CO_2 Offloading, Storage Facility and Solvent Reclaiming Facility

WP1 Solvent degradation

D2.1.3 Design Package of Onshore CO_2 Offloading and Storage Facility and Solvent Reclaiming Facility

D4.4.1 CO_2 Offloading and Receiving Port

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Executive Summary

The maritime sector aims to reduce CO_2 emissions from international shipping, reaching net zero by 2050.. Ship-Based Carbon Capture (SBCC) is proposed as a low-cost alternative to decarbonize the maritime sector, as compared to zero-emission fuels (ammonia, hydrogen). The objective of the EverLoNG project is to accelerate the implementation of SBCC technology by:

- Demonstrating SBCC on-board liquid natural gas (LNG) fueled ships
- Optimizing SBCC integration with the existing ship infrastructure
- Facilitating the development of SBCC-based full carbon capture, utilization, and storage (CCUS) chains
- Facilitating the regulatory framework for the technology

Los Alamos National Lab (LANL) and NexantECA (subcontractor to LANL) participated in the EverLoNG project from the U.S.A side to provide analytical support for quantifying the solvent degradation rates and develop an overall solvent management strategy as well as a CO_2 offloading strategy for the solvent-based SBCC system. We carried out detailed testing to quantify the monoethanolamine (MEA) concentration, CO_2 loading, and MEA degradation. We also developed the process design package and cost estimate for the Onshore Facility for the EverLoNG project, which includes CO_2 offloading and processing as well as spent solvent reclaiming infrastructure.

For MEA quantification, we analyzed MEA concentration, the net CO_2 loading, and impurities and degradation products in the spent MEA. We received three batches of MEA samples from the SBCC-equipped ships. The first and second samples were from the TotalEnergies campaign received in December 2023 and March 2024, respectively. The third sample was from the Sleipnir campaign, received in November 2024. The MEA concentration for the initial TotalEnergies campaign was only 18%, which was later increased to 30% for the second TotalEnergies campaign and the Sleipnir campaign. The CO_2 loading with carbamate was in the range of 0.4-0.45 mol_{CO2}/mol_{MEA}. The major cation was in the form of sodium, which was due to use of NaOH for quenching the flue gas to adjust the pH (at some point in the start of the campaigns, quench water was carried over to the solvent). For anions, MEA oxidation was the major cause for the formation of formate, acetate, and oxalate, while NOx in the flue gases resulted in nitrate salts. For MEA degradation products, we identified HEPO as the major product, followed by OZD and acetamide for the TotalEnergies campaign, with similar results seen in the Sleipnir campaign.

When a ship equipped with SBCC completes a journey and reaches a port, it needs to offload the captured and stored CO_2 (besides the normal operations of cargo off-loading, bunkering, etc.). This means that the port needs a CO_2 offloading infrastructure. Logically, the port also must be connected to a CO_2 transport network, via which the CO_2 shall be destined to geological storage sites, direct CO_2 usage applications, or CO_2 conversion plants. We developed the design for CO_2 receiving and processing as well as spent solvent receiving and reclaiming to treat spent MEA solvent from the SBCC system. The full Onshore Facility is thus composed of two main systems: the CO_2 Plant, for CO_2 receiving from the ship and processing to CO_2 pipeline specifications, and the MEA Reclamation Plant, for spent solvent receiving and solvent reclaiming to provide reclaimed MEA back to the ship. The cost estimates for the full Offshore Facility, including CO_2 offloading and processing and MEA receiving and reclamation was 222 $\$/ton_{CO2}$ due to the low capacity factor of 12.5%. This is due to the low frequency of ship arrivals to the port, arriving every 32 days to offload CO_2 and spent MEA. However, the cost significantly decreased to 48 $\$/ton_{CO2}$ with more ships coming to the port every 4 days (based on the ship turnaround time at the port) for CO_2 offloading and spent solvent reclaiming. This shows that the Onshore Facility is significantly more economical with several ship arrivals at the port compared to a single ship arriving every 32 days.

1. Identification of the project and report

Project title: Demonstration of ship-based carbon capture on LNG fueled ships (EverLoNG)
Project ID: LANL-AE-314-281
Coordinator: Dr. ir. M.J.G. (Marco) Linders
Reporting date: 3/27/25

2. Description of Activities and Intermediate Results

2.1. WP1: Quantifying Solvent Degradation Rates (Samples from Ship)

The EverLoNG project included two pilot scale demonstrations of ship-based carbon capture (SBCC); the TotalEnergies campaign and the Sleipnir campaign. The CO_2 in the flue gas from the ship's engine was directly captured using monoethanolamine (MEA). We received 3 MEA samples from the ships, to quantify the MEA concentrations in water, the amount of CO_2 captured, and MEA degradation products. The first 2 samples were from the TotalEnergies ship campaigns received in December 2023 and March 2024, while the third sample was from Sleipnir campaign received in November 2024.

2.1.1. Quantifying solvent degradation rates from the 1st pilot test on TotalEnergies

MEA concentration and CO_2 loading

The first sample we received from the TotalEnergies campaign was in December 2023, the second was in March 2024 and the third one was received in November 2024. For the first sample, we only estimated the MEA concentration using ^{1}H NMR (Nuclear magnetic resonance). We carried out NMR testing of these samples to quantify the MEA concentration and CO_2 captured. An aliquot of sample solution was pipetted into an NMR tube for each sample we received without further diluting in any deuterated solvent. Solution ^{1}H NMR spectra were collected on a 400 MHz Avance III Nanobay spectrometer. Then we completed the integrations for the 1H data of these samples. The following assumptions were made for analyzing the data: 1) we assume that the MEA and carbamate are fully protonated to calculate the molar mass, and 2) we average the total intensity of the two MEA and two carbamate peaks instead of just using the best-separated peaks. Figure 1 shows the MEA concentration and net CO_2 loading (assuming CO_2 is only captured as carbamate). The MEA concentration for 6 samples was in the range of 17-19 wt.% (see Figure 1a). The average MEA concentration was 18.2 ±0.5%. It may be noted that the MEA concentration is much lower than the desired concentration of 30 wt.% in water. Therefore, an additional 170 g of pure MEA per kg of exiting MEA-water solution needs to be added to existing mixture, to reach a desired concentration of 30 wt.%. Due to higher water content, the CO_2 was not regenerated at the desired rate, and the concentration of lean was in range of 35% while for rich sample was in range of 40%.

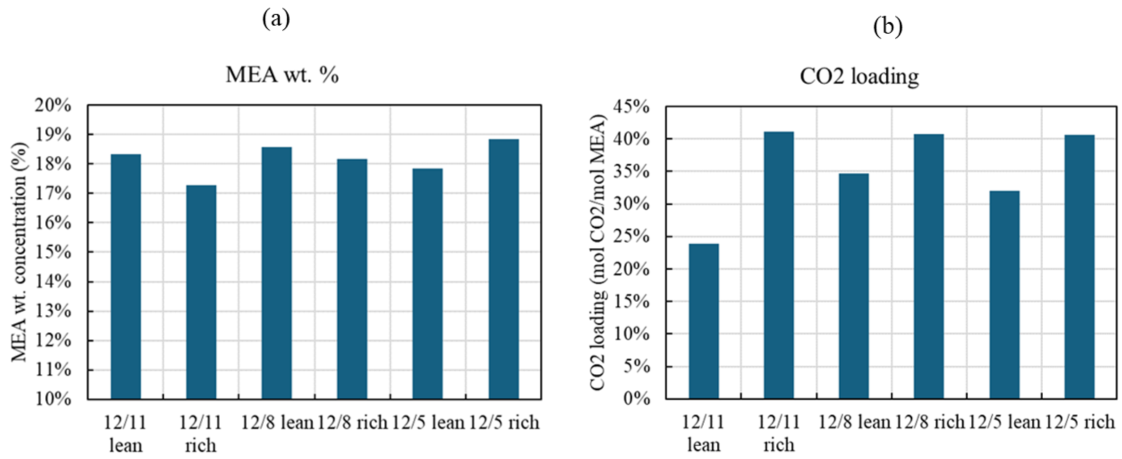


Fig. 1: *MEA wt. concentration in water (a) and CO_2 loading in (b) for 6 different sample received in December from 1st pilot test on TotalEnergies*

We received additional MEA samples from ship in March of 2023. We carried out tests for MEA concentration, CO_2 loading, and MEA degradation. Additional fresh MEA was added to samples in the ship, and the MEA concentration measured was in range of 30-25wt% (see Figure 2, from 12/23 when additional MEA was added). The MEA concentration gradually reduced, suggesting degradation over time.

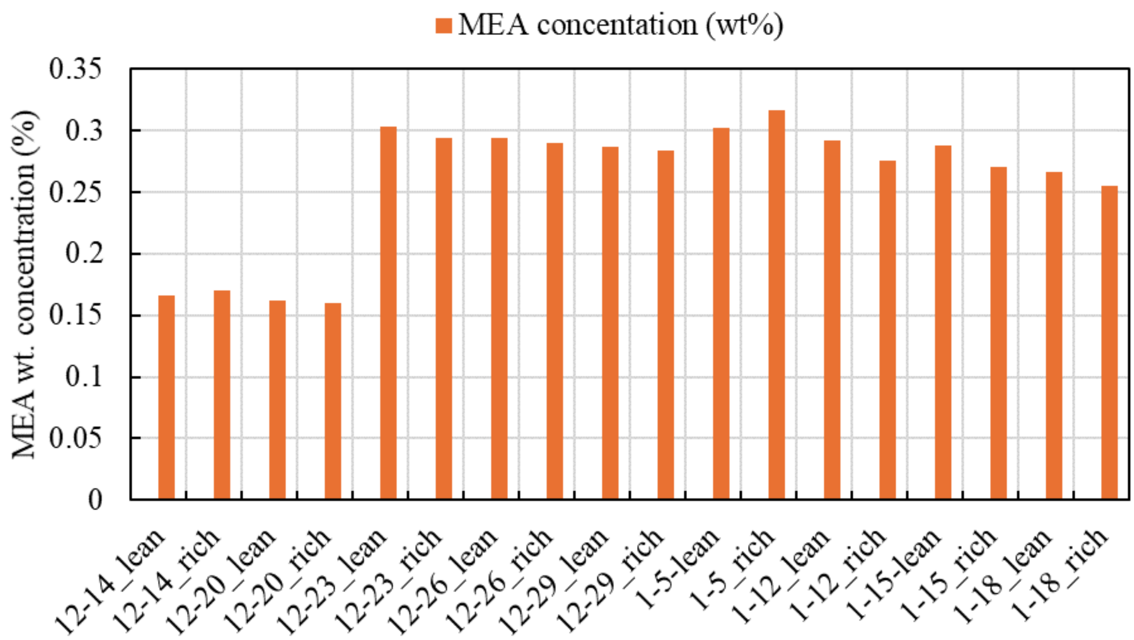


Fig. 2: *MEA concentration in water from 1st pilot test on TotalEnergies*

Figure 3, shows the average CO_2 loading capacity for MEA. For the rich MEA samples, the average CO_2 concentration was in close to 40-45%, while the lean mixture CO_2 concentration varied from 20-25%. The rich MEA, here signifies, the carbamate ion (MEACOO-) formed due to reaction with CO_2. The carbamate ion, when heated close to 110 °C, releases the CO_2 to form lean MEA. Guo et al. [1] suggested the reaction mechanism for CO_2 absorption on MEA. At low CO loading, CO_2 absorption into MEA is an exothermic reaction to form Carbamate ion (MEACOO-) and is given as:

$HCO_3^- + MEA = MEACOO^- + H_2O$ (Eq. 1)

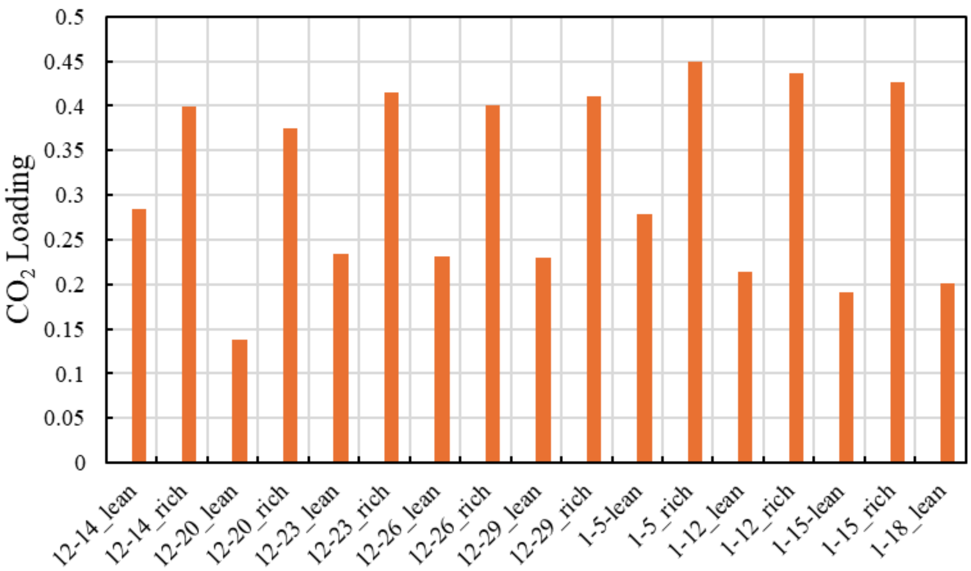


Fig. 3: *CO_2 loading for Second batch received in March from 1st pilot test on TotalEnergies calculated using ^{13}C NMR*

We also performed NMR experiments to determine the CO_2 loading. Solution ^1H and ^{13}C NMR spectra were collected on a 400 MHz Avance III Nanobay spectrometer. Due to the aqueous nature of the solutions and the abundance of exchangeable proton moieties (e.g. -OH, -NH, $-NH_2$) the samples were not diluted in a deuterated solvent due to the pH dependence of the ^1H and ^{13}C chemical shifts (vida infra) and to prevent differences in reaction equilibria potentially altering the compound abundances. The samples were shimmed with solvent locking using the Bruker TopSpin program and minimizing the ^1H linewidth of the dominant water solvent peak. The results from the ^1H and ^{13}C NMR experiments show that despite the lack of a deuterated solvent, that suitable spectra with good resolution can be obtained on the neat reaction solvents. From the ^{13}C data, we observe that >90% of the C in each sample is represented by MEA and carbamate. A plethora of small peaks can also be observed.

