CO_2 quality in the ship-based CO_2 capture context

Deliverable 2.4.1

Author: Juliana Monteiro (TNO)

Release Status: FINAL

Dissemination level: Public

Date: 10 April 2025

Filename and version: EverLoNG_D2.4.1 CO2 quality in the OCC context v 1.0

The EverLoNG project is funded through the ACT programme (Accelerating CCS Technologies, Horizon2020 Project No 691712). Financial contributions have been made by the Ministry of Economic Affairs and Climate Policy, the Netherlands; The Federal Ministry for Economic Affairs and Climate Action, Germany; the Research Council of Norway; the Department for Business, Energy & Industrial Strategy, UK; and the U.S. Department of Energy. All funders are gratefully acknowledged.

1. Document History

This document is stored in the following location:

Filename	D 2.4.1 CO2 quality in the OCC context v 1.0
Location	ACT Everlong/ WP2/ Deliverables

1.1. Revision History

This document has been through the following revisions:

Version No.	Revision Date	Filename	Brief Summary of Changes
1.0			

1.2. Authorisation

This document requires the following approvals:

AUTHORISATION	Name	Signature	Date
WP Leader	Ragnhild Skagestad	Ragnhild Skagestad	10/04/25
Project Coordinator	Marco Linders	Marco Linders Marco Linders (Apr 10, 2025 11:18 GMT+2)	10/04/25

Disclaimer

2. Executive summary

The EverLoNG project covers multiple aspects of the marinization of CO_2 capture – from techno-economic to environmental and regulatory aspects. In this deliverable, the quality of captured CO_2 is discussed, in view of expected impurities and the most recent CO_2 specifications from transport and storage CCS projects.

Onboard Carbon Capture (OCC) was demonstrated in EverLoNG onboard 2 vessels. In both campaigns, the impurities content in the exhaust gases and from the OCC pilot were monitored. The most relevant observation made in the context of CO_2 quality is the relatively high NOx content in the exhaust gas of marine engines. At the Technology Centre Mongstad (TCM), a large CO_2 capture pilot plant in Norway, the NOx content in the raw CO_2 is measured at 0.5 ppmv, which is close to the Northern Lights and Aramis specifications (1.5 ppmv[1]). However, the reported NO_2 content in the flue gases of TCM is below 2.5 ppmv, whereas in the EverLoNG campaigns values in the 50-250 ppmv range were measured (data publicly shared in EverLoNG webinars[2]). This indicates that the NOx content in OCC-produced CO_2 will potentially be higher than specifications.

There are different approaches to tackle this challenge. The first would be to (further) remove NOx from the exhaust gases, for instance by applying selective catalytic reduction (SCR) and/or removing NO_2 in the quench column by applying a sulphite-thiosulphate solution (this could also be integrated in a SOx scrubber). The proposed solutions would add to the treating costs onboard, but have the benefit of protecting the amine-based solvent from NO_2-induced oxidative degradation. Alternatively, and if the presence of relatively high NO_2 content in the liquid CO_2 wouldn't affect the onboard storage tanks, the on-shore CO_2 receiving terminals could be equipped with NOx separation technologies.

Future research should focus on: a) measuring the NOx content in the raw and liquid CO_2 in OCC pilots; b) verifying whether the risks of a potentially high NOx content is acceptable for the on-board storage tanks; c) evaluating and comparing different NOx removal technologies, both from technical and economic aspects. In the EverLoNG campaigns as well as in related literature, it was identified that the NO_2 leads to increased rate of oxidative degradation of solvents. This implies increased rate of formation of degradation products. Therefore, monitoring the presence of other impurities, in particular NH_3 and aldehydes in the raw and liquified CO_2 should also be a focus point in future research.

