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**PURITY REQUIREMENTS OF CARBON DIOXIDE FOR CARBON
CAPTURE AND STORAGE**

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1 INTRODUCTION ON CARBON CAPTURE AND STORAGE (CCS)

According to the House of Commons Committee of Public Accounts, “without CCS, there is a gap in the government’s plans for achieving decarbonisation at least cost while ensuring a secure supply of electricity.” The report further highlights that the cost of not implementing CCS into UK energy industry would be much higher than if we do with an estimated cost of “£1 billion to £2 billion per year in the 2020s, rising to between £4 billion and £5 billion per year in the 2040s” if no action is taken.¹ The Department for Business, Energy and Industrial Strategy (BEIS) estimates that “it would cost the UK £30 billion more to meet the 2050 target without CCS in the power sector because a more expensive mix of low-carbon technologies would be required.”

As well as enabling carbon reductions in the electricity industry, CCS also allows for the production of clean hydrogen.² There are various hydrogen projects across the UK that require CCS, such as the H21 Leeds City Gate project which aspires to convert part of the UK natural gas grid to 100% hydrogen. To enable this conversion to be a viable option, CCS would be needed to capture the carbon dioxide produced during steam methane reformation (the process that converts methane to hydrogen).³ The 2016 executive summary report from Leeds City Gate lists Teesside as a suitable location for CCS in the UK.

There are specific measurement capabilities that need to be developed to support CCS in the UK. For example, flow metering is important for calculating the amount of carbon dioxide that has been sent into storage sites. Materials testing provides scientific evidence to help understand which impurities (and levels) in carbon dioxide cause corrosion and degradation. This report focuses on carbon dioxide purity. Various literature is available which outlines the issues of carbon dioxide purity in CCS processes. The presence of large amounts of impurities during the compression stage could lead to large inefficiencies or cause corrosion of storage/pipeline materials. An additional concern is the possible leakage of hazardous impurities to the atmosphere during storage; this risk can be minimised by simply ensuring that harmful impurities are not present in the carbon dioxide before the storage step. The aim of this report is to review available literature on the required purity of carbon dioxide for the different stages of carbon capture and storage for energy processes (combustion and steam methane reforming). All stages of the process that may be affected by carbon dioxide purity, and the detrimental effects, are discussed. Finally a proposed purity specification is provided based on the findings of this review and identification of new metrology requirements.

While this report focusses on the carbon dioxide purity requirements, NPL have previously carried out a review of the requirements and measurement technologies available for the measurement of carbon dioxide emissions from the capture, transport and storage elements of the CCS chain.⁴ The key metrology requirements for emissions monitoring are summarised later in this report. It should also be noted that this report only discusses carbon capture and storage and does not include utilisation.

2 THE CCS PROCESS

The entire carbon capture, utilisation and storage process is represented in Figure 1 which was taken from an online article on carbon capture, utilisation and storage.⁵

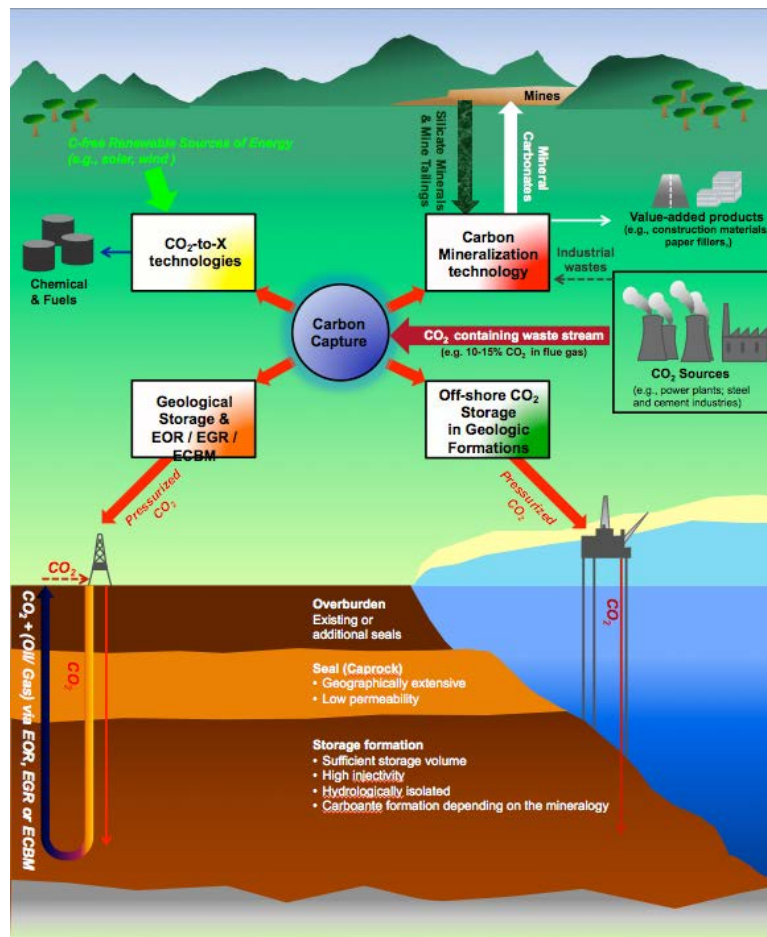


Figure 1: Schematic of the carbon capture and storage process (including enhanced oil recovery and utilisation)

As shown in Figure 1 the carbon dioxide source can be stored or utilised in several ways. This section will provide a brief overview of the different stages that can take place in a carbon capture, utilisation or storage process.

2.1 PRODUCTION

This section provides an overview of the energy production processes that produce carbon dioxide as a by-product; this includes fuel combustion and hydrogen production by steam methane reforming. It should be noted that there are other industrial processes that may also produce carbon dioxide, such as cement production, which are not covered in this section.

2.1.1 Pre-combustion

Pre-combustion is the process where carbon dioxide is removed before the actual conversion of fuel to energy. This may involve reforming (gas) or gasifying (coal) the fuel to syngas, and utilising water gas shift to produce more hydrogen from water (which also converts carbon monoxide to carbon dioxide). The carbon dioxide can be removed leaving a hydrogen rich fuel. In this case, the likely impurities that may be present in the carbon dioxide are nitrogen, oxygen, hydrogen, methane, carbon monoxide and sulphur-based compounds such as hydrogen sulphide. There is not expected to be significant levels of impurities that would originate from air, such as sulphur dioxide or nitrogen oxides, as the carbon dioxide is removed before the combustion step.⁶

2.1.2 Post-combustion

Post-combustion is the process where the fuel is directly combusted using air without an initial reforming or gasification step. The trace elements that may be present in carbon dioxide for this process are nitrogen, oxygen, water, sulphur oxides, nitrous oxides, particulates, hydrochloric acid, hydrofluoric acid, mercury, other metals and other trace contaminants. Combustion of coal is likely to provide more sulphur oxides and nitrous oxides, but lower oxygen compared to combustion of natural gas.⁶

2.1.3 Oxy-fuel

An oxy-fuel process utilises pure oxygen instead of air to perform combustion. By removing inert nitrogen from the oxidising gas, the process can reduce fuel consumption (however there may be additional costs from the air separation unit). The possible contaminants could be argon, oxygen, nitrogen, sulphur dioxide, sulphur trioxide, nitrogen monoxide, nitrogen dioxide, carbon monoxide and other trace contaminants from the air.⁷

2.1.4 Steam methane reforming

Steam methane reforming is a process similar to combustion but where methane from natural gas is reacted with water instead of air. The resulting gas then goes through a water gas shift reaction to produce a stream of hydrogen and carbon dioxide. The carbon dioxide can be separated off and captured whilst the pure hydrogen can be used in chemical processes or as a clean fuel (for example for powering fuel cell hydrogen vehicles).