With an increase in the CO_2 loading for MEA beyond 0.4 mol_{CO2}/mol_{MEA}, also referred to as high CO_2 loading, the hydration reaction of CO_2 is enhanced (Lv et al. 2015). The reaction is expressed as follows:

$CO_2 + H_2O = H^+ + HCO_3^-$ (Eq. 2)

$CO_2 + H_2O = 2H^+ + CO_3^{2-}$ (Eq. 3)

Considering the bicarbonate peak, a very small peak is observed in ^{13}C NMR at 160 ppm, the CO_2 loading slightly increases by 0.004 mol_{CO2}/mol_{MEA} in the rich sample. It may be noted that the net CO_2 vapor equilibrium pressure was around 5 kPa, and the CO_2 loading observed is similar to the values reported in literature (Aronu, 2011). It may also me noted the carbamate values calculated from ^{1}H NMR were also in the range similar to ^{13}C NMR.

Anions results

We also focused on analysis and characterization of degraded MEA products for selection of anions: fluoride, chloride, bromide, iodine, acetate, oxalate, carbonate, nitrate, nitrite, phosphate, and sulfate. Ion chromatography (IC) was utilized for anions analysis while high-performance liquid chromatography (HPLC) was chosen for MEA and degradation products analysis. A sub-group of six MEA samples were selected as representatives of the full sample set received from the ship to be utilized in validating the existing IC analysis method and establishing a new HPLC method. The six sub-group MEA samples were collected on: December 26, 2023, January 18, 2024, and February 1, 2024.

A DIONEX ICS-6000 ion chromatograph with AS-19 column was used to quantitatively measure anions. The eluent was aqueous potassium hydroxide (KOH) with a mobile phase gradient of 20-35 mM. Sample injection was 10 µL and the flow rate was kept consistent at 0.25 ml/min. Calibration standards were prepared using SPEX CertiPrep certified reference standards diluted with 18 MΩ de-ionized water. The calibration standard concentrations ranged from 0.25-1 ppm. MEA samples were prepared by vortexing the containers for 3 minutes and filtering through a 0.22 µm disc filter. Samples were diluted 100x with 18 MΩ de-ionized water to minimize matrix interference. All samples were prepared in triplicate and results averaged. The IC method used in this analysis was sufficient in separating the analytes of interest with linear correlation values above 0.999.

Four major components were observed: acetate/formate, carbonate, oxalate, and nitrate (see Table 1). Acetate/formate suggests the oxidation product of MEA and the concentration gradually increases from 1500 mg/L to 2300 mg/L. Similarly, the oxalate is an oxidation by product of MEA. The carbonate salts are formed due to hydration reaction of CO_2 (see Eq. 2&3). The nitrate salts are predominantly formed due to the NOx emission, which reacts with the MEA to eventually form nitrate salts (Fostås 2011).

Table 1: Results of IC analysis for anions from 1st pilot test on TotalEnergies

	Concentration in mg/L								
Sample Name	Acetate	Chloride	Nitrite	Bromide	Nitrate	Carbonate	Sulfate	Oxalate	Phosphate
12-26_Rich	1570	46	3	7	295	1444	180	384	4
12-26_Lean	1501	51	1	1	85	1577	134	463	3
01-18_Rich	2065	58	6	1	351	1480	343	887	5
01-18_Lean	1947	59	6	1	158	1428	275	944	4
02-01_Rich	2364	57	8	4	377	1419	536	1227	6
02-01_Lean	2218	58	4	4	204	1059	515	1369	4

Cations results

ICP-OES was utilized for cation quantification. For ICP-OES the samples were diluted by a factor of 200 in DI water. The final 1:100 dilution was done in 2.5 volume% optima grade nitric acid. The total sample volume after dilution was 5 mL. These samples were then analyzed using an Agilent 7500 cx ICP-MS. A 0-1000 ppb calibration curve for each analyzed ion was conducted before samples were run. The results for ICP-OES are shown in Table 2.

The sodium is the major cation present in the sample, which is due to use of NaOH for quenching the flue gas to adjust the pH before it enters the adsorption column for reaction with MEA (some quench liquid inadvertently entered the solvent system in the beginning of the campaign). The other cations are predominantly small, <1% of the Na amount. The additional cations might be present from before and could be carried from the humid air coming from sea which then enters the natural gas combustion chamber.

Table 2: Results of ICP-OES analysis for cations from 1st pilot test on TotalEnergies.

	Concentration in mg/L									
Sample Name	Li	Na	Mg	Al	K	Cr	Mn	Fe	Sr	Cs
08 Dec Rich	2.7	1469.3	0.8	3.1	11.4	0.0	0.7	6.2	2.1	0.6
08 Dec Lean	2.6	1436.8	0.0	3.7	0.8	0.0	0.6	3.4	4.2	0.6
26 Dec Rich	2.5	1425.5	2.1	4.0	13.3	0.0	1.3	13.7	4.2	0.5
26 Dec Lean	2.5	1404.4	2.4	4.0	22.6	0.0	1.3	13.4	4.3	0.5
05 Jan Rich	2.4	1365.5	1.9	4.9	7.9	0.2	1.7	16.6	4.4	0.5
5 Jan Lean	2.5	1338.8	0.0	4.4	0.7	0.0	1.8	17.2	4.4	0.5
18 Jan Rich	2.5	1359.3	3.3	4.3	0.0	0.6	2.1	24.3	4.4	0.5
18 Jan Lean	2.4	1453.9	0.4	4.5	7.2	0.0	2.2	27.4	4.4	0.5
1 Feb Rich	2.4	1408.1	3.8	5.3	8.7	0.4	2.7	29.8	4.6	0.5
1 Feb Lean	2.3	1344.4	0.0	4.4	0.0	0.0	2.6	28.6	4.6	0.5

Degradation products

Gas chromatograph mass spectrometry (Agilent 8890 GC/5977B MSD) was utilized to separate and determine% composition of monoethonolamine (MEA) and degradation products in the liquid samples. The system was outfitted with a CP-Volamine column (60 m x 0.32 mm widebore). The temperature gradient used was 40 °C initial temperature, held for 1 minute then raised to 265 °C at 12 °C/min and held for 3 minutes. Helium was used as carrier gas with a flow rate of 1.2 ml/min. An aliquot of 0.5 µL was injected in split mode with a split ratio of 50:1. The transfer line temperature to the MS detector was set at 250°C while the electronic ionization (EI) source (70 eV) was heated to 230°C. The acquisition was made in scan mode with a range of 29-350 amu.

Samples were prepared by vortexing the containers for 3 minutes and filtering through a 0.22 µm disc filters. All samples were analyzed in triplicate and results averaged. The GC-MS method used in this analysis was sufficient in separating many analytes of interest as well as additional degradation products. Identification was done by comparing mass spectra to the NIST library database and existing data base. Results in Table 3 were calculated by averaging peak areas for each compound, then dividing that to the total peak area detected in the sample. The results are reported in g/kg. The amount of MEA+carbamate gradually decreases with number of MEA cycles, due to enhanced degradation, and decreases from 29% from Dec 26, 2023 to 26% Feb 1. The major degraded compound was HEPO and is in the range of 2-3%, acetamide, N-(2-hydroxyethyl) around 2%. Formic acid was in 0.2% range.

Table 3: Degradation compound analysis for cations from 1st pilot test on TotalEnergies.

	Compound degradation (g/kg)					
Compound Name	**December 26_Lean**	**December 26_Rich**	**January 12_Lean**	**January 12_Rich**	**February 1_Lean**	**February 1_Rich**
Monoethanolamine	255.5	238.4	263.8	206.2	256.9	215.0
Carbamate	38.8	51.8	28.4	69.2	10.0	40.7
Ethanol, 2-(methylamino)-	1.7	1.6	2.5	1.9	4.8	3.2
Ethanol, 2-(ethylamino)-	0.1	0.0	0.2	0.2	1.1	0.5
Acetamide, N-(2-hydroxyethyl)-	11.0	2.1	6.3	7.4	46.1	21.2
1H-Imidazole, 2-ethenyl-	0.4	0.2	0.3	0.3	0.4	0.3
Oxazolidin-2-one	1.6	1.2	1.3	1.2	3.4	1.4
Oxazolidine, 2-methyl-	1.0	0.7	0.8	0.8	2.1	1.1
Triethylamine	0.3	0.2	0.3	0.2	0.7	0.3
HEPO	29.1	0.0	17.8	9.2	64.6	0.0
Methyl Alcohol	0.0	1.4	0.0	0.9	0.0	0.1
Formic acid	2.6	1.3	2.2	1.7	5.5	2.1
Acetic acid	0.0	0.1	0.0	0.3	3.5	0.7
N-[2-Hydroxyethyl]succinimide	0.0	0.0	0.3	0.2	1.4	0.9
Pyridine, 3-methyl-	0.6	0.3	0.5	0.3	0.0	0.9
Pyrazole-5-carboxylic acid, 1,3-dmethyl-	0.0	0.0	0.9	0.0	7.0	2.2
Formamide, N-formyl-N-methyl-	5.3	4.4	4.1	5.3	11.7	6.9
Pentane, 2,3-dimethyl-	5.7	4.1	4.7	3.2	29.8	9.2
3-Pyridinamine, 2,6-dimethyl-	0.0	0.0	1.2	0.8	4.0	3.1

2.1.2 Quantifying solvent degradation rates from the 2nd pilot test on Sleipnir campaign

MEA concentration and CO_2 loading

Figure 4 shows the MEA concentration for the Sleipnir campaign, which decreased from 34% to 25% in a two-month time period. The CO_2 loading in the rich sample was in range of 0.44 mol_{CO2}/mol_{MEA}, while for the lean sample was around 0.17 mol_{CO2}/mol_{MEA} (see Figure 5).

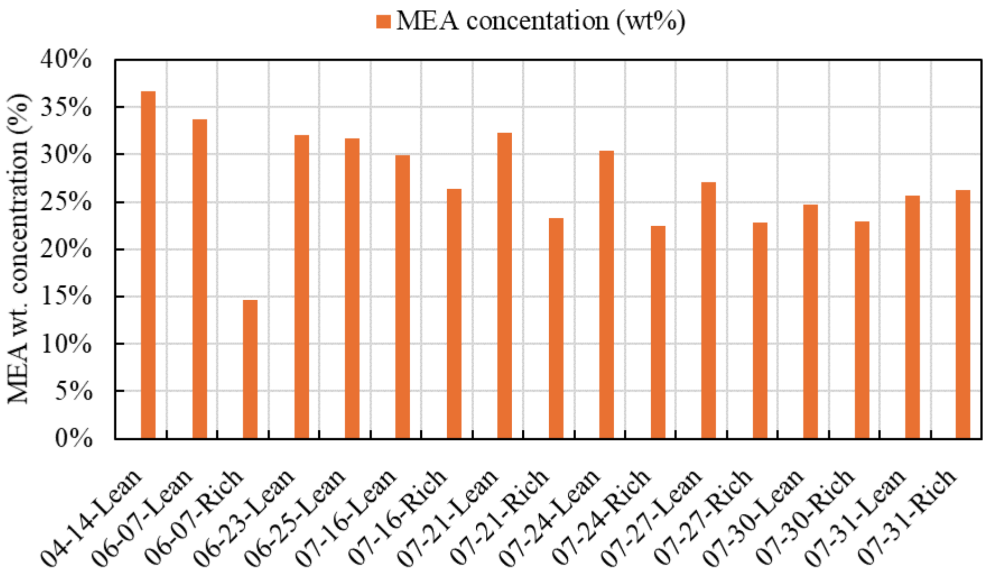


Fig. 4: *MEA wt. concentration in water for 2nd pilot test on Sleipnir campaign*

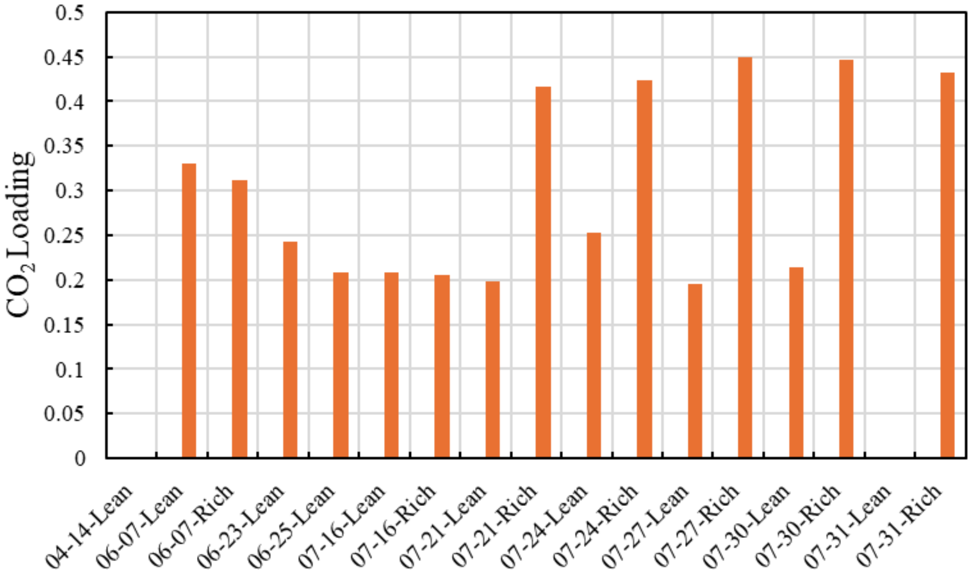


Fig. 5: CO_2 loading as carbamate for Second batch received in March from 2nd pilot test on Sleipnir campaign