---

[1] Websites of Northern Lights (NorthernLights-GS-co2-spec2024.pdf) and Aramis (ARM-Template_Memo) projects

[2] Events | EverLoNG, please refer to webinars #1 and #2 for NOx content data and discussions

Table of Contents

1. Document History 1

1.1. Revision History 1

1.2. Authorisation 1

2. Executive summary 3

3. Introduction 5

4. CO_2 quality specifications 6

5. Raw CO_2 quality data 8

6. Conclusions 11

7. References 12

8. Acknowledgements 12

3. Introduction

In the EverLoNG project, the feasibility of capturing CO_2 from the exhaust gas emissions of ships is investigated. The technology proposed for CO_2 capture, amine scrubbing, has reached high technology readiness level (TRL9), and is currently being implemented in different industries, such as cement, power and waste-to-energy. While many aspects of the technology are well documented in literature, the quality of the captured CO_2 remains an under-explored topic.

In CO_2 capture with amines, the exhaust gas is contacted with an aqueous solution of amine (in EverLoNG, the 1st generation solvent 30wt% monoethanolamine in water was used), and CO_2 is transferred from the gas to the liquid phase. In this process, also other gases are absorbed in the liquid, albeit to a much lower extent. This includes O_2, N_2, NO, NO_2 and SO_2. Some of these gases are reactive towards amines (O_2, NO_2, SO_2) and will be at least partially reacted, forming amine degradation products and heat stable salts, while other gases are inert (N_2, NO). The molecules that remain dissolved (as opposed to reacted to other products) in the amine solution when it reaches the regeneration side of the process are likely to be stripped along with CO_2, constituting impurities in the raw captured CO_2.

The onboard carbon capture (OCC) concept proposed in EverLoNG includes a CO_2 liquefaction plant onboard, so that the CO_2 can be stored in tanks as a liquid at ca. 20 bar, -20°C. The steps towards liquefaction include compression, cooling and drying, and it is also common for liquefaction plants to be equipped with additional purification steps. This may include an active carbon bed for adsorbing impurities, a catalytic oxidation step for consuming oxygen (e.g., by reacting it with hydrogen, forming water), and a distillation column for removing non-condensables (O_2, N_2).

The design of the liquefaction plant is generally guided by the CO_2 quality specification, which can be food-grade, or dictated by a CO_2 transport and storage project, such as Northern Lights, Porthos or Aramis. For OCC, we propose that the liquefaction plant is designed only with process constraints in mind. This means that the impurities are separated only to the extent required by the process (e.g., water dew-point to avoid dry ice formation), but without taking any particular specification in mind. We assume that ships equipped with OCC will deliver CO_2 to multiple ports, which will be connected to different transport and storage or utilization projects, and these end-users will have imposed different CO_2 quality specifications. The port-side infrastructure would include a CO_2 purification and re-conditioning unit, so that the pressure, temperature and composition of the CO_2 is adequate to the specific CCUS chain it connects to. This ensures seamless integration between OCC and existing and proposed CCUS projects.

It was the intention of the EverLoNG project to produce data on the composition of the liquefied CO_2 in its 2 on-board demonstration campaigns. However, during the first campaign, the liquefaction unit faced technical challenges and could not be operated. During the second campaign, approximately 1550 kg of CO_2 was successfully liquified and stored on-board in a tank. Unfortunately, potentially due to a mistakenly open valve, all the CO_2 was vented before a sample could be retrieved. Therefore, the project did not achieve its initial target of providing data on CO_2 quality.