2.2 CAPTURE AND TRANSPORT

The capture step refers to the stage of the process where pure carbon dioxide is extracted from the waste stream of an industrial process. The carbon dioxide could be present in flue gas from power plants, steam methane reforming or chemical processes. The gas will usually go through a purification step, such as amine scrubbing, to produce a stream of pure carbon dioxide which can be liquefied before transporting for storage or utilisation.⁸ According to the literature amine scrubbing usually captures 85 – 90% of the carbon dioxide from flue gas⁹ but it should be noted that this would entirely depend on the set up and type of scrubbers used. The purity of the carbon dioxide following amine scrubbing can be better than 99.95% depending on the performance and lifetime of the scrubber.¹⁰

Before transporting through pipelines, the carbon dioxide is usually dehydrated to ensure levels of water are below $50 \mu\text{mol mol}^{-1}$. According to an article by the World Resources Institute there are three main types of pipelines that are categorised based on the different purity levels of carbon dioxide that can be present (as shown in Figure 2).¹¹

Parameter	Type I	Type II	Type III
CO ₂ —% by volume	>95%	>95%	>96%
H ₂ S—ppmbw	<10	<20	<10,000
Sulphur—ppmbw	<35	<30	-
Total hydrocarbons—% by volume	<5	<5	-
CH ₄ —% by volume	-	-	<0.7
C ₂ + hydrocarbons—% by volume	-	-	<23,000
CO—% by volume	-	-	<1,000
N ₂ —% by volume/weight	<4	<4	<300
O ₂ —ppm by weight/volume	<10	<10	<50
H ₂ O—#/mmcf* or ppm by volume**	<25*	<30*	<20**
C ₂ = carbon; CH ₄ = methane; CO = carbon monoxide; CO ₂ = carbon dioxide; H ₂ O = water; H ₂ S = hydrogen sulfide; mmcf = millions of cubic feet; N ₂ = nitrogen; ppm = parts per million; O ₂ = oxygen; ppmbw = ppm by weight			

Figure 2: Acceptable purity levels of carbon dioxide for the different types of pipelines used for carbon dioxide transportation

2.3 STORAGE

2.3.1 Deep saline aquifers

Saline aquifers are underground rocks that are water permeable and end up saturated with brine. Storage of carbon dioxide via saline aquifers is optimised by injecting the carbon dioxide as a supercritical fluid. Once injected into the aquifers, the carbon dioxide is trapped beneath a layer of gas impermeable rock (such as caprock) as shown in Figure 3.

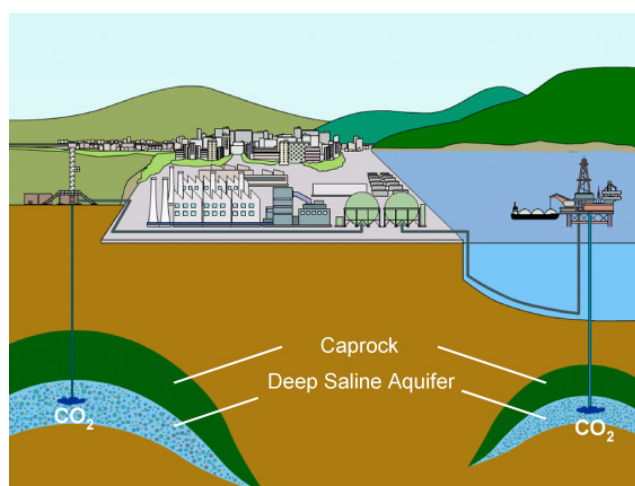


Figure 3: The process of capturing carbon dioxide in saline aquifers¹²

Any requirements for quality may arise from concerns around carbon dioxide leaks as some impurities present in the gas could be hazardous to humans and/or the environment. Additionally, the presence of non-condensable impurities may lead to difficulties with the compression step, and limit storage

capacity (as these impurities may reduce overall density).¹³ Some impurities, such as water and sulphur dioxide may react together to form sulphuric acid which could cause mineral dissolution.¹³

2.3.2 Unmineable coal seams

Studies have shown that porous coal is efficient at trapping carbon dioxide.¹⁴ Therefore coal mines that are not accessible for mining may be suitable for storing carbon dioxide. This process provides the additional benefit that the carbon dioxide can displace methane from the mine which can be extracted and utilised as a source of energy (for example, this methane could be injected into the natural gas grid following clean up).¹⁵

2.3.3 Depleted oil and gas reservoirs

Enhanced oil recovery (EOR) is the process of feeding carbon dioxide into depleted oil reservoirs to extract remaining oil. This provides two benefits as the process allows carbon dioxide to be securely stored underground whilst displacing the remains of oil that otherwise would have been unobtainable. It is estimated that an additional 470 billion barrels of oil could potentially be extracted by EOR from discovered oil sites worldwide, which would lead to the sequestration of 140 billion metric tons of carbon dioxide.¹⁶ This is already a widely used technique where carbon dioxide is readily available, however there may be issues over the suitability of a given depleted reservoir for long-term carbon dioxide storage.

2.4 UTILISATION

There are many uses for carbon dioxide in industry that includes preparation of food and chemical processing. In Europe, it is a strong recommendation that food grade carbon dioxide should meet quality specifications similar to that provided in 'EIGA document 70/17'; this may require additional clean up and analysis following carbon dioxide capture.¹⁷ There are several uses for carbon dioxide in chemical processing to manufacture oxygenated organics, minerals, carbon fuels and plastics. Companies are likely to set their own quality specifications for their chemical processes, therefore purity requirements for carbon dioxide utilisation will not be included in this report.

3 QUALITY REQUIREMENTS FOR CCS

This section provides a literature review of various reports that provide information on the effects of impurities in the CCS process and recommended quality specifications.

3.1 IMPACT OF IMPURITIES ON CARBON DIOXIDE CAPTURE, TRANSPORT AND STORAGE (2004)¹⁸

This report identifies different impurities that may be present in carbon dioxide captured from the combustion of nine different types of fuels such as coal, orimulsion, oil, petroleum coke and lignite. Potential impurities include hydrogen sulphide, sulphur dioxide, nitrogen oxides, hydrogen, carbon monoxide, constituents of air and possibly trace elements of metals such as mercury, arsenic and selenium. The authors suggest that the maximum levels of impurities found in captured carbon dioxide (for a worst case scenario) would be as shown below in Figure 4.

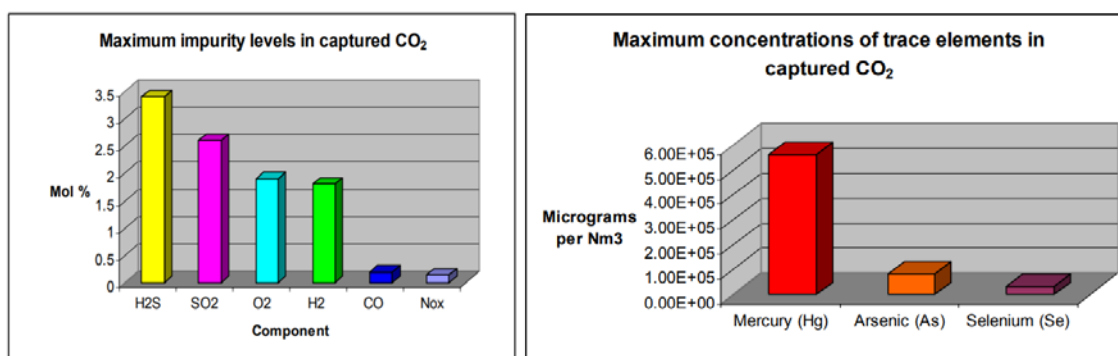


Figure 4: Maximum impurity levels present in carbon dioxide captured from the nine fuels specified in the report

It was recognised that the levels of hydrogen sulphide and sulphur dioxide in the carbon dioxide would pose a hazardous scenario should there be a leak from the storage site. The gas leak would need to be diluted by up to 500-1000 times to be rendered harmless. The report states that there would be no anticipated corrosion issues due to the presence of these impurities as long as the carbon dioxide is sufficiently dry. However, higher levels of hydrogen sulphide or hydrogen would require careful selection of the pipeline steel.