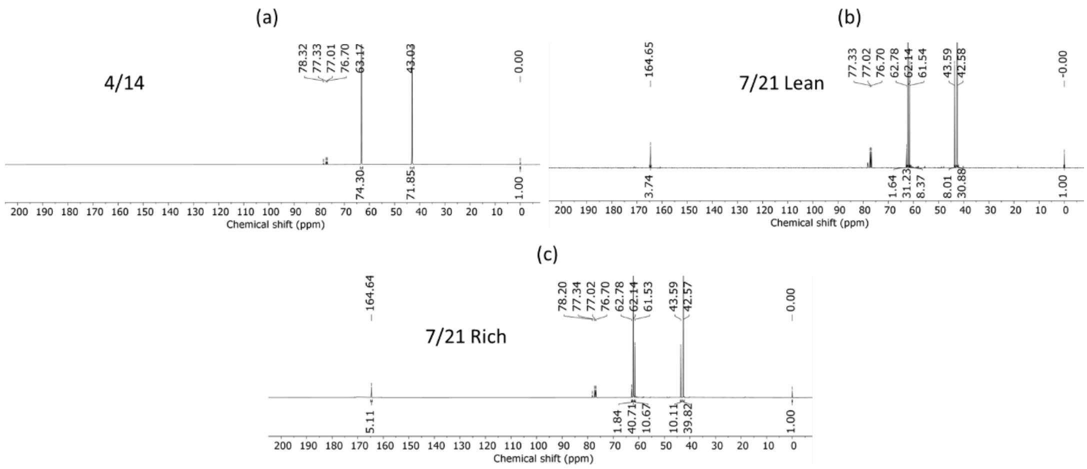


Fig. 6: ^{13}C NMR spectra for (a) Pure MEA in water, (b) Lean MEA of 7/21, and (c) Rich MEA for 7/21 Rich for Sleipnir campaign

Representative ^{13}C NMR spectra are shown in Figure 6a. Before CO_2 loading, free MEA in water appears as two peaks at 63 ppm (CH_2OH) and 42 ppm (CH_2NH_2), respectively. Upon initiating the CO_2 absorption, MEA is converted into carbamate, resulting in three distinct peaks corresponding to MEA-carbamate: 165 ppm (COO^-), 62 ppm (CH_2OH), and 44 ppm (CH_2NH), which are observed in both rich and lean samples (Figures 6b and 6c), similar peaks were reported by Bottinger et al. (2008). Although the peak at 165 ppm is a clear diagnostic marker of carbamate formation, it was not used for quantifying CO_2 loading due to its weak signal intensity, long relaxation time (T_1), and potential overlap with other carbonyl-containing species such as bicarbonate. Instead, the CH_2 peaks at 62 ppm and 44 ppm were used for accurate and reproducible quantification of CO_2 loading. Additionally, a small bicarbonate peak is observed at 160 ppm, similar to Behrens et al. (2019) and Bottinger et al. (2008). However, the bicarbonate amount calculated was only 0.004 mol/mol$_{MEA}$. The CO_2 loading calculated from ^{1}H spectra (figure 7) is simar to ^{13}C spectra.

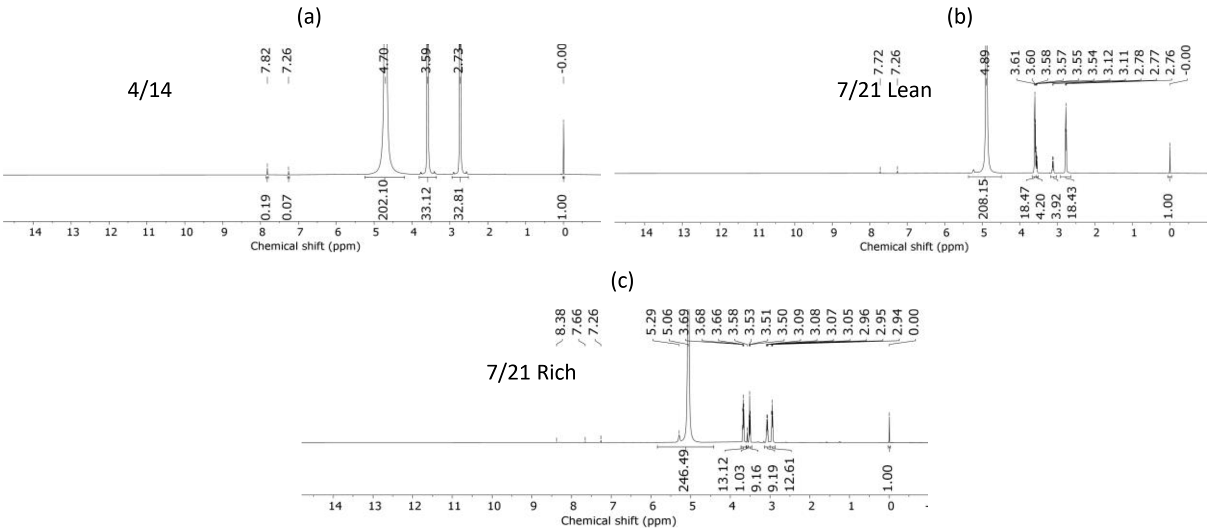


Fig. 7: ^{1}H NMR spectra for (a) Pure MEA in water, (b) Lean MEA of 7/21, and (c) Rich MEA for 7/21 Rich for Sleipnir campaign

Anions results

Four major components were observed, acetate/formate, carbonate, oxalate, and nitrate (see Table 4). Acetate/formate suggests the oxidation product of MEA and the concentration gradually increases from 1500 mg/L to 2300 mg/L. Similarly, oxalate is an oxidation by product of MEA. The carbonate salts are formed due to hydration reaction of CO_2 (see Eq. 2&3). The nitrate salts are predominantly formed due to the NOx emission, which reacts with the MEA to eventually form nitrate salts. The chloride ion might have entered the combustion chamber from humid air.

Table 4: Results of IC analysis for anions from 2nd pilot test on Sleipnir campaign

	Concentration (ppm)							
Sample Name	**Fluoride**	**Acetate/formate**	**Chloride**	**Nitrite**	**Nitrate**	**Carbonate**	**Oxalate**	**Phosphate**
04-14-Lean (1L)	92.4	0	17.8	0.9	3.3	5.5	0	n.d
06-07-Lean (2L)	0	2009.8	60.9	6.3	6	711.7	0	16.2
06-07-Rich (1R)	0	2246.9	65.5	6	4.3	1286.5	0	n.d
06-23-Lean (3L)	0	1315.9	81.1	4.6	23	584.8	10.7	13.1
06-25-Lean (4L)	0	997.4	97	7.3	26.7	393.2	6.4	13.2
07-16-Lean (5L)	0	1062.4	112.4	11.5	29.6	422.1	20.5	13
07-16-Rich (2R)	0	1036.1	113.4	11.4	28.9	380.6	12.9	12.7
07-21-Lean (6L)	0	1037.9	147.2	3.1	42.2	557.5	25.2	13.4
07-21-Rich (3R)	0	1321.8	114.7	4.7	34.6	737.2	34.4	12.7
07-24-Lean (7L)	0.1	1245.3	122.8	3.7	48.2	594.1	46.8	18.5
07-24-Rich (4R)	0	1329.6	136	4.4	45.2	804.9	106.2	18.6
07-27-Lean (8L)	0.3	1014	122.5	2.7	54	407	69.1	14.9
07-27-Rich (5R)	0	1290.7	112.4	3	46.9	827.3	88.2	12.2
07-30-Lean (9L)	0.5	991.9	113.3	3.5	60.5	424.9	71.2	13.5
07-30-Rich (6R)	0	1185.3	108.1	4.2	51.3	813.3	96.1	14.4
07-31-Lean (10L)	0.9	1032.4	116.8	2.8	64.1	472.2	80.3	15.4
07-31-Rich (7R)	1.1	1275.2	116.6	3.8	59.6	826.6	116.6	13.7

Cations results

Table 5: Results of ICP-OES analysis for cations from 2nd pilot test on Sleipnir campaign

	Concentration (mg/L)									
	Ca	Cr	Fe	K	Mg	Na	Zn	Co	Ni	Cu
04-14-Lean (1L)	1.1	-	0.8	-	-	5.6	3.2	1.3	2.0	18.0
06-07-Lean (2L)	3.3	-	1.0	-	0.2	19.8	-	0.8	1.2	10.7
06-07-Rich (1R)	3.2	-	1.0	-	-	17.9	-	0.5	0.9	7.6
06-23-Lean (3L)	5.2	0.6	10.7	-	0.4	1242.5	3.7	0.8	1.3	8.5
06-25-Lean (4L)	4.4	0.6	3.3	2.0	0.4	1220.1	4.4	0.8	1.3	7.9
07-16-Lean (5L)	3.6	0.6	2.8	2.0	0.4	1132.2	4.6	0.8	1.1	7.3
07-16-Rich (2R)	4.0	0.7	3.1	-	0.5	1173.6	5.2	1.1	1.3	9.3
07-21-Lean (6L)	3.5	0.8	3.3	2.0	0.4	1197.9	5.7	0.9	1.2	7.1
07-21-Rich (3R)	3.1	0.7	2.9	2.0	0.4	1064.5	5.4	0.9	1.2	6.2
07-24-Lean (7L)	3.4	0.9	3.2	2.1	0.4	1188.2	6.1	0.9	1.2	6.5
07-24-Rich (4R)	3.2	0.9	3.0	-	0.4	1062.0	5.6	0.8	1.1	5.8
07-27-Lean (8L)	3.4	1.0	3.3	1.9	0.4	1164.1	6.4	0.8	1.1	6.1
07-27-Rich (5R)	3.1	1.0	2.9	-	0.4	1039.2	6.0	0.8	1.1	5.4
07-30-Lean (9L)	3.9	0.9	3.5	-	0.5	1226.0	6.9	0.8	1.2	6.0
07-30-Rich (6R)	2.9	1.0	2.8	-	0.4	994.4	6.0	0.9	1.2	5.3
07-31-Lean (10L)	3.6	1.1	3.3	2.2	0.5	1129.0	6.7	0.9	1.3	5.6
07-31-Rich (7R)	3.6	1.1	3.2	-	0.4	1069.7	6.5	0.9	1.4	5.3

Similar to first campaign, the sodium is the major cation present in the sample, which is due to use of NaOH for quenching the flue gas to adjust the pH before it enters the adsorption column for reaction with MEA. The other cations are predominantly small; <1% of Na amount (see Table 5). The additional cations might be present from before, and could be carried from the humid air coming from sea which then enters the natural gas combustion chamber.

Degradation products

Table 6 shows the degradation products for MEA. The results are reported in g/kg. The amount of MEA+carbamate gradually decreases with the number of MEA cycles, due to enhanced degradation, and decreases from 36% on April 14, 2024, to 26% on July 31st, 2024. The major degraded compound was HEPO and is in the range of 0.5%.