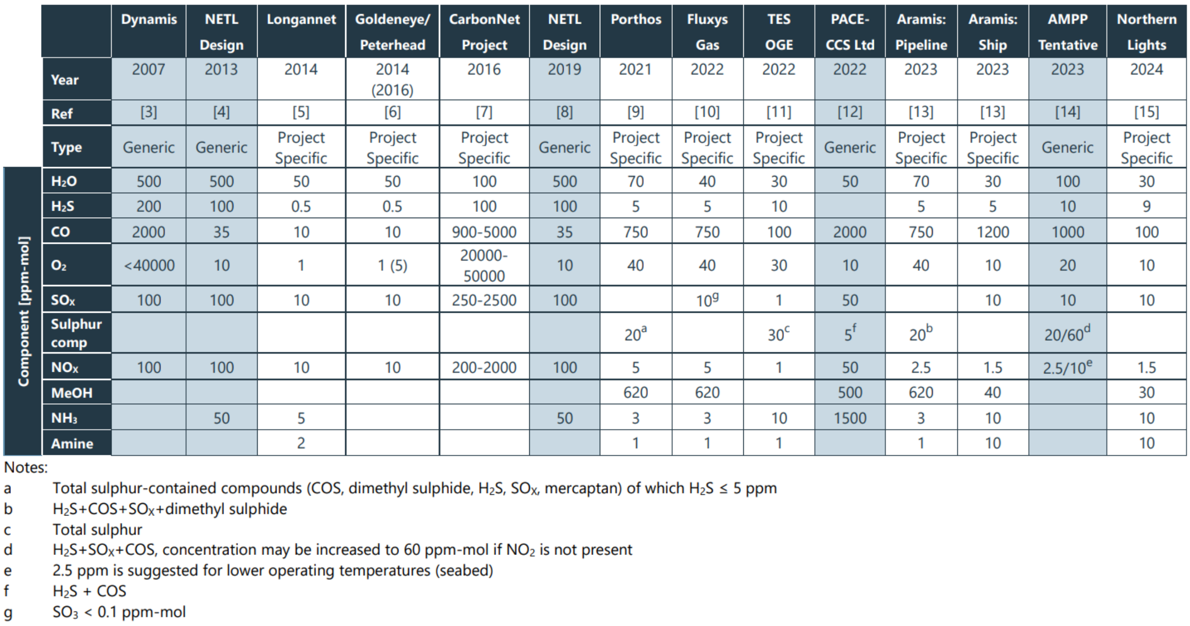
Instead, this report offers a discussion on CO_2 quality in the OCC context, which we believe will be useful in informing future scale-up projects.

4. CO_2 quality specifications

While there is no universal CO_2 quality standard, it is common for transport and storage projects to set their own CO_2 quality specifications. These are typically informed by lab experiments made with CO_2 mixed with impurities, in which the phase behaviour of the mixture is observed, as well as its corrosivity. A recent overview of published CO_2 specifications is given in the Industry Guidelines for Setting the CO_2 Specification in CCUS Chains (Wood, 2024).

There is a wide range of variations amongst the projects, as illustrated in Table 1. When considering only the most recent specifications (2020 onwards), specifications for maximum O_2 content range from 10 to 40 ppmv; SOx from 1 to 50 ppmv; and NOx from 1 to 50 ppmv.

Table 1. CO_2 specifications of various transport and storage projects. Source: Wood, 2024



		Dynamis	NETL Design	Longannet	Goldeneye/ Peterhead	CarbonNet Project	NETL Design	Porthos	Fluxys Gas	TES OGE	PACE-CCS Ltd	Aramis: Pipeline	Aramis: Ship	AMPP Tentative	Northern Lights
	Year	2007	2013	2014	2014 (2016)	2016	2019	2021	2022	2022	2022	2023	2023	2023	2024
	Ref	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[13]	[14]	[15]
	Type	Generic	Generic	Project Specific	Project Specific	Project Specific	Generic	Project Specific	Project Specific	Project Specific	Generic	Project Specific	Project Specific	Generic	Project Specific
Component [ppm-mol]	**H_2O**	500	500	50	50	100	500	70	40	30	50	70	30	100	30
	H_2S	200	100	0.5	0.5	100	100	5	5	10		5	5	10	9
	CO	2000	35	10	10	900-5000	35	750	750	100	2000	750	1200	1000	100
	O_2	<40000	10	1	1 (5)	20000-50000	10	40	40	30	10	40	10	20	10
	SO_x	100	100	10	10	250-2500	100		10^g	1	50		10	10	10
	Sulphur comp							20^a		30^c	5^f	20^b		$20/60^d$	
	NO_x	100	100	10	10	200-2000	100	5	5	1	50	2.5	1.5	$2.5/10^e$	1.5
	MeOH							620	620		500	620	40		30
	NH_3		50	5			50	3	3	10	1500	3	10		10
	Amine			2				1	1	1		1	10		10