For the storage step, the authors believe that these impurities may not effect reservoir rock or caprock, but they recommend further studies to be carried out to confirm this as not all reservoirs are the same. However, should the carbon dioxide be used to recover oil or gas from a reservoir, the presence of hydrogen sulphide may turn the gas sour which would affect production equipment. For compressibility, the presence of lighter gases such as nitrogen or oxygen was expected to increase compression requirements, whereas sulphur dioxide and hydrogen sulphide would have the opposite effect. The presence of high levels of hydrogen sulphide or sulphur dioxide may be a concern with regards to corrosion of equipment, particularly in the additional presence of water.

3.2 CARBON DIOXIDE QUALITY REQUIREMENT FOR A SYSTEM WITH CARBON DIOXIDE CAPTURE, TRANSPORT AND STORAGE (2005)¹⁹

This report discusses the detrimental effects of impurities being present in the carbon dioxide during transport and storage. These include compounds that form hydrates through reaction with water, ones that cause corrosion and toxic components. The report interestingly also discusses the advantage of including toxic impurities in carbon dioxide during storage as a means of removing these harmful pollutants (presuming these impurities do not escape from the storage site).

Figure 5 shows the level of impurities measured at the different stages of a CCS process and an assessment of whether these levels would be critical to compression, transport, storage and safety.

Case		Capture from					CO ₂ Com- pression train	Transport		Storage				Environment, health		Haza- dous waste
		Oxyfuel		Post- combustion	IGCC									Risk transport	Risk storage	
		CO ₂ /SO ₂	CO ₂ +SO ₂	MEA absorption	CO ₂ /H ₂ S	CO ₂ +H ₂ S			Pipeline	Ship	Ability to move oil ("EOR")	Injection equipment	Cap rock	reservoir		
Component	Type* Unit	Concentration														
H ₂ O	1 vol%	0.14	0.14	0.14	0.14	0.14	C ^[a,c]	C ^[a,c]	C ^[a,c]	NC	C ^[a,c]	NC	NC	NC	NC	NC
CO ₂	2 vol%	91	90	99.8	97.8	95.6										
SO ₂	2 vol%	0.076	1.5	0.001	-	-	C ^[c]	NA	NA	NC**	C ^[a]	C ^[a]	C ^[a]	C ^[a]	C ^[a]	NC
NO	2? 3 vol%	0.25	0.24	0.002	unknown	unknown	NA	NA	NA	NC	C ^[a]	C ^[a]	C ^[a]	C ^[a]	C ^[a]	NC
H ₂ S	2 vol%	-	-	-	0.01	2.3	NA	C ^[c,a] /NC ^[a]	C ^[c,a]	NC**	C ^[a,c]	NC	NC	C ^[a]	C ^[a]	NC
HCl	2, W ppmv	Trace	Trace	Trace	Trace	Trace	NC	NC	NC	NC	NC	NC	NC	NC	NC	NA
HF	2, W ppmv	Trace	Trace	Trace	Trace	Trace	NC	NC	NC	NC	NC	NC	NC	NC	NC	NA
CO	2? 3? ppmv	unknown	unknown	10	1700	1700	NA	NA	C ^[b]	NC	NC	NC	NC	C ^[a]	NC	NC
Ar	3 vol%	5.7	5.6	0.021	0.050	0.049	C ^[b]	C ^[b,a]	C ^[b,a]	C ^[a]	NC	NC	NC	NC	NC	NC
O ₂	3 vol%	1.6	1.6	0.003	unknown	unknown	C ^[a,b]	C ^[a,b]	C ^[a,b]	C ^[a]	NC	C ^[a]	C ^[a]	C ^[a]	NC	NC
N ₂	3 vol%	0.61	0.60	0.021	0.030	0.030	C ^[b]	NC	C ^[b]	C ^[a]	NC	NC	NC	NC	C ^[a]	NC
H ₂	3 vol%	-	-	-	1.7	1.7	C ^[b]	C ^[b]	C ^[b]	C ^[a]	NC	NC	NC	NC	NC	NC
CH ₄	3, 4 ppmv	-	-	-	350	350	C ^[c]	C ^[b]	C ^[b,a]	C ^[a]	C ^[a]	NC	NC	NC	NC	NC
Hydrocarbons	4 ppmv	-	-	30	unknown	unknown	NA	NC	NC	NA	NC	NC	NC	NA	NA	NA
HCN	4 ppmv	Trace	Trace	-	< 5	< 5	NC	NA	NA	NA	C ^[a]	NC	NC	C ^[a]	NC	NC
COS	4 ppmv	-	-	-	< 5	< 5	NC	NC	NA	NA	NA	NA	NA	NC	NC	NC
Mercaptanes	4 ppmv	-	-	-	220	220	NA	C ^[a,c]	C ^[a,c]	NA	NA	NA	NA	C ^[a,c]	C ^[a,c]	NC?
NH ₃	5, W ppmv	Trace	Trace	unknown	30	30	NC	NA	NA	NC	NC	NC	NC	NC	NC	NC
Hg	6 ppmv	Trace	Trace	Trace	Trace	Trace	NC	NC	NC	NC	NC	NC	NC	NC	C ^[a]	NA
Metals	6 ppm	Trace	Trace	Trace	Trace	Trace	NC	NC	NC	NC	NC	NC	NC	NC	NC	NA
Particulates	7 ppm	< 1	< 1	< 1	< 1	< 1	NC	NC	NC	NC	NC	NC	C ^[a]	NC	NC	NA
MEA	8, 4 ppm	-	-	unknown	-	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solxol	8, 4 ppm	-	-	-	unknown	unknown	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Figure 5: List of impurities and effects to the CCS process (C - Critical, NC – Not expected to be critical)

The report does not specify recommended maximum limits for these impurities.

3.3 IPCC SPECIAL REPORT - CARBON DIOXIDE CAPTURE AND STORAGE (2005)²⁰

This report emphasises the need for quality standards for carbon dioxide in CCS processes (as is currently available for natural gas²¹ and hydrogen²²⁻²⁴). Although the recommended maximum levels are not specified, some of the main impurities and rationale are detailed. It is noted that moisture in carbon dioxide could be corrosive to conventional pipelines and hydrogen sulphide should be reduced in case of a leak (for health and safety reasons).

3.4 DYNAMIS CARBON DIOXIDE QUALITY RECOMMENDATIONS (2007)⁶

This report provides detailed information on the quality requirements for carbon dioxide at different stages of the CCS process including transport, storage and EOR. A summary of the recommended quality and rationale of each impurity is shown in Figure 6. These recommendations are based on the results of the European Enhanced Capture of Carbon Dioxide (ENCAP) project along with additional modifications based on other evidence obtained by the DYNAMIS project partners.