Table 6: Degradation compound analysis for cations from 2nd pilot test on Sleipnir campaign.

		g/kg											
Compound Name	**MEA**	**Carbamate**	**Methyl Alcohol**	**1,2-Ethanediol**	**Ethanol, 2-(methylamino)-**	**Oxazolidine, 2-methyl-**	**HEPO**	**Dimethyl fumarate**	**Pyridine, 3-methyl-**	**Formamide, N-formyl-N-methyl-**	**Diisopropanolamine**	**Oxazolidin-2-one**	**Pentane, 2,3-dimethyl-**
04-14-Lean (1L)	367.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
06-07-Lean (2L)	286.50	50.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
06-07-Rich (1R)	122.22	24.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
06-23-Lean (3L)	277.62	43.34	0.13	1.30	0.65	0.00	1.63	0.00	0.26	0.00	0.00	1.14	0.00
06-25-Lean (4L)	283.77	33.44	0.00	4.57	0.65	0.20	1.63	0.00	0.26	0.00	0.00	1.47	0.33
07-16-Lean (5L)	268.25	31.29	0.09	4.96	0.62	0.22	2.32	0.00	0.28	0.00	0.00	1.55	0.00
07-16-Rich (2R)	236.76	26.34	0.00	3.94	0.54	0.11	2.44	0.00	0.19	0.00	0.00	1.09	0.00
07-21-Lean (6L)	292.13	30.81	0.10	4.67	0.67	0.23	2.33	0.00	0.27	0.00	0.00	2.00	0.47
07-21-Rich (3R)	184.22	48.16	0.05	3.13	0.36	0.10	1.93	1.59	0.12	0.89	0.00	0.89	0.00
07-24-Lean (7L)	264.16	39.59	0.06	4.43	0.57	0.16	3.48	0.00	2.66	0.00	0.00	0.95	0.63
07-24-Rich (4R)	178.57	45.72	0.09	2.80	0.37	0.09	4.20	0.00	0.16	0.00	0.00	0.70	0.47
07-27-Lean (8L)	246.40	24.70	0.09	3.85	0.57	0.20	7.14	0.00	0.26	0.00	0.00	1.14	1.14
07-27-Rich (5R)	184.33	43.30	0.00	2.98	0.40	0.12	4.02	0.00	0.17	0.00	0.00	0.71	0.47
07-30-Lean (9L)	222.07	25.46	0.08	3.67	0.52	0.26	6.82	0.00	0.21	0.00	1.31	0.92	1.05
07-30-Rich (6R)	185.30	44.58	0.07	2.63	0.39	0.12	5.30	0.00	0.14	0.00	0.65	0.00	0.00
07-31-Lean (10L)	230.22	26.62	0.11	3.84	0.55	0.19	7.96	0.00	0.19	0.00	1.92	1.37	1.37
07-31-Rich (7R)	210.28	52.29	0.11	3.20	0.48	0.17	5.05	3.93	0.22	0.00	2.10	1.12	0.95

2.2. WP2: Design of CO_2 off-loading facilities and onshore CO_2 purification and conditioning plants

2.2.1 General Evaluation Basis for CO_2 Plant

The SBCC-equipped vessel will transport liquefied natural gas (LNG) from Port Arthur, Texas in the United States (U.S.) to Europe. The receiving port in Europe was selected to be the Port of Rotterdam, which imports a significant volume of LNG each year.

Onshore Facility Location

Port Arthur was selected as the U.S. port location since it has several LNG export facilities and there is a CO_2 pipeline which potentially could provide access to storage infrastructure in the region. The U.S. Gulf Coast region, of which Port Arthur is a part, is a hub for CCUS projects due to its large industrial base and existing pipeline networks. The U.S. Gulf Coast region also offers numerous geological formations suitable for CO_2 sequestration.

The Denbury Green Pipeline (Green Pipeline) is relatively close to the proposed onshore facilities at Port Arthur, and potentially could be used to transport CO_2 from the Onshore Facility to a site at which the CO_2 could be sequestered. The Denbury Green Pipeline (ExxonMobil, 2023) is a ~500-kilometer (320-mile) pipeline that runs from Texas to Louisiana, passing within 20 to 40 kilometers of the Port Arthur area. The pipeline can carry up to 23 million cubic meters of CO_2 per day (Exxon Mobil, 2023 & American Oil and Gas Reporter). Based on public announcements, the

Green Pipeline primarily serves enhanced oil recovery (EOR) operations but also has the potential to transport CO_2 for permanent sequestration. Key injection sites for EOR along the Green Pipeline include oil fields in Texas and Louisiana, where the CO_2 is injected for EOR. Denbury is also expanding its CO_2 sequestration portfolio to include dedicated storage sites in Louisiana and Mississippi, where CO_2 will be permanently stored underground.

The Onshore Facility is assumed to be built within an existing LNG port facility—a number of which exist in the Port Arthur area—that is already a developed site. This design assumes that on-site facilities, including utilities, warehouses, operations buildings, and maintenance shops are already on the premises.

Vessel Type and Frequency

The vessel was assumed to be a large LNG-fueled tanker (174,000 m^3 LNG) that loads LNG at Port Arthur, Texas and delivers LNG to a port location in Western Europe (Rotterdam). The LNG tankers will be equipped with an onboard CO_2 capture and storage system. Upon reaching the Port Arthur facilities, the onboard captured CO_2, as well as spent solvent from the capture system, will be offloaded to the Onshore Facility, which will receive and process the CO_2 and spent solvent.

It is assumed that the ship will arrive from Rotterdam to the Port Arthur facility every 32 days for CO_2 offloading and spent solvent reclaiming. A ship turnaround time of 4 days was assumed, based on discussions with the EverLoNG consortium members.

Utilities and Waste Disposal

It is assumed that most general utilities are already available on-site at the existing port facility. This includes potable water, sanitary systems, electricity, cooling water, and process water.

Service water and wastewater systems are assumed to be available at the existing port facility. Service water and wastewater piping to transport the water to and from the Onshore Facility are included in the design. Cooling water is assumed to be available at the port facility at the specifications shown in Table 7. Waste is assumed to be treated off-site. Waste treatment is not included in the Onshore Facility design.

Table 7: Cooling Water Specifications for the Onshore Facility.

Parameter	Value
Cooling Water Supply	
Temperature, °C (°F)	30.6 (87)
Pressure, barg (psig)	5.17 (75)
Cooling Water Return	
Temperature, °C (°F)	37.8 (100)
Pressure, barg (psig)	4.5 (65)

Capacity Factor

Capacity factor (CF) for the full Onshore Facility is based on the frequency of ship arrivals and ship turnaround time. For a single ship arrival every 32 days and a ship turnaround time of 4 days, it is assumed that the Onshore Facility is operating 46 days out of the year. This leads to a CF for the onshore plant of 12.5 percent. It is assumed that plant shutdowns for planned maintenance will occur in between ship arrivals.

2.2.2 Design Basis for CO_2 Receiving and Processing

CO_2 Quantity and Quality from the Ship

A quantity of 5,000 tonnes of liquefied CO_2 will be offloaded per ship. This is the expected maximum amount of CO_2 based on a 95% CO_2 capture rate from a 174,000 m^3 LNG carrier travelling to Port Arthur via several global shipping routes. Estimates are based on calculations provided by EverLoNG consortium partners.

It is assumed that the CO_2 will be captured, processed, and cryogenically liquefied on the vessel. The CO_2 will be provided in liquid form to the Onshore Facility and will be 99.99% pure at 15 bar (218 psia) and -28 °C (-18 °F). The CO_2 quality received off the ship is assumed to reflect the specification data from the Northern Lights Project Concept Report, shown in Table 8 (Northern Light, 2019).

Table 8: CO_2 Specifications Received Off Vessel

Component	Concentration, ppm_v
H_2O	≤ 30
O_2	≤ 10
SOx	≤ 10
NOx	≤ 10
H_2S	≤ 9
CO	≤ 100
Amine	≤ 20
NH_3	≤ 10
H_2	≤ 50
Formaldehyde	≤ 20
Acetaldehyde	≤ 20
Hg	≤ 0.03
Cd and Tl (sum)	≤ 0.03

Notes:
The component specifications are replicated from the Northern Lights Project Concept Report RE-PM673-00001.

CO_2 Offloading

CO_2 will be pumped (via cryogenic pump on the ship) from the ship's storage tank to the Onshore Facility using a flexible hose connection. There will be two lines between the ship and the CO_2 Plant: one liquid line to offload CO_2, and one vapor equilibrium vent line to return CO_2 gas to the ship to maintain pressure equilibrium between the ship storage tank and the onshore storage tank.

It is assumed that it will take 10 hours to offload the CO_2 from the ship storage tanks to the onshore CO_2 storage tanks at a rate of 500 tonnes per hour (5,000 tonnes / 10 hours = 500 tonnes per hour), based on commercially available cryogenic pumps.

CO_2 Processing and Product Specifications

CO_2 offloaded from the ship will be processed to meet CO_2 pipeline export specifications. It is assumed that it will take 12 hours to process each ship delivery of CO_2 at a rate of 417 tonnes per hour (5,000 tonnes / 12 hours = 417 tonnes per hour).

The final CO_2 composition after onshore receipt and processing will be greater than 99% CO_2 and meets specifications for CO_2 pipelines shown in Table 9, replicated from the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) "Quality Guidelines for Energy System Studies (QGESS): CO_2 Impurity Design Parameters" report (issued January 2019, NETL Report No. NETL-PUB-22529). It is assumed that it will take 12 hours to process each ship delivery of CO_2 at a rate of 417 tonnes per hour (5,000 tonnes / 12 hours = 417 tonnes per hour). The CO_2 processing time is assumed based on the commercially available export pump.

Table 9: CO_2 Product Export Specifications

Parameter	Limit	Requirement
Temperature, °C (°F)	30 (86)	Transportation pipeline specification
Pressure, barg (psig)	152 (2,200)	Transportation pipeline specification
CO_2, vol%	> 95	Minimum miscible pressure for EOR
N_2, vol%	< 4	Minimum miscible pressure for EOR
H_2O, ppmv	< 500	Transportation pipeline corrosion / hydrate formation
O_2, ppmv	< 10	Transportation pipeline corrosion
CO, ppmv	< 35	Safety and corrosion

CO_2 Boil-off Gas (BOG) System

Due to the time between shipments at the port, a boil-off gas (BOG) system is included at the CO_2 receiving and processing facility to re-liquefy boiled-off CO_2 from the onshore CO_2 storage tanks.

A BOG system is needed since a residual volume of CO_2 (20 percent of the tank volume, or the tank heel) will remain in the onshore CO_2 storage tanks. The CO_2 can be recirculated within the onshore CO_2 Plant to maintain the cryogenic temperature of the system between shipments, or a portion of the CO_2 can be used to cool the system prior to CO_2 offloading from the ship. In both cases, a portion of the residual CO_2 is boiled off when it absorbs thermal energy from ambient conditions. This gaseous CO_2 will be directed to the BOG system, where it will be re-liquefied and returned to the storage tanks. This will reduce the CO_2 that is vented in the Onshore Facility.

The CO_2 BOG system is designed for a 0.15 percent per day boil-off rate of the residual CO_2 in the tanks after pumping the CO_2 product to the pipeline. In scenarios where higher utilization of the Onshore Facility is projected, the BOG system may be under-utilized, and any gaseous CO_2 produced during the interim between ship arrivals may be recompressed with the on-ship BOG system through the equalizing vent line. This study assumes that the CO_2 BOG system is utilized 80 percent of the time, thus, it will typically be running except when a ship is unloading CO_2 or during maintenance activities.

2.2.4 Process Description and Modeling for CO_2 Receiving and Processing

Figure 8 shows the proposed block flow diagram for the onshore CO_2 processing facility. The onshore CO_2 Plant will receive liquid CO_2 pumped from the ship and will process the CO_2 such that it meets the CO_2 pipeline specifications at the onshore facility boundary. The scope of the CO_2 Plant includes receiving liquid CO_2 pumped off the ship, onshore CO_2 storage, and processing equipment up to the plant boundary where it will connect to the inlet of the pipe that transports CO_2 to the CO_2 pipeline.

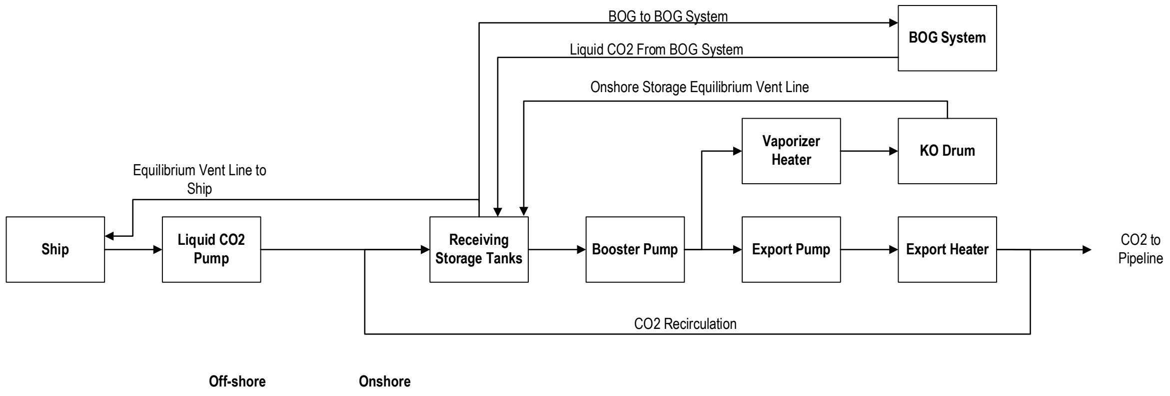


Fig. 8: Block diagram for CO_2 receiving and processing.