Notes:

a	Total sulphur-contained compounds (COS, dimethyl sulphide, H_2S, SO_X, mercaptan) of which $H_2S \leq 5$ ppm
b	$H_2S+COS+SO_X$+dimethyl sulphide
c	Total sulphur
d	H_2S+SO_X+COS, concentration may be increased to 60 ppm-mol if NO_2 is not present
e	2.5 ppm is suggested for lower operating temperatures (seabed)
f	H_2S + COS
g	SO_3 < 0.1 ppm-mol

While Table 1 presents an overview of specifications for different components, it is not exhaustive. For illustration, the complete current specification for the Aramis project is presented in Table 2. We highlight the presence of NH_3, aldehydes, carboxylic acids and amides within the volatile organic compounds (VOCs). These are oxidative degradation products of amines and are expected to be formed regardless of the amine-based solvent chosen. Oxidative degradation and the formation of some of these components have been followed during the EverLoNG onboard carbon capture demonstrations (see confidential deliverables D1.5.1 and D1.5.2, and public webinars #1 and #3).

Online monitoring of the composition of the CO_2 product is a challenge. Aramis is working with sensor providers to establish methodologies. Nevertheless, recent discussions with Aramis partners, point at the direction of leaving monitoring as a responsibility of the CO_2 supplier, as the project's receiving terminal currently does not include any CO_2 purification steps.

Table 2. CO_2 specifications for the Aramis project. Source: [Aramis CCS | CO_2 specifications for Aramis transport infrastructure]

Class	Component	Constraint	Unit	Ships	Pipeline infrastructure
	CO_2	larger than	mol%	balance	95
	H_2O	less than	ppmmol	30	70(1)
inerts	N_2	less than	mol%	-	2.4
inerts	O_2	less than	ppmmol	10	40
inerts	H_2	less than	ppmmol	500	7500
inerts	Ar	less than	mol%	-	0.4
inerts	CH_4	less than	mol%	-	1
inerts	CO	less than	ppmmol	1200	750
inerts	$O_2+N_2+H_2+Ar+CH_4+CO$	sum less than	ppmmol	2000	40000
	NO_x	sum less than	ppmmol	1.5	2.5(4)
sulphur	SO_x	sum less than	ppmmol	10	-
sulphur	H_2S	less than	ppmmol	5	5
sulphur	CarbonylSulphide	less than	ppmmol	-	-(1)
sulphur	DimethylSulphide	less than	ppmmol	-	-(1)
sulphur	H_2S + COS + SO_x + DMS	sum less than	ppmmol	-	20
VOCs	Amine	less than	ppmmol	10	1
VOCs	Formaldehyde	less than	ppmmol	20	-
VOCs	Acetaldehyde	less than	ppmmol	20	-(1)
VOCs	Aldehydes	sum less than	ppmmol	-	10
VOCs	carbolylic acids & amides	sum less than	ppmmol	-	1
VOCs	phosphorus-containing compounds	sum less than	ppmmol	-	1
VOCs	NH_3	less than	ppmmol	10	3
VOCs	Ethylene (C_2H_4)	sum less than	ppmmol	-	-(1)
VOCs	H-Cyanide (HCN)	less than	ppmmol	-	2
VOCs	Total volatile organic compounds (excl. MeOH, EtOH, aldehydes)	sum less than	ppmmol	10	10
VOCs	Methanol	less than	ppmmol	40	620
VOCs	Ethanol	less than	ppmmol	20	20
Heavies	glycols (TEG)	sum less than		-	Follow dew-point specification
Heavies	C_{2+} (aliphatic hydrocarbons)	sum less than	ppmmol	-	1200
Heavies	Aromatic Hydrocarbons	sum less than	ppmmol	-	0.1
Metals	Hg	less than	ppbmol	30	-
Metals	Cadmium + Thalium	sum less than	ppbmol	30	-
Dew-point	Dew point (any liquid phase)	sum less than	°C (@ 20 bar)	-	-10 (2)
Solids	Full removal cut-off diameter	Less than	micron	1(3)	1(3)

