>≤8</td><td rowspan="7">≤1</td><td>-</td><td>-</td></tr>
<tr><td>Formaldehyde</td><td>ppm mol</td><td>≤20</td><td><1</td><td>-</td><td>-</td></tr>
<tr><td>MEA</td><td>ppm mol</td><td rowspan="2">≤1</td><td>ND</td><td>-</td><td>-</td></tr>
<tr><td>Amines</td><td>ppm mol</td><td>ND</td><td>-</td><td>-</td></tr>
<tr><td>Methanol</td><td>ppm mol</td><td>≤30</td><td>ND to ≤0.2</td><td>-</td><td>-</td></tr>
<tr><td>Ethanol</td><td>ppm mol</td><td>≤20</td><td>≤0.3 to ≤1.9</td><td>-</td><td>-</td></tr>
<tr><td>Other Alcohols</td><td>ppm mol</td><td>≤50</td><td>ND to ≤0.5</td><td>-</td><td>-</td></tr>
<tr><td>TOC/VOC</td><td>ppm mol</td><td>≤20</td><td>TOC ≤8</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>C3+</td><td>ppm mol</td><td>≤1,100</td><td>C6+ ≤1.5 to 3.5</td><td>-</td><td>-</td><td>-</td></tr>
</table>

<u>Notes</u>

1. Whilst the CO2 minimum purity is set by the shipping element as "Balance"(i.e. the limit between 100% pure CO2 and the level of dissolved impurities), the minimum purity of CO2 from the capture stage is assumed as 95% minimum.
2. For this project example it is assumed that the maximum total limit of H_2S + SO_X of 4 ppm-mol from Appendix C Table C-1 WP3 Materials and Corrosion [3] will always be met at the blended CO_2 flowrates.

SPECIFICATION

A comparison of the latest specification and the conditioned CO_2 composition to T&S reveals all impurities are now within the project's limits and thus the specification is met and may be frozen as final. If in future phases of the project, changes are made to infrastructure or new CO2 sources are to be introduced, the workflow should be re-iterated to account for all new impurities and limitations introduced.

Table 3-12: Final Project CO_2 Specification – (FOR EXAMPLE PROJECT USE ONLY)

Component	Units	SPECIFICATION Limit
CO_2	mol%	Balance (min 99.60%)
H_2O	ppm mol	≤20
N_2	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000
O_2	ppm mol	≤10
Ar	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000
NO_X	ppm mol	≤1.5
SO_X	ppm mol	≤4
CO	ppm mol	≤100
NH_3	ppm mol	≤10
H_2	ppm mol	≤500 (Total N_2, Ar, H_2, CH_4 ≤2,000)
CH_4	ppm mol	Total N_2, Ar, H_2, CH_4 ≤2,000
H_2S	ppm mol	≤4
COS	ppm mol	≤5
HCl	ppm mol	≤100 mg/Nm^3
HCN	ppm mol	
Other Noble Gases	ppm mol	See above
Other Non-Noble Gases	ppm mol	
Particulates	µm	≤1
Acetaldehyde	ppm mol	≤20
Formaldehyde	ppm mol	≤20
MEA	ppm mol	≤1
Amines	ppm mol	
Methanol	ppm mol	≤30
Ethanol	ppm mol	≤20
Other Alcohols	ppm mol	≤50
TOC/VOC	ppm mol	≤20
C3+	ppm mol	≤1,100

4.0 References

[1] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 1: Thermodynamics, 522240-WP1-REP-001 Rev 2, 2024.

[2] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 2: Reaction Chemistry, 522240-WP2-REP-001 Rev 2, 2024.

[3] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 3: Materials & Corrosion, 522240-WP3-REP-001 Rev 7, 2024.

[4] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 4: Safety and Environment, 522240-WP4-REP-001 Rev 2, 2024.

[5] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 5: Capture and Conditioning, 522240-WP5-REP-001 Rev 5, 2024.

[6] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 6: Compression and Pumping, 522240-WP6-REP-001 Rev 2, 2024.

[7] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 7.1: Metering, 522240-WP7-REP-001 Rev 2, 2024.

[8] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 7.2: Sampling, 522240-WP7-REP-002 Rev 3, 2024.

[9] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 8: Pipeline Transport, 522240-WP8-REP-001 Rev 4, 2024.

[10] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 9: Ship Transport, 522240-WP9-REP-001 Rev 4, 2024.

[11] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 10: Geological Storage, 522240-WP10-REP-001 Rev 3, 2024.

[12] CO2 Specification JIP, Industry Guidelines for Setting the CO2 Specification in CCUS Chains - Work Package 11: Economics, 522240-WP11-REP-001 Rev 2, 2024.