CO_2 Receiving and Onshore Storage

Liquid CO_2 at -28 °C, 15 barg, and 99% purity is pumped from the ship's CO_2 storage tank(s) via a cryogenic pump on the ship at a rate of 500 tonnes per hour using a flexible hose from the ship to permanent piping onshore. The onshore pipeline delivers the CO_2 to the receiving CO_2 storage tanks at the CO_2 Plant. There are two lines between the ship and the CO_2 Plant: one liquid line to offload CO_2, and one vapor equilibrium vent line to return CO_2 gas to the ship to maintain pressure equilibrium between the ship storage tank and the onshore storage tank. Liquid CO_2 from the onshore storage tanks is pumped for CO_2 processing at a rate of 417 tonnes per hour.

CO_2 Processing

Liquid CO_2 is processed to pipeline specifications at the onshore facility boundary. The booster pump downstream of the storage tanks provides a net positive suction head for the export pump, which delivers liquefied CO_2 to an export heater. The CO_2 export pump and electric export heater provide CO_2 at 152 barg and 30 °C to meet pipeline export conditions. The product CO_2 travels through the CO_2 export pipeline to deliver the CO_2 to the CO_2 pipeline for offtake.

A fraction of the CO_2 from the booster pump is sent to an electric vaporizer heater and knockout drum to vaporize a portion of the liquid CO_2 and provide a gaseous equalizing vent to the onshore storage tanks.

Figure 9 shows the process flow diagram (PFD) for the CO_2 receiving and processing system. Table 10 shows the associated heat and material balance (HMB) for the CO_2 receiving and processing system.

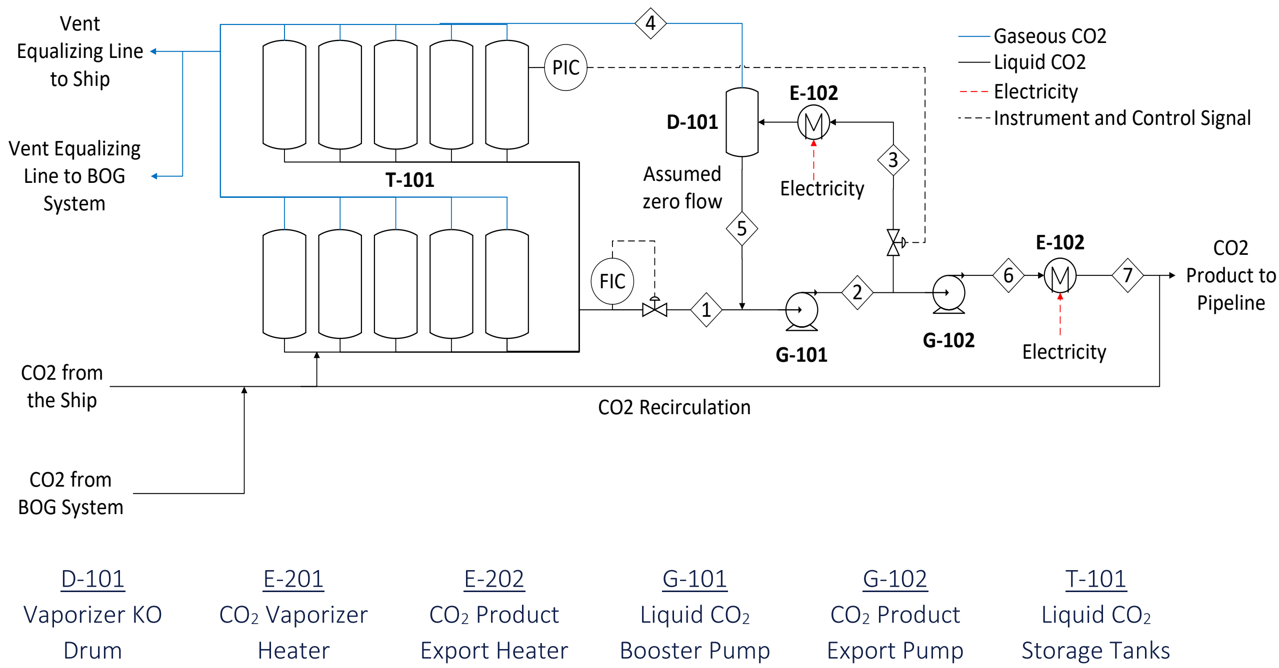


Fig. 9: CO_2 Processing Facility Process Flow Diagram

Table 10: CO_2 Processing Heat and Material Balance

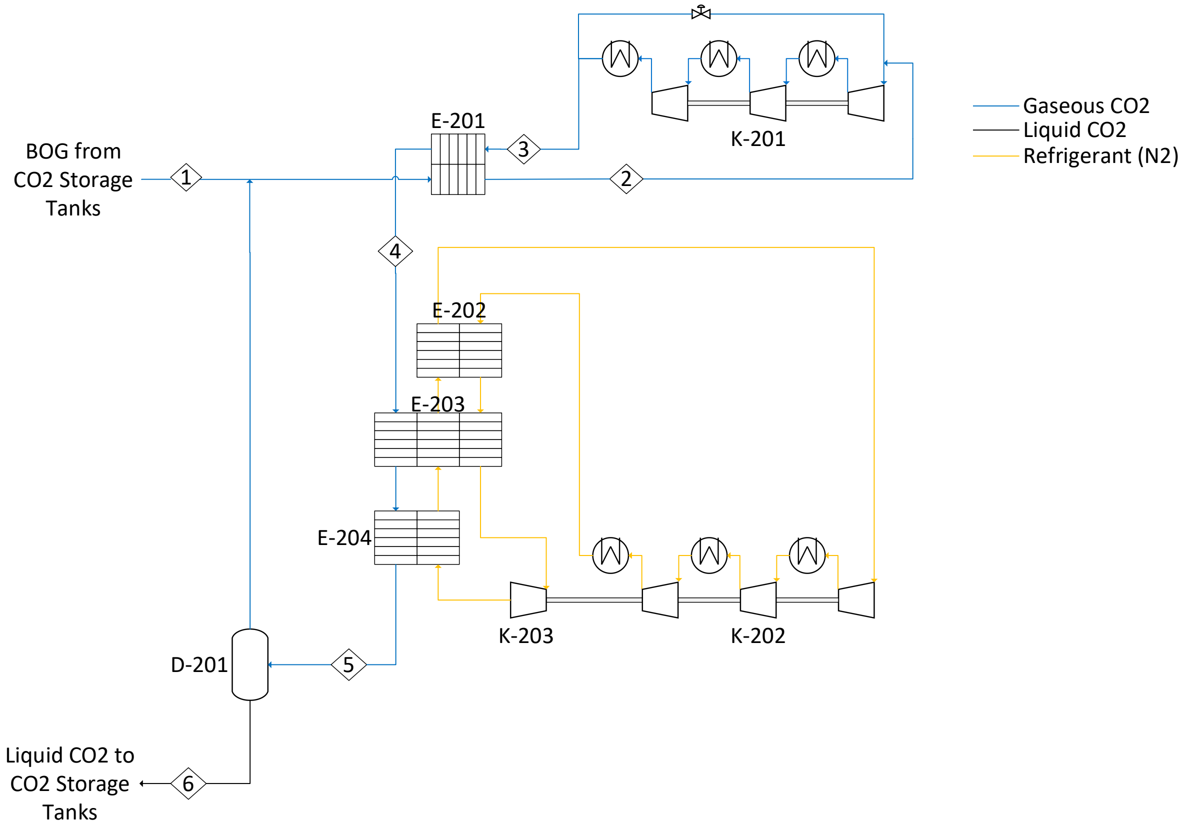
Stream Number	1	2	3	4	5	6	7
Stream Description	Liquid CO2 From Storage Tanks	Liquid CO2 from Booster Pump	Liquid CO2 to Vaporizer	Gaseous CO2 to Storage Tanks	KO Liquid [A]	Liquid CO2 to Heater	CO2 Product to Pipeline
Composition, kg/hr							
CO2	416,625	416,625	15,207	15,207	0.00	401,419	401,419
H2O	12.50	12.50	0.46	0.46	0.00	12.04	12.04
N2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2	4.17	4.17	0.15	0.15	0.00	4.01	4.01
CO	25.00	25.00	0.91	0.91	0.00	24.09	24.09
Total, kg/hr	**416,667**	**416,667**	**15,208**	**15,208**	**0.00**	**401,459**	**401,459**
Density, kg/m3	1,055	1,051	1,051	41	0.00	1,014	629
Temperature, °C	-28	-25	-25	-26	0.00	-17	30.0
Pressure, barg	15	30	30	15	0.00	153	152
Enthalpy Flow, GJ/hr [B]	-3,878	-3,877	-142	-137	0.00	-3,730	-3,688

Notes:
A) Knockout liquid is assumed to be zero flow.
B) Enthalpy flow is calculated at a reference 25 °C and 1 atm.

BOG System

The BOG system is used in between shipments at port to re-liquefy a portion of residual CO_2 that is boiled off when it absorbs thermal energy from ambient conditions.

The gaseous CO_2 is first compressed in a BOG compressor and then cross-exchanged with the inlet, cold gaseous CO_2 for cooling. The semi-cooled BOG is then chilled and reliquefied using a nitrogen (N_2) refrigeration loop, to provide reliquefied CO_2 to the CO_2 storage tanks at -28 °C and 15 barg. Figure 10 shows the PFD for the BOG system and Table 11 shows the associated HMB.



D-201	E-201	E-202	E-203	E-204	K-201	K-202	K-203
BOG Flash Drum	BOG Inlet Cross Exchanger	Refrigerant Cross Exchanger	BOG CO_2 Chiller 1	BOG CO_2 Chiller 2	BOG Compressor	BOG Refrigerant Compressor	BOG Refrigerant Expander

Fig. 10: CO_2 BOG System PFD

Table 11: BOG System Heat and Material Balance

Stream Number	1	2	3	4	5	6
Stream Description	BOG from CO_2 Storage Tanks	BOG to CO_2 Compressor	Compressed CO_2 to BOG Cross Exchanger	Semi-Cooled CO_2 to BOG Chiller 1	Chilled CO_2 to BOG Flash Drum	Liquid CO_2 to CO_2 Storage Tanks
Composition, kg/hr						
CO_2	101.18	101.18	101.18	101.18	101.18	101.18
H_2O	0.003	0.003	0.003	0.003	0.003	0.003
N_2	0.000	0.000	0.000	0.000	0.000	0.000
O_2	0.001	0.001	0.001	0.001	0.001	0.001
CO	0.006	0.006	0.006	0.006	0.006	0.006
Total, kg/hr	**101.19**	**101.19**	**101.19**	**101.19**	**101.19**	**101.19**
Density, kg/m^3	25.72	20.43	31.36	39.51	1,063	1,064
Temperature, °C	-20	30	40	-7.01	-28	-28
Pressure, barg	10	10	16	16	16	15
Enthalpy Flow, GJ/hr [A]	-0.910	-0.905	-0.905	-0.910	-0.942	-0.942
Notes: A) Enthalpy flow is calculated at a reference 25 °C and 1 atm.						

Performance Results

Table 12 shows the performance results for the CO_2 Onshore Facility and Tables 13 and 14 show the power summary and cooling water summaries for the CO_2 Onshore Facility, respectively.

Table 12: CO_2 Processing Facility Performance Results

Parameter	Unit	Value
CO_2 Receiving and Processing		
Total Mass CO_2 Handled – per ship	tonne	5,000
Liquid CO_2 Ship Offloading Rate	kg/hr	500,000
Liquid CO_2 Flow from Storage Tanks to Processing	kg/hr	416,667
Product CO_2 Flow to Pipeline	kg/hr	401,419
CO_2 Export Pressure	barg	152
CO_2 Export Temperature	°C	30.0
BOG System [A]		
Inlet BOG from Storage Tanks	kg/hr	101
Reliquefied CO_2 Returned to Storage Tanks	kg/hr	101
Notes: A) The BOG system is only running when a ship is not at port to maintain cold temperatures throughout the CO_2 processing system.		

Table 13: CO_2 Processing Facility Power Summary

Power Summary	kW
CO_2 Receiving and Processing	
CO_2 Vaporizer Heater	1,264
CO_2 Product Export Heater	11,368
Liquid CO_2 Booster Pump	242
CO_2 Product Export Pump	1,911
Subtotal	**14,785**
BOG System	
BOG Compressor	1.07
Refrigerant Compressor	19.13
Subtotal	**20.20**
Total	**14,805**

Table 14: CO_2 Processing Facility Cooling Water Summary

Cooling Water Summary	GJ/hr	kg/hr
CO_2 Receiving and Processing		
-	-	-
Subtotal	**0.00**	**0.00**
BOG System		
BOG Compressor Intercooling	0.0004	12
Refrigerant Compressor Intercooling	0.033	1,098
Subtotal	**0.0334**	**1,110**
Total	**0.0334**	**1,110**

2.2.5 Equipment specifications for CO_2 Plant

Due to the low-temperature operation of the CO_2 Plant, equipment material of construction (MOC) is chosen as Low Temperature Carbon Steel (LTCS) with a 2.5 mm corrosion allowance based on the Northern Lights Concept Report (Northern Light, 2019). Vessels are insulated with Polyisocyanurate/Polyurethane (PIR/PUR) insulation, with a 150 mm thickness. 1 mm aluminum cladding is used for all vessels.