It is unlikely that every OCC ship will be fully equipped with sensors to monitor the quality of the produced CO_2 to ensure meeting the desired specifications. Particularly in cases in which the ships will be delivering CO_2 to various projects (with potentially different specifications). This reinforces the need for CO_2 receiving terminals in the OCC-compliant ports which are equipped with CO_2 purification steps and sensors to monitor the CO_2 quality delivered to downstream CO_2 transport and storage projects.

To our knowledge, apart from the food and beverage sector specifications, there are no CO_2 specifications developed particularly for utilization projects. Many of the CO_2 conversion technologies are (electro)catalytic, and impurities even in the ppb level could potentially affect the downstream processes. One can speculate that CO_2 utilization specifications will be even more stringent when it comes to e.g., sulphur-containing impurities (known to poison catalysts).

Another important consideration is regarding how specifications may vary in time. For instance, the Northern Lights specifications shown in Table 1 are a revised and more stringent version than their previous list. With gained operational experience, it is possible that specifications will evolve and could become either more relaxed or more stringent.

5. Raw CO_2 quality data

Information of impurities present in the raw CO_2 stream, produced out of MEA-based capture plants is only scarcely available in literature. Table 3 shows a compilation of raw CO_2 quality data measured in 2 different campaigns at the Test Center Mongstad (TCM), using MEA as the capture solvent. By raw CO_2, we mean the CO_2 produced at the stripper top. Many of the products monitored in the 2015 campaign where below the detection limit. Most of the impurities are within the limits of the Aramis specifications, but the results indicate that O_2 and aldehydes would potentially require control.

Table 3. Compilation of raw CO_2 quality data from TCM campaigns. Sources: Johnsen et al., 2018 and Flø et al., 2017

Component	unit	2015	21-6-2017	11-7-2017	13-7-2017	7-11-2017	9-11-2017	17-11-2017
Acetaldehyde	ppmv	8.51	2.9	6.9	7.1	6.3	6.5	7.7
Formaldehyde	ppmv	0.11	int	int	int	int	int	int
MEA	ppmv	0.030	nd	nd	nd	nd	nd	nd
Diethylamine	ppmv	0.0010	nd	nd	nd	nd	nd	nd
Acetone	ppmv	<0.4	nd	0.2	0.4	0.5	0.4	0.5
O_2+Ar	ppmv		49	cont	cont	28	36	17
N_2	ppmv		420	cont	cont	220	370	310
CO	ppmv		nd	nd	nd	nd	nd	nd
NOx	ppmv		nd	nd	0.5	0.5	0.5	0.5
THC	ppmv		4.8	12	10	11	22	9.3

NH_3	ppmv		1	nd	nd	0.5	nd	0.5
Formamide	mg/Sm^3	<0.03						
Acetamide	mg/Sm^3	<0.03						
Dipropylamine	mg/Sm^3	<0.001						
Dimethylamine	mg/Sm^3	<0.00065						
Methylamine	mg/Sm^3	<0.0006						
Ethylamine	mg/Sm^3	<0.0006						
Propylamine	mg/Sm^3	<0.0006						
Ethylmethylamine	mg/Sm^3	<0.0006						
DEA	mg/Sm^3	<0.0003						
TEA	mg/Sm^3	<0.0003						
TONO	mg/Sm^3	<0.001						
NDMA	mg/Sm^3	<0.0003						
NDELA	mg/Sm^3	<0.0001						
NMOR, NMEA, NPYR, NDEA, NPIP, NDPA, NDBA	mg/Sm^3	<0.0001						

To illustrate the difficulties in monitoring the quality of CO_2, data on impurities content as measured at TCM is given in Table 4. Two methodologies were used for the measurements: (i) online monitoring with gas chromatography (GC) and Fourier Transformed Infrared Spectroscopy (FTIR), and (ii) gas sampling and offline determination by an external lab using multiple methods (see Johnsen et al. 2018 for details).