Component	Concentration	Limitation
H ₂ O	500 ppm	Technical: below solubility limit of H ₂ O in CO ₂ . No significant cross effect of H ₂ O and H ₂ S, cross effect of H ₂ O and CH ₄ is significant but within limits for water solubility.
H ₂ S	200 ppm	Health & safety considerations
CO	2000 ppm	Health & safety considerations
O ₂ ²	Aquifer < 4 vol%, EOR 100 – 1000 ppm	Technical: range for EOR, because lack of practical experiments on effects of O ₂ underground.
CH ₄ ²	Aquifer < 4 vol%, EOR < 2 vol%	As proposed in ENCAP project
N ₂ ²	< 4 vol % (all non condensable gasses)	As proposed in ENCAP project
Ar ²	< 4 vol % (all non condensable gasses)	As proposed in ENCAP project
H ₂ ²	< 4 vol % (all non condensable gasses)	Further reduction of H ₂ is recommended because of its energy content
SO _x	100 ppm	Health & safety considerations
NO _x	100 ppm	Health & safety considerations
CO ₂	>95.5%	Balanced with other compounds in CO ₂

Figure 6: Recommended carbon dioxide quality for CCS taken from the DYNAMIS project

As shown in Figure 6, the rationale for the selected impurities are based on health and safety (hazards caused by carbon dioxide leaks), non-compressible gases and reactivity (i.e. presence of high levels of both water and hydrogen sulphide could lead to formation of sulphuric acid). It is recommended to keep hydrogen content low to avoid losing high energy content (i.e. hydrogen is a valuable product).

3.5 PURIFICATION OF OXYFUEL-DERIVED CARBON DIOXIDE FOR SEQUESTRATION OR EOR (2007)²⁵

As previously mentioned in Section 2.1.3, oxy-fuel combustion is the process where a fuel is burnt in oxygen opposed to air; this provides a flue stream which is richer in carbon dioxide compared to the conventional combustion method (utilising air). According to this paper, the process can produce acidic impurities such as sulphur trioxide, sulphide dioxide, hydrochloric acid and nitrogen oxides. These impurities need to be removed before the carbon dioxide can be transported via pipelines (as acidic impurities can cause corrosion of metal). This paper also states that the level of oxygen in carbon dioxide must be below 10 $\mu\text{mol mol}^{-1}$ before it can be used for EOR (this is to avoid oxygen from reacting with hydrocarbons in the oil field). The amount of oxygen that could be present from flue gas leaving an oxyfuel combustion can be as high as 1 cmol mol^{-1} . Although this paper states that the acidic impurities must be removed, there is no mention of what the threshold limits should be.

3.6 GUIDELINES FOR CARBON DIOXIDE CAPTURE, TRANSPORT AND STORAGE (2008)¹¹

This report provides rationale for removal of impurities that agree with previous reports reviewed in this section. Additionally, it is mentioned that water may react with carbon dioxide to form carbonic acid which is corrosive. A maximum limit of 10 $\mu\text{mol mol}^{-1}$ is stated for oxygen when organic materials are present to avoid growth of bacteria. The acceptable purity levels of carbon dioxide for different types of pipelines are shown in Figure 2. The report states that exposure to hydrogen sulphide at levels higher than 50 $\mu\text{mol mol}^{-1}$ will be hazardous to health.

3.7 DESIGN AND OPERATION OF CARBON DIOXIDE PIPELINES (2010)²⁶

DET NORSKKE VERITAS (DNV) produced a report which includes detailed information regarding possible impurities in carbon dioxide and the detrimental effects. The key impurities and effects are summarised in Figure 7.

Component	Properties									Comment
	Health & Safety	Pipeline capacity	Water solubility	Hydrate formation	Materials	Fatigue	Fracture	Corrosion	Operations	
CO ₂	•	•	•	•	•	•	•	•	•	Non-flammable, colourless, no odour at low concentrations, low toxicity, vapour heavier than air
H ₂ O				•	•	•	•	•	•	Non-toxic
N ₂		•	•							Non-toxic
O ₂			•					•		Non-toxic
H ₂ S	•	(•)			•	•	(•)	•		Flammable, strong odour, extremely toxic at low concentrations
H ₂		•	•				•			Flammable, non-condensable at pipeline operating condition
SO ₂	•		•					•		Non-flammable, strong odour
CO	•		•							Non-flammable, toxic
CH ₄ +		•	•						•	Odourless, flammable
Amines	•									Potential occupational hazard
Glycol	(•)							(•)		Potential occupational hazard

Figure 7: Summary of impurities and effects if present in carbon dioxide

The report provides detailed information about the different possible effects from the presence of these impurities, but recommended maximum amount fractions limits are not specified.

3.8 EFFECTS OF IMPURITIES ON GEOLOGICAL STORAGE OF CARBON DIOXIDE (2011)¹³

This report recognises that impurities in the carbon dioxide stream could affect pipelines and injection wells (mainly due to corrosion). In a reference to a study performed by COORETEC it was recognised that carbon dioxide captured from an oxy-fuel combustion plant may provide different purity grades of carbon dioxide depending on the process as shown in Figure 8.

Component	Pre-combustion		Post-combustion			Oxyfuel		
	Selexol	Rectisol	Comp.1	Comp.2	Comp.3	Comp.1	Comp.2	Comp.3
CO ₂ (vol %)	97.95	99.7	99.93	99.92	99.81	85.0	98.0	99.94
O ₂ (vol %)	-	-	0.015	0.015	0.03	4.70	0.67	0.01
N ₂ (vol %)	0.9	0.21	0.045*	0.045*	0.09*	5.80	0.71	0.01
Ar (vol %)	0.03	0.15				4.47	0.59	0.01
H ₂ O (ppm)	600	10	100	100	600	100	100	100
NO _x (ppm)	-	-	20	20	20	100	100	100
SO ₂ (ppm)	-	-	10 [†]	10 [†]	20 [†]	50	50	50
SO ₃ (ppm)	-	-				20	20	20
CO (ppm)	400	400	10	10	20	50	50	50
H ₂ S+COS (ppm)	100	100	-	-	-	-	-	-
H ₂	1 vol%	20 ppm	-	-	-	-	-	-
CH ₄ (ppm)	100	100	-	-	-	-	-	-
NH ₃ (ppm)	-	-	-	50	-	-	-	-
CH ₃ OH (ppm)	-	200	-	-	-	-	-	-

*Total concentration of N₂ + Ar

†Total concentration of SO₂ + SO₃

Figure 8: Composition of carbon dioxide expected from different combustion processes

Levels of non-condensables in the carbon dioxide as high as 15% could reduce storage capacity by 40% and increase buoyancy by as much as 50%, both due to the reduction in overall density. The buoyancy effects could lead to reduce trapping of the carbon dioxide. Regarding chemical effects, impurities of sulphur dioxides, nitrogen oxides and hydrogen sulphide are reported to have the most significant impact on rocks and wellbore cements. Nitrogen oxides catalyse oxidation of sulphide dioxide to sulphuric acid which dissolves mineral and may leave sulphur precipitates. The authors mention that injection of both hydrogen sulphide and sulphur dioxide could result in deposition of sulphur which would cause severe pore blocking. Oxygen is also noted to have an effect on dissolution of caprock, but levels would need to be significant and is not likely due to its low solubility.

The conclusions of this study are that there was limited information on how impurities affect storage of carbon dioxide.