The onshore CO_2 storage tank farm consists of 10 cylindrical storage tanks sized to store the volume of CO_2, including allowance for the minimum tank level (heel) as well as an operating margin and extra buffer space for variances in the frequency of ship arrivals to the port. Each tank has an inner diameter (ID) of 6.25 meters and tangent to tangent (T/T) height of 25 meters. The tank farm consists of 10 storage tanks (2 banks of 5) for onshore CO_2 storage. The tank MOC is LTCS with a 2.5 mm corrosion allowance. The tank design pressure and temperature are 22 barg and -45 °C.

The sized major equipment list for the CO_2 Plant is shown in Table 15.

Table 15: CO_2 Plant Major Equipment List

Process Vessels

Plot No.	Item No.	Item Name	Type	Design Conditions		MOC	Liquid Volume	Vessel ID	T/T Height	Total Weight	#
				barg	°C		m3	m	m	kg	
CO2	D-101	Vaporizer KO Drum	Vertical Drum	16.7	18.0	LTCS	3.4	1.07	3.81	1,700	1
BOG	D-201	BOG Flash Drum	Vertical Drum	16.7	18.0	LTCS	3.4	1.07	3.81	1,700	1

Tanks

Plot No.	Item No.	Item Name	Type	Design Conditions		MOC	Tank ID	T/T Height	Tank Volume	Total Weight	#
				barg	°C		m	m	m^3	kg	
CO2	T-101	Liquid CO_2 Storage Tanks	Cylindrical	22.0	-46.0	LTCS	6.3	25.0	766.9	413,000	10

Electric Heaters and Reboilers

Plot No.	Item No.	Item Name	Type	Operating Conditions		MOC	Duty	Electricity Consumption	#
				barg	°C		GJ/hr	MWe	
CO2	E-201	CO_2 Vaporizer Heater	Electric Heater	30	-26	LTCS	4.5	1.3	1
CO2	E-202	CO_2 Product Export Heater	Electric Heater	153	-17	LTCS	6.8	1.9	6

Plate Frame Heat Exchangers

Plot No.	Item No.	Item Name	Type	Design Conditions		Plate MOC	Heat Transfer Area	Total Weight	#
				barg	°C		m^2	kg	
BOG	E-201	BOG Inlet Cross Exchanger	Plate Frame	16.7	125.0	CS	1.0	90	1
BOG	E-204	BOG CO_2 Chiller 2	Plate Frame	16.7	-47.8	CS	1.0	90	1

Shell and Tube Heat Exchangers

Plot No.	Item No.	Item Name	Type	Design Pressure, barg		Design Temperature, °C		Heat Transfer Area	MOC		Total Weight	#
				Shell	Tube	Shell	Tube	m^2	Shell	Tube	kg	
BOG	E-202	Refrigerant Cross Exchanger	Shell and Tube	13.7	8.8	125	194	5.4	SS304	CS	360	1

Multi-Stream Heat Exchangers

Plot No.	Item No.	Item Name	Type	Operating Pressure, barg			Operating Temperature, °C			No. of Streams	Core Height	Core Length	Core Width	MOC	Total Weight	#
				Hot	Hot	Cold	Hot	Hot	Cold		m	m	m		kg	
BOG	E-203	BOG CO_2 Chiller 1	Multi-Stream Plate Fin	15	45	11	-7	-2	-6	3.00	0.4	0.2	0.1	CS	22	1

Table 15: CO_2 Plant Major Equipment List – *Continued*

Compressors

Plot No.	Item No.	Item Name	Type	No. Stages	Design Pressure, barg		Design Temp	MOC	Operating Gas Flow	Motor Power	Total Weight	Total # Req.	# Operating	# Spare
					Inlet	Outlet	°C	Impeller & Casing	m³/hr	kW	kg			
BOG	K-201	BOG Compressor	Cent.	3	10.0	15.0	30.00	CS	5.48	1.11	2,500	2	1	1
BOG	K-202	BOG Refrigerant Compressor	Recip.	3	11.1	45.0	40.00	CS	49.18	37.50	12,000	2	1	1

Pumps

Plot No.	Item No.	Item Name	Type	Design Conditions		MOC	Operating Liquid Flow	Motor Power	Total Weight	Total # Req.	# Operating	# Spare
				barg	°C	Impeller & Casing	L/hr	kW	kg			
CO2	G-101	Liquid CO_2 Booster Pump	Cent.	33.5	18.0	LTCS	120.5	236	2,400	2	1	1
CO2	G-102	CO_2 Product Export Pump	Cent.	160.2	18.0	LTCS	27.5	450	7,700	3	2	1

Pipelines

Plot No.	Item No.	Item Name	Description	Operating Conditions		MOC	Operating Flow, m³/hr		Length	ID	Insulation		#
				barg	°C		Liquid	Vapor	m	mm	Type	Thickness, mm	
CO2	L-101	Onshore CO_2 Offloading Pipeline	Pipeline from ship flexible hose line to intermediate CO2 storage tanks	15	-28	CS	456	-	305	300	PIR/ PUR	150	1
CO2	L-102	CO_2 Vent Line	Vent line from intermediate CO2 storage tanks to ship	15	-26	CS	-	456	305	300	PIR/ PUR	150	1
CO2	L-103	Onshore CO_2 Transfer Pipeline	Pipeline from intermediate CO2 storage tanks to CO2 Plant boundary	15	-28	CS	380	-	305	300	PIR/ PUR	150	1
CO2	L-104	CO_2 Export Pipeline	Pipeline from CO2 Plant to export pipeline	152	30	CS	639	-	25,000	300	PIR/ PUR	150	1

2.3 WP2: Design of Spent Solvent Reclaiming Facility

2.3.1. Design Basis for Spent Solvent Reclaiming

General Evaluation Basis

The general evaluation basis (site location, vessel type and frequency, and ship turnaround time) for the onshore MEA Reclamation plant is the same as for the CO_2 Plant described in Section 2.2.1.

Spent Solvent Quantity and Composition

The expected spent solvent quantity per ship visit is estimated at 60 cubic meters. This is a conservative estimate based on expected spent solvent quantities of 30 to 60 cubic meters provided by EverLoNG onboard SBCC partners. Spent solvent composition used for the basis of the MEA

Reclamation Plant design is based on solvent degradation sample analysis from WP1. The spent solvent composition used for the MEA reclaiming design is shown in Table 16. The spent solvent is assumed to enter the MEA Reclamation Plant at 22.53 °C (72.6 °F) based on spent solvent analysis in WP1.

Spent Solvent Offloading and Return

The spent solvent is assumed to be offloaded from the ship using a pump on the ship and a flexible hose connection to an onshore tank truck. The spent solvent is transported by truck to the spent solvent storage tank at the MEA Reclamation Plant. The reclaimed solvent is transported by truck to shipside, where it is pumped onto the ship via a flexible hose.

Spent Solvent Reclaiming

The scope of the MEA Reclamation Plant includes receiving the spent solvent, reclaiming the MEA, and sending the reclaimed MEA back to the ship. Waste generated during the MEA reclaiming process will be sent off-site to a waste disposal facility, where it will be incinerated. It is assumed that it will take 8 hours to process the spent solvent based on the small size of the system. An 8-hour processing time results in ~125 liters per minute (~33 gallons per minute [gpm]) throughput for the system.

Thermal reclaiming at atmospheric pressure was chosen for spent solvent reclaiming based on NexantECA's prior work on similar systems and publicly available literature (Fisher et al. 2007). Atmospheric pressure reclaiming is deemed suitable to recover easy amines such as MEA. MEA exhibits thermal stability at temperatures up to 148 °C (298.4 °F), so a maximum reclaiming temperature of approximately 138 °C (280.4 °F) was used as the design basis for the reclaimer. Caustic injection is used to treat the spent MEA solvent with 30% by weight NaOH solution to neutralize heat stable salts (HSS) and allow them to be removed as sodium salts in the reclaimer.

Based on non-confidential information, thermal reclaiming of MEA results in 95% by weight MEA recovery, with approximately 100% by weight heat stable salts (HSS) removal and 100% by weight metals/non-ionic product removal (Reid, 2015).

To provide reclaimed MEA at the high concentration required for return to the ship, an MEA concentrator unit is included to boil off excess water in the reclaimed solvent and remove trace amounts of CO_2. The reclaimed MEA is delivered back to the ship concentrated to 80% MEA and 20% water, by weight. The reclaimed MEA is cooled to 40 °C (104 °F) prior to transport to shipside. The reclaimed MEA is assumed to have 100% removal of contaminants, degradation products, and other impurities.

Table 16: Spent Solvent Composition

Component	Mass Fraction
MEA	0.230
H_2O	0.709
CO_2	0.0290
HEEDA	0.000
MEA-Urea	0.00126
BHEOX	0.000579
HEA	0.00205
HEI	0.00105

HEIA	0.000160
HEPO	0.00907
OZD	0.000639
Ammonium	0.000143
Chloride	0.00107
Nitrate	0.00234
Nitrite	0.000633
Phosphate	0.00217
Sulfate	0.00206
Acetic Acid	0.00107
Formic Acid	0.00312
Oxalic Acid	0.000989
Al^{3+}	0.000206
Ca^{2+}	5.56E-05
Cr^{3+}	0.000
Cu^{2+}	1.59E-05
Fe^{3+}	0.000103
K^{+}	0.000191
Mg^{2+}	7.94E-06
Mn^{3+}	0.000
Mo^{3+}	0.000
Na^{+}	0.00328
Ni^{2+}	1.59E-05
V^{2+}	0.000
Zn^{2+}	1.59E-05

2.3.2 Process Description and Modeling

The onshore MEA Reclamation Plant will receive spent solvent from the ship and reclaim and process the spent MEA such that it meets solvent requirements on the ship. The scope of the MEA Reclamation plant includes receiving the spent solvent in the onshore tank, solvent reclaiming to remove contaminants and degradation products, concentrating the MEA, and storing the reclaimed MEA onshore for return to the ship. Figure 11 shows the block flow diagram from MEA reclamation plant.