The relative differences between online and manual measurements are high, particularly considering that the values measure for some of the components (e.g. ammonia, aldehydes, NOx) are in the same order of magnitude as the specifications considered.

A direct comparison between the two measurements for oxygen content determination is not possible, as the offline method gives the sum of oxygen and argon. We have estimated the amount of argon and subtracted it from the offline measurements. While this is not a precise calculation, it points at large discrepancies between the online and offline monitoring methods for oxygen content determination. More data would be required to determine which method is closer to the true O_2 content, and the difference is large enough so that in one case (online) there is no need for oxygen separation, whereas in the other case, there is.

While a large discrepancy is also observed for N_2, this is of less concern as the measured values are in the 100s of ppm range, whereas specifications are in the vol% range. When separating oxygen in a CO_2 liquefaction plant, N_2 will also be separated (along with any other non-condensable). In contrast, if oxygen is combusted (catalytic oxidation), the nitrogen will remain in the final CO_2 product.

Table 4. TCM data on impurities in raw CO_2: online monitoring vs. manual sampling. Source: Johnsen et al. 2018

	21-6-2017		**9-11-2017**	
	Online	Sampling	Online	Sampling
Ammonia	2.2	1	6.1	3.4
NO + NO_2	Nd	Nd	Nd	0.5
SO_2	0.2	Nd	Nd	Nd
Acetaldehyde	1.7	2.9	5.4	6.5
Formaldehyde	0.3	Int	0.6	0.2
N_2	220	420	300	370
O_2	1.8	40*	2	27*
O_2+Ar		49		36

*Value estimated based on calculated Ar content

In a recent report from the SCOPE project (ERA-ACT3), the quality of the liquified CO_2 produced at the Twence pilot plant was monitored by gas chromatography (online sampling). The data indicates that, while the oxygen content in CO_2 can be as high as 30-50 ppmv, optimizing the CO_2 stripper operation by increasing the CO_2 stripper boil-up ratio can lead to quite low O_2 content, meeting the more stringent specifications. This can be clearly seen in the 23rd, 24th and 25th of May data in Figure 1. Therefore, as long as the OCC systems are equipped with a liquefaction plant, which is the assumption here, it is likely that the inerts (non-volatile) content can be adequately controlled onboard.

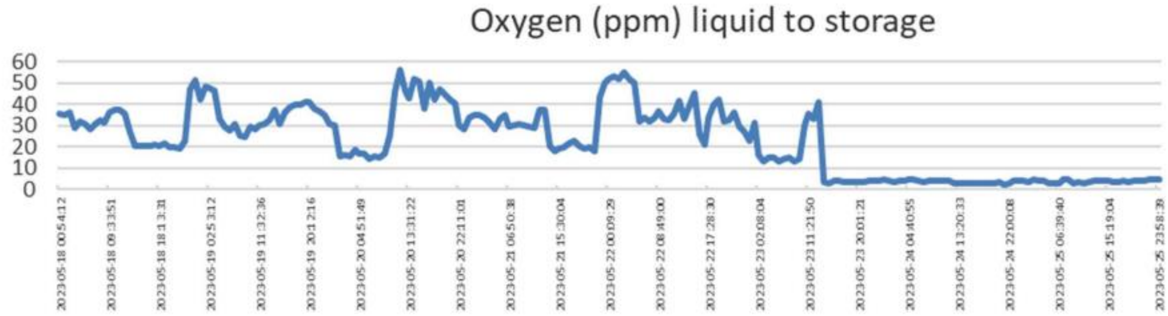


Figure 1. Twence pilot data on liquified CO_2 quality. Source: SCOPE project Deliverable 2.7 [link]