3.9 CARBON DIOXIDE IMPURITY DESIGN PARAMETERS (2013)²⁷

The National Energy Technology Laboratory (USA) prepared a report which provides recommendations for carbon dioxide purity before capture, utilisation and storage. These are based on specific requirements for various stages in the process including the transportation pipeline, enhanced oil recovery applications and storage in saline reservoirs. This includes specific purity requirements for co-sequestration of both carbon dioxide and hydrogen sulphide in saline reservoirs. The recommendations are shown in Figure 9.

Component	Unit (Max unless Otherwise noted)	Carbon Steel Pipeline		Enhanced Oil Recovery		Saline Reservoir Sequestration		Saline Reservoir CO ₂ & H ₂ S Co-sequestration		Venting Concerns (See Section 3.0)
		Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	
CO ₂	vol% (Min)	95	90-99.8	95	90-99.8	95	90-99.8	95	20 – 99.8	Yes-IDLH 40,000 ppmv
H ₂ O	ppm _{wt}	300	20 - 650	300	20 - 650	300	20 - 650	300	20 - 650	
N ₂	vol%	4	0.01 - 7	1	0.01 - 2	4	0.01 - 7	4	0.01 – 7	
O ₂	vol%	4	0.01 – 4	0.01	0.001 – 1.3	4	0.01 – 4	4	0.01 – 4	
Ar	vol%	4	0.01 – 4	1	0.01 – 1	4	0.01 – 4	4	0.01 – 4	
CH ₄	vol%	4	0.01 – 4	1	0.01 – 2	4	0.01 – 4	4	0.01 – 4	Yes-Asphyxiate, Explosive
H ₂	vol%	4	0.01 - 4	1	0.01 – 1	4	0.01 – 4	4	0.02 – 4	Yes-Asphyxiate, Explosive
CO	ppm _v	35	10 - 5000	35	10 - 5000	35	10 - 5000	35	10 - 5000	Yes-IDLH 1,200 ppmv
H ₂ S	vol%	0.01	0.002 – 1.3	0.01	0.002 – 1.3	0.01	0.002 – 1.3	75	10 - 77	Yes-IDLH 100 ppmv
SO ₂	ppm _v	100	10 - 50000	100	10 - 50000	100	10 - 50000	100	10 - 50000	Yes-IDLH 100 ppmv
NO _x	ppm _v	100	20 - 2500	100	20 - 2500	100	20 - 2500	100	20 - 2500	Yes-IDLH NO-100 ppmv, NO ₂ - 200 ppmv
NH ₃	ppm _v	50	0 - 50	50	0 - 50	50	0 - 50	50	0 - 50	Yes-IDLH 300 ppmv
COS	ppm _v	trace	trace	5	0 - 5	trace	trace	trace	trace	Lethal @ High Concentrations (>1,000 ppmv)
C ₂ H ₆	vol%	1	0 - 1	1	0 - 1	1	0 - 1	1	0 - 1	Yes-Asphyxiant, Explosive
C ₃ +	vol%	<1	0 - 1	<1	0 - 1	<1	0 - 1	<1	0 - 1	
Part.	ppm _v	1	0 - 1	1	0 - 1	1	0 - 1	1	0 - 1	
HCl	ppm _v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 50 ppmv
HF	ppm _v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 30 ppmv
HCN	ppm _v	trace	trace	trace	trace	trace	trace	trace	trace	Yes-IDLH 50 ppmv
Hg	ppm _v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 2 mg/m ³ (organo)
Glycol	ppb _v	46	0 - 174	46	0 - 174	46	0 - 174	46	0 - 174	
MEA	ppm _v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	MSDS Exp. Limits 3 ppmv, 6 mg/m ³
Selexol	ppm _v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	

*Not enough information is available to determine the maximum allowable amount

Figure 9: Recommended maximum impurity levels in carbon dioxide for various stages of CCS

As shown in Figure 9, the report agrees with previous reports reviewed in the section, with limits assigned for nitrogen, oxygen, water, argon, hydrogen sulphide, sulphur dioxide and nitrous oxides. The report provides rationales for setting limits for these impurities which are based on:

- Minimising ductile fracture potential of pipelines
- Reducing amount of compression work by minimising amounts of non-condensable gases

- Reducing toxicity of impurities in case of a carbon dioxide leak
- Reducing oxygen specifically for EOR to reduce reactions with hydrocarbons and prevent growth of aerobic bacteria.

A summary of the rationales for each maximum impurity level is shown below in Table 1.

Table 1: Rationale for maximum impurity levels set in ‘Carbon Dioxide Impurity Design Parameters’ report

Impurity	Rationale
Water (H ₂ O)	Reacts with sulphur to produce sulphuric acid which is corrosive
Nitrogen (N ₂)	Non-condensable gas
Oxygen (O ₂)	Non-condensable gas, thinning of pipeline, reacts with hydrocarbons, enhances growth of aerobic bacteria
Argon (Ar)	Non-condensable gas
Methane (CH ₄)	Non-condensable gas, pipeline ductility issues
Hydrogen (H ₂)	Non-condensable gas, lower recovery of oil
Carbon monoxide (CO)	Toxic
Hydrogen sulphide (H ₂ S)	Toxic
Sulphur dioxide (SO ₂)	Toxic
Nitrous oxides (NO _x)	Toxic
Ammonia (NH ₃)	Toxic
Carbonyl sulphide (COS)	Toxic
Hydrogen cyanide (HCN)	Toxic
Ethane (C ₂ H ₆)	Explosive, might cause asphyxiation at high concentrations
Propane+ (C ₃ +)	Explosive, might cause asphyxiation at high concentrations
Particulates	<i>Not specified</i>
Hydrochloric acid (HCl)	Toxic
Hydrofluoric acid (HF)	Toxic
Mercury (Hg)	Toxic
Glycol	Damage to seals and other components
Monoethanolamine (MEA)	Toxic
Selexol	Effects not known

As highlighted in Table 1, the authors of this report suggest that further work is required to set maximum impurity levels for hydrochloric acid, hydrofluoric acid, hydrogen cyanide, mercury and selexol.

3.10 THE EFFECT OF CARBON DIOXIDE PURITY ON THE DEVELOPMENT OF PIPELINE NETWORKS FOR CARBON CAPTURE AND STORAGE SCHEMES (2014)²⁸

This paper provides some expected impurities in carbon dioxide following pre-combustion, post-combustion and oxyfuel combustion and compares these to the carbon dioxide purity specifications provided by the Dynamis report (Section 3.4). The authors focus particularly on effects impurities have to the pipeline design and it was found that large amounts of impurities may affect the inlet pressure. For example, hydrogen at 1 cmol mol⁻¹ was found to increase the inlet pressure by 6%. It was recognised that there are many factors to consider when assigning purity requirements for the pipeline including fracture control, corrosion, cracking, hydrate formation and health and safety.

3.11 DEVELOPMENT OF A CARBON DIOXIDE SPECIFICATION FOR A CCS HUB NETWORK (2017)²⁹

This report was produced as a deliverable of the CarbonNet Project and provides recommendations for the allowable level of impurities in carbon dioxide used for CCS. The final specification the report provides is shown in Figure 10.