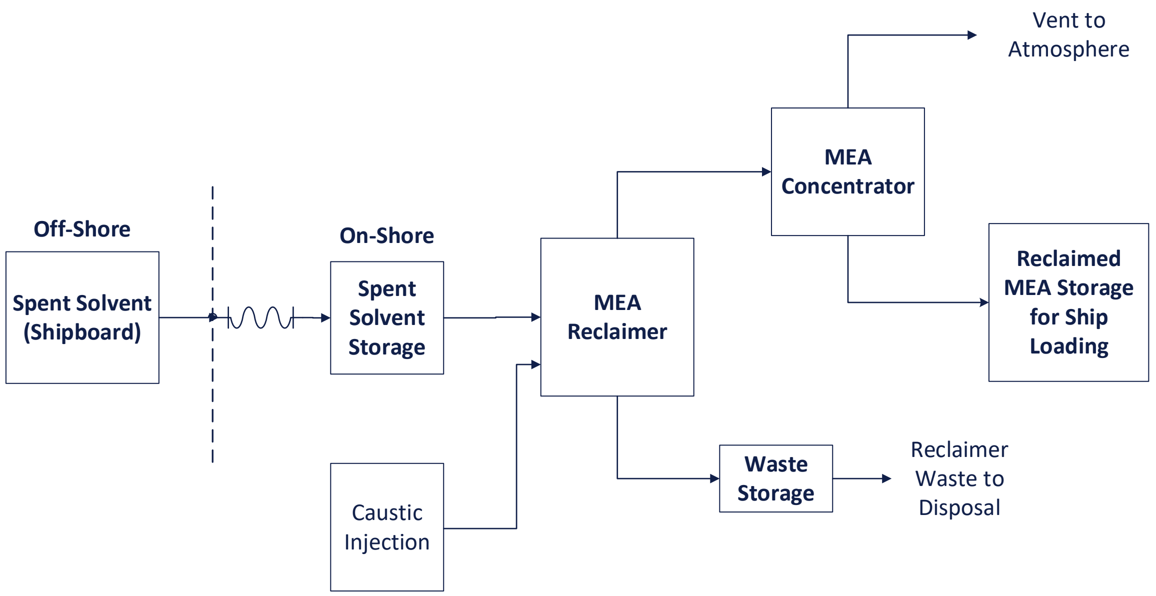


Fig. 11: MEA Reclamation Plant BFD MEA Reclamation Plant BFD

Spent Solvent Receiving

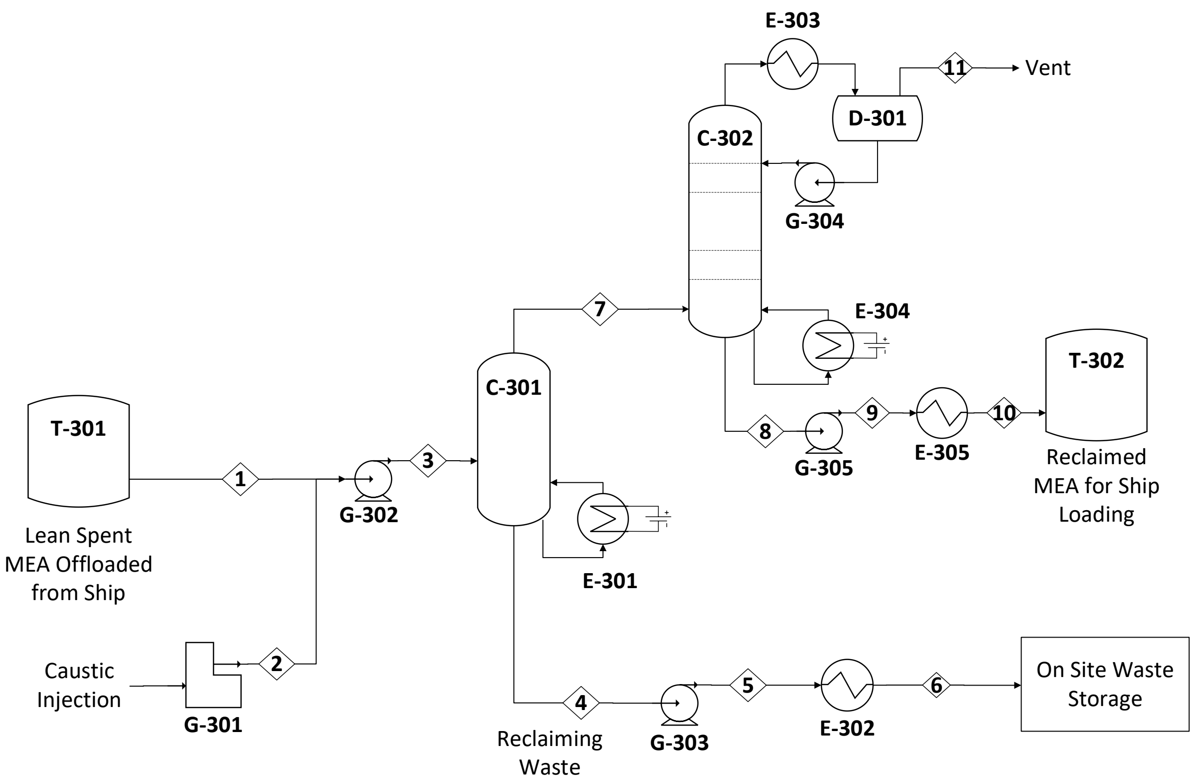
The spent solvent is offloaded from the ship using a pump on the ship and a flexible hose connection to an onshore tank truck. The spent solvent is transported via truck to the onshore spent solvent storage tank at the MEA Reclamation Plant. A total volume of 60 cubic meters of spent solvent is received at the MEA Reclamation Plant per ship.

MEA Reclaiming

The spent solvent is treated with caustic solution (30% NaOH by weight) to neutralize HSS to allow them to be removed as sodium salts in the reclaimer. The reclaimer unit consists of a stripping still and electric reboiler, which thermally reclaims the spent solvent to remove ~100% of the degradation products and contaminants and recover 95% MEA by weight. The reclaimer operates at atmospheric pressure. The reclaimer waste stream consists of a slurry of contaminants and degradation products which are cooled with cooling water and sent to on-site storage prior to disposal. Since MEA is stable at temperatures up to 148 °C, the reclaimer is kept below 138 °C to avoid additional thermal degradation to the solvent.

The reclaimer overhead consists of around 23% MEA by weight, with the balance of water and a small amount of CO_2 that exists after solvent regeneration on board. The reclaimer overhead is sent to the MEA concentrator to concentrate the reclaimed solvent stream to 80% MEA by weight for return to the ship. The MEA concentrator uses an electric reboiler to remove the excess water and trace amounts of CO_2 from the reclaimed solvent. The concentrated, reclaimed solvent is cooled and pumped to onshore storage prior to returning to the ship. The reclaimed solvent is transported via tank truck to shipside, and then loaded onto the ship using a flexible hose connection.

Figure 12 shows the PFD for the spent solvent receiving and MEA reclaiming process. Table 17 shows the associated HMB for spent solvent receiving and MEA reclaiming.



C-301 MEA Stripping Still
C-302 MEA Concentrator
D-301 MEA Conc Reflux Drum
E-301 MEA Reclaimer Reboiler
E-302 Reclaimer Waste Cooler
E-303 MEA Concentrator OVHD Cond
E-304 MEA Concentrator Reboiler
E-305 Reclaimed MEA Cooler

G-301 Caustic Metering Pump
G-302 Reclaimer Inlet Feed Pump
G-303 Reclaimer Waste Pump
G-304 MEA Concentrator Reflux Pump
G-305 Reclaimed MEA Pump
T-301 Spent MEA Storage Tank
T-302 Caustic Storage Tank
T-303 On-Site Waste Storage

Fig. 12: MEA Reclaiming Process Flow Diagram

Table 17: MEA Reclaiming Heat and Material Balance

Stream Number	1	2	3	4	5
Stream Description	Spent MEA from Tank	Caustic Injection	Feed to Reclaimer	Reclaimer Waste	Reclaimer Waste to Waste Cooler
Total, kg/hr	7,618	109	7,727	581	581
Composition, mass fraction					
MEA	0.229757	0.000	0.227	0.151	0.151
H2O	0.709149	0.700	0.711	0.397	0.397
CO2	0.028959	0.000	0.029	0.000	0.000
NaOH	0.000000	0.300	0.000	0.000	0.000
HEEDA	0.000000	0.000	0.000	0.000	0.000
MEA-Urea	0.001259	0.000	0.001	0.016	0.016
BHEOX	0.000579	0.000	0.001	0.008	0.008
HEA	0.002048	0.000	0.002	0.027	0.027
HEI	0.001049	0.000	0.001	0.014	0.014
HEIA	0.000160	0.000	0.000	0.002	0.002
HEPO	0.009070	0.000	0.009	0.119	0.119
OZD	0.000639	0.000	0.001	0.008	0.008
Ammonium	0.000143	0.000	0.000	0.002	0.002
Chloride	0.001069	0.000	0.000	0.000	0.000
Nitrate	0.002344	0.000	0.002	0.031	0.031
Nitrite	0.000633	0.000	0.001	0.008	0.008
Phosphate	0.002169	0.000	0.002	0.028	0.028
Sulfate	0.002061	0.000	0.002	0.027	0.027
Acetic Acid	0.001069	0.000	0.000	0.000	0.000
Formic Acid	0.003117	0.000	0.000	0.000	0.000
Oxalic Acid	0.000989	0.000	0.000	0.000	0.000
Sodium Acetate	0.000000	0.000	0.001	0.019	0.019
Sodium Formate	0.000000	0.000	0.004	0.060	0.060
Sodium Oxalate	0.000000	0.000	0.001	0.019	0.019
Urea	0.000000	0.000	0.000	0.000	0.000
Al^{3+}	0.000206	0.000	0.000	0.003	0.003
Ca^{2+}	0.000056	0.000	0.000	0.001	0.001
Cr^{3+}	0.000000	0.000	0.000	0.000	0.000
Cu^{2+}	0.000016	0.000	0.000	0.000	0.000
Fe^{3+}	0.000103	0.000	0.000	0.001	0.001
K^{+}	0.000191	0.000	0.000	0.002	0.002

Table 17: MEA Reclaiming Heat and Material Balance – Continued

Stream Number	1	2	3	4	5
Stream Description	Spent MEA from Tank	Caustic Injection	Feed to Reclaimer	Reclaimer Waste	Reclaimer Waste to Waste Cooler
Composition, mass fraction – continued					
Mg^{2+}	0.000008	0.000	0.000	0.000	0.000
Mn^{3+}	0.000000	0.000	0.000	0.000	0.000
Mo^{3+}	0.000000	0.000	0.000	0.000	0.000
Na^{+}	0.003278	0.000	0.003	0.043	0.043
Ni^{2+}	0.000016	0.000	0.000	0.000	0.000
V^{2+}	0.000000	0.000	0.000	0.000	0.000
Zn^{2+}	0.000016	0.000	0.000	0.000	0.000
Density, kg/m^3	1,016	1,162	1,009	1,003	1,003
Temperature, °C	22.5	25.0	25.0	134.4	134.4
Pressure, bara	1.013	1.013	1.366	1.066	1.366
Enthalpy Flow, GJ/hr^A	-97.11	-1.44	-98.18	-5.01	-5.01
Notes: A) Enthalpy flow is calculated at a reference 25 °C and 1 atm.					

Table 18 shows the performance results for the MEA Reclamation Facility. Table 19 and 20 show the power summary and the cooling water summary for the MEA Reclamation Facility.

Table 18: Performance Summary for the MEA Reclamation Facility

Parameter	Unit	Value
Spent Solvent Receiving and Reclaiming		
Total Volume of Spent Solvent Handled	m^3	60
Mass Flow of Spent MEA to Processing	kg/hr	7,618
Concentration of MEA in Spent Solvent	wt.%	23%
kg NaOH / kg Spent Solvent	-	0.004
Conversion Acetic Acid → Sodium Acetate	%	99%
Conversion Formic Acid → Sodium Formate	%	99%
Conversion Oxalic Acid → Sodium Oxalate	%	99%
MEA Reclaimer Duty	GJ/hr	16.27
Reclaimer Temperature	°C	134
Reclaimer MEA Recovery	wt.%	95%
Reclaimer Waste Flow	kg/hr	581
Concentrator Reboiler Duty	GJ/hr	0.77
wt.% MEA in Concentrated Reclaimed Solvent	wt.%	80%
Total Reclaimed Solvent Flow	kg/hr	2,058
Notes: A) The BOG system is only running when a ship is not at port to maintain cold temperatures throughout the CO_2 processing system.		

Table 19: Power Summary for the MEA Reclamation Facility

Power Summary	kW
MEA Reclaiming	
Reclaimer Electric Reboiler	4,519
MEA Concentrator Electric Reboiler	214
Caustic Metering Pump	0.00
Reclaimer Inlet Feed Pump	0.03
Reclaimer Waste Pump	0.02
MEA Concentrator Reflux Pump	0.04
Reclaimed MEA Pump	0.06
Total	**4,733**

Table 20: Cooling Water Summary for the MEA Reclamation Facility

Cooling Water Summary	GJ/hr	kg/hr
MEA Reclaiming		
Reclaimed MEA Cooler	0.6	19,190
Reclaimer Waste Cooler	0.1	3,603
MEA Concentrator Overhead Condenser	3.5	118,074
Total	**4.2**	**140,867**

2.3.3 Equipment Specifications for MEA Plant

The construction material for the MEA Reclamation Plant was chosen as carbon steel (CS) based on publicly available literature that states that CS is suitable for MEA reclaiming at atmospheric pressure. The major equipment used for the MEA Reclamation Plant are shown in Table 21.