6. Conclusions

OCC was demonstrated in EverLoNG onboard 2 vessels. In both campaigns, the impurities content in the exhaust gases and from the OCC capture pilot were monitored. The most relevant observation made in the context of CO_2 quality is the relatively high NOx content in the exhaust gas of marine engines. At TCM, the NOx content in the raw CO_2 is measured at 0.5 ppmv (Table 3), which is close to the Northern Lights and Aramis specifications. However, the reported NO_2 content in the flue gases of TCM is below 5 ppmv (Hume et al., 2022, Campbell et al., 2022), whereas in the EverLoNG campaigns values in the 50-250 ppmv range were measured. This indicates that the NOx content in OCC-produced CO_2 could potentially be higher than specifications.

There are different approaches to tackle this challenge. The first would be to (further) remove NOx from the exhaust gases, for instance by applying selective catalytic reduction (SCR) and/or separating NO_2 in the quench column by applying a sulphite-thiosulphate solution (this can also be integrated in a SOx scrubber). These add to the treating costs onboard, but has the benefit of protecting the amine-based solvent from NO_2-induced oxidative degradation.

Alternatively, and if the presence of relatively high NO_2 content in the liquid CO_2 wouldn’t affect the onboard storage tanks, the on-shore CO_2 receiving terminals could be equipped with NOx separation technologies.

Future research should focus on: measuring the NOx content in the raw and liquid CO_2 in OCC pilots; verifying whether the risks of a potentially high NOx content is acceptable for the on-board storage tanks; evaluating and comparing different NOx removal technologies, from both technical and economic aspects. In the EverLoNG campaigns as well as in related literature, it was identified that the NO_2 leads to increased rate of oxidative degradation of solvents. This implies increased rate of formation of degradation products. Therefore, monitoring the presence of other impurities, in particular NH_3 and aldehydes in the raw and liquified CO_2 should also be a focus point in future research.

7. References

Campbell, M., Akhter, S., Knarvik, A., Muhammad, Z., Wakaa, A., 2022. CESAR1 Solvent Degradation and Thermal Reclaiming Results from TCM Testing. SSRN Electron. J. https://doi.org/10.2139/ssrn.4286150

Flø, N.E., Faramarzi, L., De Cazenove, T., Hvidsten, O.A., Morken, A.K., Hamborg, E.S., Vernstad, K., Watson, G., Pedersen, S., Cents, T., Fostås, B.F., Shah, M.I., Lombardo, G., Gjernes, E., 2017. Results from MEA Degradation and Reclaiming Processes at the CO2 Technology Centre Mongstad. Energy Procedia 114, 1307–1324. https://doi.org/10.1016/j.egypro.2017.03.1899

Hume, S., McMaster, B., Drageset, A., Shah, M.I., Kleppe, E.R., Campbell, M., 2022. Results from Cesar1 Testing at the Co2 Technology Centre Mongstad. Verification of Residual Fluid Catalytic Cracker (Rfcc) Baseline Results. SSRN Electron. J. https://doi.org/10.2139/ssrn.4280571

Johnsen, K., Kleppe, E.R., Faramarzi, L., Benquet, C., de Koeijer, G., de Cazenove, T., Morken, A.K., Flø, E., Shah, M.I., Aronsson, M., Ullestad, Ø., 2018. CO2 product quality: assessment of the range and level of impurities in the CO2 product stream from MEA testing at the Technology Centre Mongstad (TCM).

Wood, 2024. Industry Guidelines for Setting the CO_2 Specification in CCUS Chains (522240-WP12-REP-001). Wood. Available at: Industry Guidelines for Setting the CO2 Specification in CCUS Chains | Wood

8. Acknowledgements

The EverLoNG project is funded through the ACT programme (Accelerating CCS Technologies, Horizon2020 Project No 691712). Financial contributions have been made by the Ministry of Economic Affairs and Climate Policy, the Netherlands; The Federal Ministry for Economic Affairs and Climate Action, Germany; the Research Council of Norway; the Department for Business, Energy & Industrial Strategy, UK; and the U.S. Department of Energy. All funders are gratefully acknowledged.