COMPONENT	UNITS	LOWER	UPPER
CO ₂	vol%	Balance of stream (> 93.5)	
H ₂ O	Max. ppmv		100
N ₂	Max. vol%	2 (total non-condensables)	5 (total non-condensables)
H ₂	Max. vol%		
Ar	Max. vol%		
O ₂	Max. vol%		
CH ₄	Max. vol%		
CO	Max. ppmv	900	5000
H ₂ S	Max. ppmv	100	100 ²
SO ₂	Max. ppmv	200	2000
NO _x	Max. ppmv	250	2500
HCN	Max. vol%	Subject to materiality threshold ³	
Other hydrocarbons	Max. vol%	0.5% on total "Other Hydrocarbons"	
Temperature	°C	Critical Point ⁴	50
Pressure	bar	(Subject to hydraulic modelling and the location of the CO ₂ source)	

Figure 10: Proposed carbon dioxide quality specification

The authors state a lower as well as upper limit for each impurity, which they call an 'envelope' approach, to allow a range of potential sources to participate. However, it may be even more flexible to eliminate the lower limit altogether. They also state that there may be other minor impurities present in the carbon dioxide depending on the production process, such as hydrogen cyanide, hydrochloric acid, hydrofluoric acid and amines. In the cases where these impurities pose a health safety risk (from a potential leak), the impurity levels should at least be below the short term exposure limits or time weighted averages as shown in Figure 11.

MINOR COMPONENT	STEL [PPMV] ⁹
Amines (MEA)	6
HCN	4.7
Hg	0.003
HF	3*
HCL	5*
C ₂ H ₄ O (Acetaldehyde)	50
Ethylene glycol (vapour)	40
Ethylene glycol dinitrate	0.05*

Figure 11: Short term exposure limits (or *time weighed averages) taken from the report.

4 RATIONALE FOR PURITY SPECIFICATIONS

Table 2 provides a summary of the purity requirements taken from each of the reports or papers reviewed in Section 3. The rationale for these selected impurities are also explained in Section 3, but where different reports provide alternative maximum limits, a rationale for the selected limit is provided. Where maximum impurity levels are selected based on the long term exposure limits (for health and safety considerations), the work exposure limits provided by the Health and Safety Executive (HSE) have been used to ensure they comply with UK recommended best practice.³⁰ The quality requirements for carbon dioxide utilisation are not included in the table as there are various uses of carbon dioxide, some which may not adhere to national or international regulations but companies own internal practice. Not enough information on Selexol is currently known to provide maximum limits.

Table 2: Summary of purity specifications

	Pipeline	Storage		
		<i>Saline reservoir sequestration</i>	<i>Unmineable coal seams</i>	<i>Oil and gas recovery</i>
H ₂ O ^a	Use same maximum limits as storage method	300 $\mu\text{mol mol}^{-1}$	300 $\mu\text{mol mol}^{-1}$	300 $\mu\text{mol mol}^{-1}$
H ₂ S ^b		5 $\mu\text{mol mol}^{-1}$	5 $\mu\text{mol mol}^{-1}$	5 $\mu\text{mol mol}^{-1}$
CO ^b		20 $\mu\text{mol mol}^{-1}$	20 $\mu\text{mol mol}^{-1}$	20 $\mu\text{mol mol}^{-1}$
O ₂		4 cmol mol^{-1}	4 cmol mol^{-1}	100 $\mu\text{mol mol}^{-1}$
CH ₄ ^c		4 cmol mol^{-1}	4 cmol mol^{-1}	1 cmol mol^{-1}
N ₂ ^c		4 cmol mol^{-1}	4 cmol mol^{-1}	1 cmol mol^{-1}
Ar ^c		4 cmol mol^{-1}	4 cmol mol^{-1}	1 cmol mol^{-1}
H ₂ ^c		4 cmol mol^{-1}	4 cmol mol^{-1}	1 cmol mol^{-1}
SO _x ^b		0.5 $\mu\text{mol mol}^{-1}$	0.5 $\mu\text{mol mol}^{-1}$	0.5 $\mu\text{mol mol}^{-1}$
NO _x ^b		0.5 $\mu\text{mol mol}^{-1}$	0.5 $\mu\text{mol mol}^{-1}$	0.5 $\mu\text{mol mol}^{-1}$
NH ₃ ^b		25 $\mu\text{mol mol}^{-1}$	25 $\mu\text{mol mol}^{-1}$	25 $\mu\text{mol mol}^{-1}$
C ₂ H ₆		1 cmol mol^{-1}	1 cmol mol^{-1}	1 cmol mol^{-1}
C ₃ ⁺		1 cmol mol^{-1}	1 cmol mol^{-1}	1 cmol mol^{-1}
Particulates		1 $\mu\text{mol mol}^{-1}$	1 $\mu\text{mol mol}^{-1}$	1 $\mu\text{mol mol}^{-1}$
HCl ^b		1 $\mu\text{mol mol}^{-1}$	1 $\mu\text{mol mol}^{-1}$	1 $\mu\text{mol mol}^{-1}$
HF ^b		1.8 $\mu\text{mol mol}^{-1}$	1.8 $\mu\text{mol mol}^{-1}$	1.8 $\mu\text{mol mol}^{-1}$
HCN ^b		0.9 $\mu\text{mol mol}^{-1}$	0.9 $\mu\text{mol mol}^{-1}$	0.9 $\mu\text{mol mol}^{-1}$
Hg ^b		0.02 mg m^{-3}	0.02 mg m^{-3}	0.02 mg m^{-3}
Glycol		46 nmol mol^{-1}	46 nmol mol^{-1}	46 nmol mol^{-1}
MEA ^b		1 $\mu\text{mol mol}^{-1}$	1 $\mu\text{mol mol}^{-1}$	1 $\mu\text{mol mol}^{-1}$

a – water can react with sulphur containing species to produce sulphuric acid; limiting water to less than 300 ppm will prevent damage from this product

b – long term exposure limits set by HSE

c – the species increase the miscibility pressure, making it more difficult to recover oil, so the limits for oil and gas recovery are reduced to 1 cmol mol⁻¹

5 METROLOGY REQUIREMENTS

5.1 CARBON DIOXIDE PURITY

The literature reviewed in this report provide recommendations for the maximum levels of impurities that should be present in carbon dioxide used for CCS. The information is taken from different sources (no literature from the UK provided purity recommendations) and the recommendations agree quite well. However, the data that has been reviewed in this report is not enough to make informative decisions on carbon dioxide purity for storage. Further research is required to produce accurate and traceable data that can be used to assign these limit values with a sufficient degree of confidence. For example, rigorous testing of pipeline and underground storage materials is required to understand how the presence of impurities may affect, for example, corrosion. Some impurities such as nitrogen, oxygen and argon should be limited as the presence of these components at high level could reduce storage capacity. However, it is clear that the conditions of storage, such as temperature and pressure, also determine how much effect the presence of non-condensable gases would have to storage capacity.¹³ A more detailed study may be required to select an optimum condition compromising between efficiency of the compression stage and purity levels that can be achieved with conventional purification methods (ultimately looking at the economics of both). This study would require further investigation into the expected purity of carbon dioxide from amine scrubbers. Until these studies are carried out, Table 2 probably provides the best available guidance on a suitable carbon dioxide purity specification for CCS processes in the UK.

When certifying the composition and purity of carbon dioxide used in the CCS process, the measurement will need to be traceable to the SI. This ensures that the measurements are accurate (providing confidence when transporting and storing the carbon dioxide) and internationally comparable, ensuring a common global assessment that can be easily compared to Table 2 of this report. NPL is the UK's National Metrology Institute and has the role of providing traceability for measurements of gas composition performed in UK industry. New purity requirements for CCS will require NPL to provide traceable Primary Reference Materials containing the impurities listed in Table 2 in a carbon dioxide gas matrix. This may be challenging due to the unique properties of carbon dioxide compared to other gases frequently used as the matrix gas in Primary Reference Materials; as shown in Figure 12 carbon dioxide will liquefy at around 50 bar (at room temperature). Some laboratories would perhaps wish to use calibration standards in nitrogen (or alternative gas) matrices opposed to carbon dioxide; but testing would be required to ensure that changing gas matrix would not affect accuracy of the measurement.

The potential change in phase when sampling liquid carbon dioxide from a CCS site would also raise the question of whether impurities in gas would behave the same as in liquid (i.e. if low pressure carbon dioxide is sampled from a liquid storage site would the impurities be present at the same level as in the original pressurised liquid). If this did pose a problem, analytical techniques that are capable of monitoring purity whilst the carbon dioxide is in the liquid phase may need to be developed. This is a similar problem faced by liquid natural gas providers where Raman spectroscopy has been identified as a suitable technique for determining composition whilst still in the liquid phase.³¹ Additionally there is the possibility that certain impurities segregate and collect at certain locations within the storage site; this must be studied to understand whether sampling location has an effect on composition of the carbon dioxide sample.

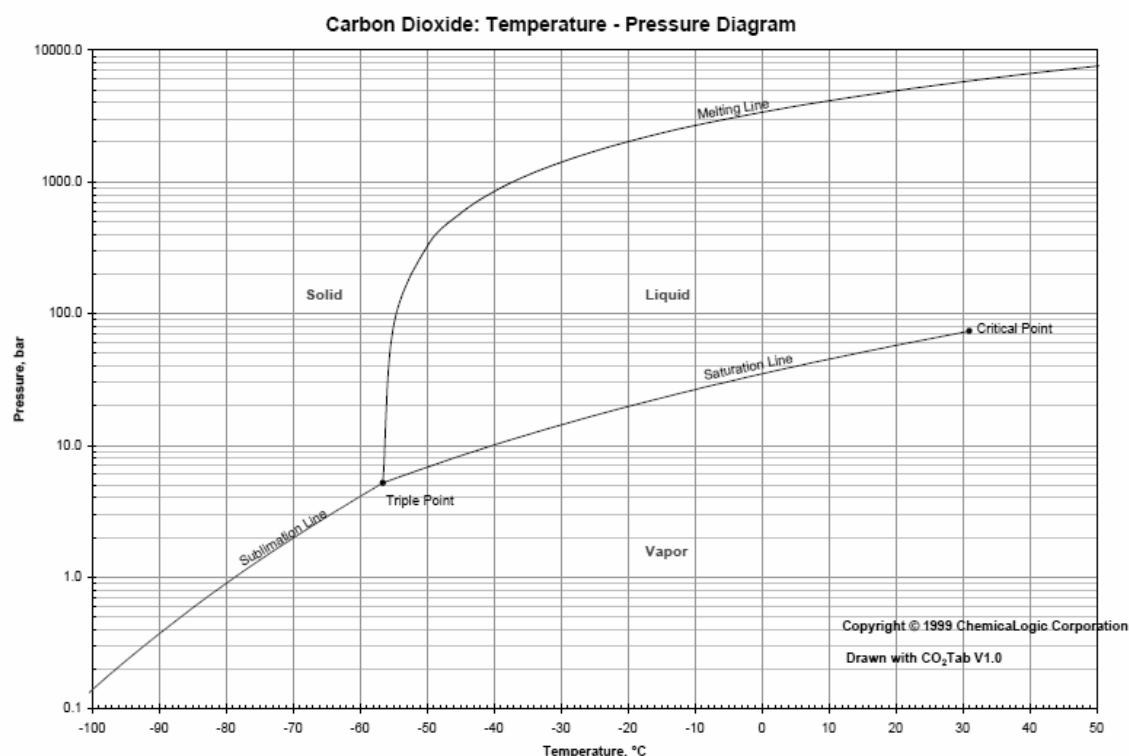


Figure 12: Carbon dioxide pressure-temperature curve

Additionally, there is little information regarding how low level impurities behave in carbon dioxide gas mixtures regarding reactivity and stability. NPL will be required to develop new gas analytical methods in order to certify these mixtures and check stability. Due to the large number of impurities that may need to be analysed, it is likely that gas analysers capability of measuring several impurities in a single method would be used (such as gas chromatography with mass spectrometer) opposed to combining several techniques that focus on a single impurity (such as cavity ringdown spectroscopy). These new analytical methods will be important for providing initial support to UK industries that require traceable measurements to verify the purity of carbon dioxide and to validate commercially available online purity analysers. There are several manufacturers who already offer gas analysers suitable for online monitoring the quality of carbon dioxide.³²⁻³³

As mentioned in a paper by NEL,³⁴ the presence of impurities will have an adverse effect on flow metering, which is necessary for regulatory measurement under the EU Emissions Trading System (ETS). Flow metering is required for custody transfer and fiscal purposes, and for monitoring the various processes across the CCS network, including controlling the volume of carbon dioxide being injected into the geological storage formation. Flow meters are generally designed to operate in one specific phase, either gas or liquid. However, even trace levels of contaminants will invalidate the phase diagram and equations of state for pure carbon dioxide. This is important because under the ETS, the mass of annually transferred carbon dioxide is required to be determined within a maximum uncertainty of less than $\pm 1.5\%$. Without knowing the exact phase envelope and physical properties of the carbon dioxide stream, it will be extremely difficult to control the CCS processes and achieve the required measurement uncertainty.

The NEL report also discusses the importance of being able to detect leaks from CCS sites. With regards to leak testing, methods are required to detect carbon dioxide leaks from underground storage and pipelines used for CCS. This may require spectral imaging to detect for leaks across a large surface.

As specified in one of the reports reviewed, quality standards for carbon dioxide used in CCS are required but currently do not exist.²⁰ A technical report is currently in development by ISO TC 265 which is the relevant International Standardisation Committee for CCS and this will likely include further information on required carbon dioxide composition. However, as this report is not available yet it cannot be used by the UK industry as guidance.

5.2 EMISSION MONITORING

As noted in Section 1, NPL have previously carried out an assessment of the requirements and potential technology solutions for monitoring the emissions in the capture, transport and storage elements of the CCS chain³. The key emission monitoring requirements are summarised below.

The EU Directive 2009/31/EC: Geological Storage of Carbon Dioxide,³⁵ forms the framework for environmental regulation of CCS across EU Member States. An Environmental Impact Assessment is mandatory and leakage scenarios must be included for any proposed location. A monitoring plan must also be set up to verify that the injected carbon dioxide is behaving as expected. The potential sources of carbon dioxide emissions are shown in Figure 13.

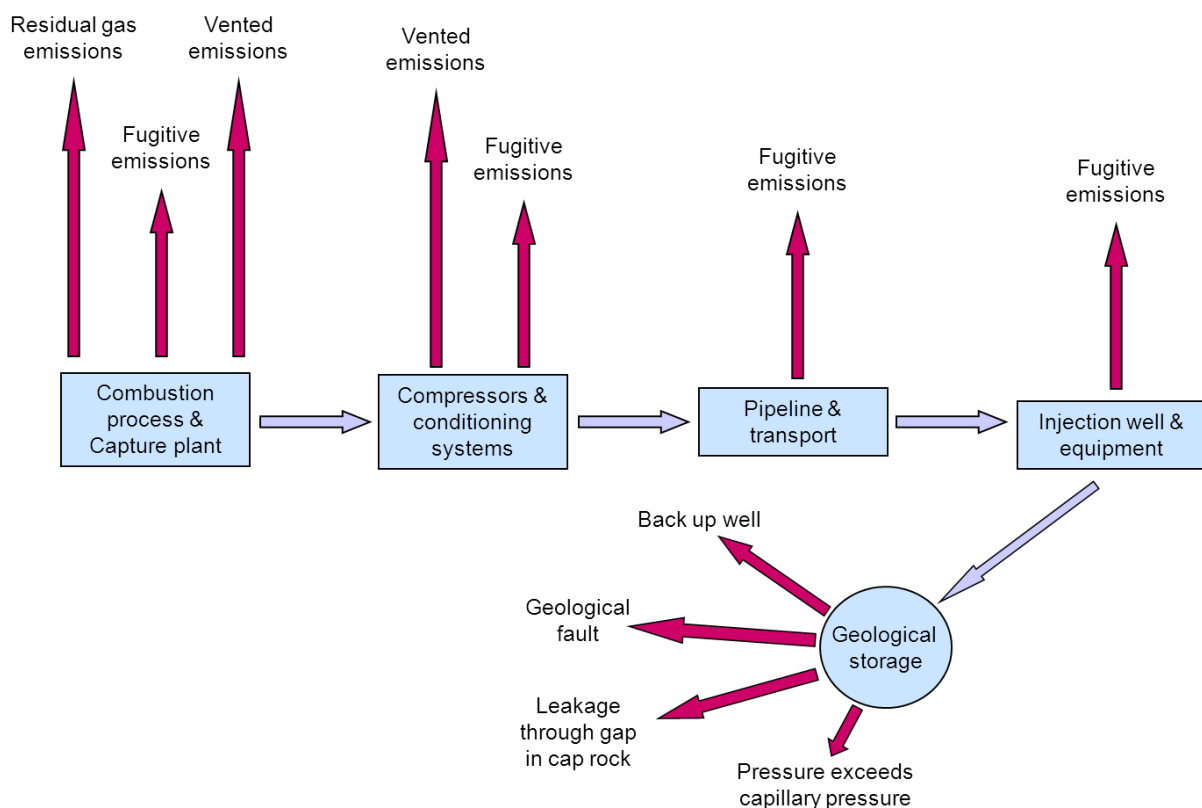


Figure 13: Potential emission sources from the CCS process.

Detection, monitoring and measurement of carbon dioxide will be required throughout the process for a number of purposes:

- Measuring the amount of carbon dioxide captured
- Measuring the amount of carbon dioxide stored
- Accounting for carbon dioxide lost during the process
- Detecting fugitive emissions

- Determining the effectiveness of the storage process
- Detecting leaks for safety reasons

The emissions of carbon dioxide can be divided into different categories:

- **Residual Gas Emissions**, which are defined as those after the capture process which are not captured and emitted to the atmosphere. It is expected that the capture process will be 85 to 95% efficient. Measurement will be on a continuous measurement basis. These emissions are from a known source and location and measured close to the point of release. In order to meet the regulations to participate in the EU ETS, measurements of the carbon dioxide in the stream before and after capture must be made to a maximum uncertainty of 2.5%.
- **Vented emissions**, these can be deliberate and pre-planned or for emergency reasons, but will occur from known sources (valves, vents, etc.). Since they are most likely to be controlled, monitoring should be possible by flow and pressure measurements unless on a low level.
- **Fugitive emissions**, which are those which are unintended or irregular such as leaks from valves, pipe connections, and mechanical seals. They will be located where carbon dioxide handling equipment is situated such as compression stages and pipelines and will generally be of a point source nature, although accumulation and pooling may occur around leaks. Fugitive emissions may also occur from the geological storage area itself such as leaks through geological faults or unknown/unsealed wells and migration through gaps in caprock. The carbon dioxide emission may take place outside the vicinity of the injection site as it may be transported through porous layers below the surface. The type of emission can therefore be both from point sources, associated with the injection site or old wells or diffuse covering a wide area.

Methods of monitoring carbon dioxide emissions can take many forms, some of which are briefly summarised below:

- Acoustic imaging and sonar bathymetry (offshore) – employed for offshore storage sites where detailed mapping of the surface and near surface can be imaged to detect gas escape structures at the seabed such as pockmarks and possibly direct detection of areas of free gas.
- Soil gas methods – sampling of the levels of carbon dioxide in surface soils above and around a storage area can be carried out using accumulation chambers or small portable probe systems most likely using non-dispersive infrared (IR) technology. Typical carbon dioxide concentrations are much higher than those in the atmosphere and detailed baseline surveys are required.
- Atmospheric measurement – measurement of atmospheric carbon dioxide concentrations in and around the CCS process will most likely rely on absorption at infrared wavelengths. Non-dispersive IR devices use a broadband IR source and a sample chamber to pass the IR light through in a closed path arrangement. Tunable diode laser instruments can be used in both open and closed paths measuring the absorption in either sampling chambers or in the open atmosphere. Differential Absorption LIDAR is another atmospheric measurement technique that can be used to directly measure carbon dioxide emissions from known and fugitive sources.³⁶⁻³⁷

Given the wide range of monitoring requirements and potential techniques that could be applied to these, a crucial metrological requirement will be the validation of measurement methods for specific CCS applications. This validation should follow the activities and capabilities that have already been

put in place to meet existing emission monitoring needs, from laboratory assessment of instrument performance and validation of techniques under field conditions, potentially through to formal instrument type approval and proficiency testing schemes.

6 RECOMMENDATIONS

It is clear that measurement challenges exist which will affect uptake of CCS in the UK; these challenges require further laboratory research and subsequent standardisation. A summary of recommendations to address these challenges are shown in Table 3.

Table 3: Recommendations on required future work to enable carbon capture and storage in the UK

CHALLENGE		IMPACT	RECOMMENDATIONS
CO ₂ purity	There is no guidance on purity requirements for storing and transporting CO ₂ in a CCS process.	Impurities present in the CO ₂ during CCS can reduce process efficiencies, damage equipment/piping and produce hazardous environments where leaks may occur. Without guidance, UK CCS sites may damage their equipment and potentially release toxic impurities in emissions.	Analysis of impurities in real samples of CO ₂ produced by SMR, combustion and other processes (including direct fuel cells, chemical processes etc.).
			Risk assessment of potential impurities from other stages of the CCS process (including from, for example, storage site).
			Development of robust sampling techniques to ensure CO ₂ samples are representative (including an understanding of how composition may change depending on location)
			Laboratory tests to understand how presence of impurities affects pipeline corrosion.
			Laboratory tests to understand how presence of impurities affects rock erosion.
			Theoretical studies to compare CCS efficiencies to CO ₂ purity.
			Recommendations on allowable levels of toxic impurities from CO ₂ leaks (from storage sites).
			Assessment on effects of impurities to accuracy of flow metering.
			Development of primary reference materials comprising expected impurities in carbon dioxide matrix to support laboratory testing.
			Development of commercial gas analysers for CO ₂ purity analysis.
			Assessment of differences in purity when sampling liquid or gaseous CO ₂ .
			An International Standard that provides guidance on CO ₂ purity for CCS should be developed.
Emission monitoring	Validated measurement capability does not yet exist to ensure CCS processes can verify CO ₂ emissions from the complete process.	CCS sites may not be able to provide evidence to meet EU Directive 2009/31/EC: Geological Storage of Carbon Dioxide.	Validation of acoustic imaging and sonar bathymetry techniques to map storage sites for CCS.
			Validation of techniques to monitor atmospheric CO ₂ emissions (or key impurities) from CCS capture, transport and storage facilities.
			Development of an official approval/certification scheme for CCS emission monitoring methods.
			An International Standard that provides guidance on monitoring CO ₂ emissions for CCS should be developed.

As UK CCS sites are already in operation or development stage, there is an immediate need for these recommendations to be carried out. Relevant funding may be from UK schemes such as Innovate UK, direct UK government funding (e.g. BEIS) or European funding such as through the European Metrology Programme for Innovation and Research.

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