Table 21: Major Equipment List for MEA Reclamation Plant

Columns

Plot No.	Item No.	Item Name	Type	Design Conditions barg	Design Conditions °C	MOC	No. Stages	Internal Type	Tray Spacing (m)	ID (m)	T/T Height (m)	Total Weight (kg)	#
MEA	C-301	MEA Stripping Still	Vertical Column	2.4	211	CS	N/A	None	N/A	1.1	4.4	2,600	1
MEA	C-302	MEA Concentrator	Vertical Trayed Column	2.4	158	CS	6	Trayed - Sieve	1	1.4	8.8	5,500	1

Process Vessels

Plot No.	Item No.	Item Name	Type	Design Conditions barg	Design Conditions °C	MOC	Liquid Volume (M^3)	Vessel ID (m)	T/T Length (m)	Total Weight (kg)	#
MEA	D-301	MEA Concentrator Reflux Drum	Horizontal Drum	1.0	131	CS	2.7	1.07	3.05	1,200	1

Tanks

Plot No.	Item No.	Item Name	Type	Design Conditions barg	Design Conditions °C	MOC	Tank ID (m)	Tank Volume (M^3)	T/T Height (m)	Total Weight (kg)	#
MEA	T-301	Spent MEA Storage Tank	Cylindrical	0.0	40	CS	4.5	99.6	6.3	6,200	1
MEA	T-302	Reclaimed MEA Storage Tank	Cylindrical	0.0	60	CS	2.5	29.5	6.0	3,000	1
MEA	T-303	On-Site Waste Storage	Cylindrical	0.0	60	CS	1.5	5.7	3.25	583	1

Electric Heaters and Reboilers

Plot No.	Item No.	Item Name	Type	Operating Conditions barg	Operating Conditions °C	MOC	Duty (GJ/hr)	Electricity Consumption (MWe)	#
MEA	E-301	MEA Reclaimer Reboiler	Electric Reboiler	1.4	134	CS	8.1	2.3	2
MEA	E-304	MEA Concentrator Reboiler	Electric Reboiler	1.1	127	CS	0.8	0.21	1

Shell and Tube Heat Exchangers

Plot No.	Item No.	Item Name	Type	Design Pressure, barg Shell	Design Pressure, barg Tube	Design Temperature, °C Shell	Design Temperature, °C Tube	Heat Transfer Area (m^2)	MOC Shell	MOC Tube	Total Weight (kg)	#
MEA	E-302	Reclaimer Waste Cooler	Shell and Tube	4.2	6.9	144	144	1.1	CS	CS	220	1
MEA	E-303	MEA Concentrator Overhead Condenser	Shell and Tube	4.2	6.9	136	136	20	CS	CS	810	1
MEA	E-305	Reclaimed MEA Cooler	Shell and Tube	4.2	6.9	158	158	11	CS	CS	550	1

Pumps

Plot No.	Item No.	Item Name	Type	Design Conditions		MOC	Operating Liquid Flow	Motor Power	Total Weight	Total # Req.	# Oper-ating	# Spare
				barg	ºC	Impeller & Casing	L/hr	kW	kg			
MEA	G-301	Caustic Metering Pump	Cent.	2.4	125	CS	0.0	0.0	80	2	1	1
MEA	G-302	Reclaimer Inlet Feed Pump	Cent.	2.4	125	CS	2.3	0.2	80	2	1	1
MEA	G-303	Reclaimer Waste Pump	Cent.	2.4	144	CS	0.2	0.2	80	2	1	1
MEA	G-304	MEA Concentrator Reflux Pump	Cent.	1.0	131	CS	0.5	0.6	110	2	1	1
MEA	G-305	Reclaimed MEA Pump	Cent.	2.4	158	CS	0.7	0.2	80	2	1	1

2.4 WP4: Techno-Economic Analysis

2.4.1 Cost Assumptions and Methodology

General Cost Basis

The capital and operating costs estimates for the EverLoNG Onshore Facility are based on the methodology described in this section. This project is considered a feasibility level study and, as such, the cost estimate is considered Class 4 accuracy. Costing methodology generally follows the US DOE NETL QGESS Cost Estimation Methodology for NETL Assessments of Power Plant Performance (NETL-PUB-22580) report. Cost estimates are on a 2023-year basis.

Facility Site

The design and cost basis assumes that the facility is located at Port Arthur, Texas and will be built within an existing LNG port facility that is already a developed site. The estimate assumes that on-site facilities, including warehouses, operations buildings, and maintenance shops are already on the premises. Thus, no buildings are costed as part of the estimate. In addition, it is assumed that most general utilities are already available on-site; this includes potable water, sanitary systems, electricity, cooling water, and process water. Costs associated with utilities include only the infrastructure to bring the utility to the required location.

Capital Costs

The capital costs for the EverLoNG Onshore Facility are based on major equipment-factored estimates for equipment, material, and labor costs developed from Aspen Process Economic Analyzer (APEA) and Aspen Capital Cost Estimator (ACCE) simulations. The APEA and ACCE results are based on Aspen Plus process simulations for CO_2 receiving and processing as well as spent solvent receiving and solvent reclaiming.

Since APEA and ACCE costs are generated in Q1-2022 dollars, those costs are escalated to 2023 dollars using Chemical Engineering Plant Cost Index (CEPCI) (Chemengonline, 2023) values.

The five levels of capital costs that are considered in this estimate are based on NETL methodology and are as follows:

- Bare Erected Cost (BEC): consists of the cost of process equipment, on-site facilities, and infrastructure that support the plant, and the direct and indirect labor required for its construction and/or installation

- Engineering, Procurement, and Construction Cost (EPCC): consists of the BEC plus the cost of services provided by the EPC contractor. The EPC services include detailed design, equipment and systems procurement, and project/construction management costs
- Total Plant Cost (TPC): consists of the EPCC plus project and process contingencies
- Total Overnight Cost (TOC) consists of the TPC plus all other “overnight” costs, including owner’s costs. TOC is an overnight cost, expressed in base-year dollars and as such does not include escalation during construction or construction financing costs
- Total As-Spent Capital (TASC) consists of the sum of all capital expenditures as they are incurred during the capital expenditure period for construction, including their escalation. TASC also includes interest during construction

Engineering and Construction Management, Home Office Fees, and Contingencies

Costs for Engineering and Construction Management and Home Office Fees (Eng’g CM & H.O. Fee) are estimated as a percentage of BEC. These costs consist of all home office engineering and procurement services as well as field construction management costs.

Both the project and process contingencies represent costs that are expected to be spent in the development and execution of the project that are not yet fully reflected in the design. Project contingency represents the “known unknowns”, and process contingency represents the “unknown unknowns” of the plant development and construction process.

Process contingency is estimated as a percentage of BEC and only applies to accounts that are viewed as not yet fully mature. CO_2 transportation and storage as well as MEA thermal reclaiming are well understood and commercialized processes. Thus, these processes do not have any contingencies applied.

Project contingency is calculated as percentage of the sum of BEC, Eng’g CM & H.O. Fee, and process contingency, and covers project uncertainty and the cost of any additional equipment that would result during detailed design.

Table 22 shows a summary of the Eng’g CM & H.O. Fee, process, and project contingencies applied for each item in the capital cost estimate.

Table 22: Eng’g CM & H.O. Fee and Contingency Basis

Cost Item	%	Rationale
Eng’g CM & H.O. Fee		
Process Equipment	10	Simple process will reduce complex engineering work
Bulk Materials	10	Simple process will reduce complex engineering work
Process Contingency		
Process Equipment	0	Commercialized equipment with minimal process risk
Bulk Materials	0	Commercialized equipment with minimal process risk
Project Contingency		
Process Equipment	20	NexantECA in-house data on standard project contingencies for commercial process
Bulk Materials	20	NexantECA in-house data on standard project contingencies for commercial process

Operating Maintenance Costs

The Operating and Maintenance (O&M) costs pertain to those costs associated with operating and maintaining the plant over its expected life. There are two components of O&M costs: fixed O&M, which is independent of plant operating status, and variable O&M, which is proportional to plant operating level. The variable O&M costs are estimated based on the capacity factor for the Onshore Facility, which is based on ship arrival frequency and time spent at the port. The capacity factor will increase as the number of vessels increases.

Fixed O&M

Fixed O&M cost assumptions used for cost development for the EverLoNG Onshore Facility are shown in Table 23. An average base labor rate of $48.55 per hour is used in this estimate, based on the U.S. Bureau of Labor Statistics data for Texas in 2023.

Table 23: Fixed O&M Cost Assumptions

Parameter	Value	Rationale
Labor Burden, % of base salary	30	NETL QGESS methodology
Labor Overhead Charge Rate, % of labor	25	NETL QGESS methodology
Maintenance Material & Labor, % of TPC	1.6	NETL QGESS methodology
Maintenance Labor, % of Maintenance Material & Labor	40	NETL QGESS methodology
Maintenance Material, % of Maintenance Material & Labor	60	NETL QGESS methodology
Administration & Support Labor, % of O&M Labor	25	NETL QGESS methodology
Taxes & Insurance, % of TPC	2	NETL QGESS methodology

Variable O&M

The cost of consumables is based on the individual rates of consumption, the unit cost of each specific consumable commodity, and the facilities' annual operating hours. Quantities for major consumables are estimated based on heat and material balances for the facility. Waste disposal costs are evaluated similarly to the consumables. Table 24 includes the consumables' costs used for the variable O&M cost estimate. Cooling water is assumed to be a purchased utility from the port facility. Waste disposal costs only consider costs for MEA reclaimer waste. It is assumed that negligible waste is generated from the rest of the facility.

Table 24: Fixed O&M Cost Assumptions

Parameter	Value	Rationale
Caustic (30 wt.%) $/m^3	$348.63	Publicly available data
N_2 Refrigerant, $/m^3	$266.17	Publicly available data
Cooling Water, $/tonne	$0.03	NexantECA in-house price data
Reclaimer Waste Disposal, $/tonne	$50.37	NETL BBR4 reference escalated from Dec 2018 dollars to 2023 dollars

Grid electricity cost is assumed to be $53.70 per megawatt-hour (MWh). This is based on NexantECA in-house pricing data.

Owner's Cost

Owner's Costs include pre-production costs, inventory capital, and other owner's costs such as land and financing costs. Items included as owner's costs for the Onshore Facility, along with relevant assumptions, are:

Pre-production costs

- 6 months operating labor
- 1-month maintenance materials at full capacity
- 1-month non-fuel consumables at full capacity
- 1-month waste disposal
- 2% of TPC

Inventory Capital

- 60-day supply of consumables at full capacity: only N_2 refrigerant is assumed to be stored on-site
- Spare parts: 0.5% of TPC

Other Costs

- Initial costs for chemicals
- Land: cost assumed to be zero, since the Onshore Facility will be located within the existing port facility, no additional land costs
- Other Owner's costs: 10% of TPC; lumped cost includes preliminary feasibility studies, including Front-End Engineering Design (FEED) study, economic development (costs for incentivizing local collaboration and support) construction and/or improvement of roads and /or railroad spurs outside of site boundary, legal fees, permitting costs, owner's engineering (staff paid by owner to give third-party advice and to help the owner oversee/evaluate the work of the EPC contractor and other contractors), owner's contingency (sometimes called "management reserve" – these are funds to cover costs relating to delayed startup, fluctuations in equipment costs, unplanned labor incentives)
- Financing costs: 2.7% of TPC; covers the cost of securing financing, including fees and closing costs but not including interest during construction or allowance for funds used during construction

CO_2 Transport and Storage

The cost of CO_2 transport and storage (T&S) is based on the DOE NETL T&S reference costs for a Texas plant location and CO_2 storage in an East Texas Basin. The DOE NETL T&S reference costs, reported in 2018 dollars, are scaled using CEPCI factors to 2023 dollars. The CO_2 T&S cost used in this study is $14.25 per tonne of CO_2.

TOC and TASC

Total Overnight Cost (TOC) is calculated as the TPC and all other "overnight" costs, including owner's costs. Total As-Spent Capital (TASC) is calculated using a TASC multiplier of 1.093 based on NETL QGESS methodology.

Capacity Factor

Capacity factor (CF) for the full Onshore Facility is based on the frequency of ship arrivals and ship turnaround time. For a single ship arrival every 32 days and a ship turnaround time of 4 days, it is assumed that the Onshore Facility is operating 46 days out of the year. This leads to a CF for the onshore plant of 12.5%. It is assumed that plant shutdowns for planned maintenance will occur in between ship arrivals.

With these same assumptions, and a CO_2 processing time of 12 hours for each ship's arrival, the capacity factor for the CO_2 processing facility alone is 1.6%. With a spent solvent reclaiming time of 8 hours, the capacity factor for the MEA reclaiming plant is 1%. It is assumed that plant shutdowns for planned maintenance will occur in between ship arrivals.

It is assumed that when the CO_2 processing system is not running, the BOG system will be running to reliquefy CO_2. The capacity factor for the BOG system is estimated at 80%.

Cost of CO_2 Capture

The cost of CO_2 capture (COC) is calculated using NETL QGESS methodology. The calculated COC in this report reflects costs for the Onshore Facility alone per tonne of product CO_2 delivered to the pipeline. This is expected to be added to the COC for the onboard SBCC system to determine the total COC for the full CCUS chain. The fixed charge rate (FCR) used for calculating the cost of CO_2 capture is based on NETL QGESS values.

2.4.2. Onshore Facility Cost Results

This section covers the cost estimates for the EverLoNG Onshore Facility including CO_2 processing and MEA reclamation. We have also conducted a sensitivity analysis to examine the costs for the Onshore Facility for a higher ship arrival frequency, in which multiple ships per month with SBCC technology are processed at the facility for CO_2 offloading and spent solvent reclaiming. This would occur when the SBCC technology is more widely implemented.

Capital Cost Estimate

Table 25 shows the capital cost results for the Onshore Facility. The BEC for the full facility is estimated at \$63 million. TPC is estimated at \$83 million. The CO_2 receiving and processing system accounts for the largest portion of TPC (84%). This is due to the high costs for the onshore CO_2 storage tanks (58% of TPC) and the 25-kilometer onshore export pipeline (22% of TPC).

Table 25: Capital Cost Estimate

	Case:	EverLoNG Ship-Board Carbon Capture (SBCC) - Onshore Facility								
	Cost Base:	2023, $/1,000								
Acct No.	Item / Description	Equip. Cost	Material Cost	Labor		BEC	Eng'g CM, H.O. & Fee	Contingencies		TPC
				Direct	Indirect			Process	Project	
1	CO_2 Receiving and Processing									
1.1	CO_2 Intermediate Storage	$20,167	$11,454	$4,381	$0	$36,002	$3,600	$0	$7,921	$47,523
1.2	CO_2 Processing	$1,794	$1,094	$216	$0	$3,103	$310	$0	$683	$4,096
1.3	Export Pipeline to Main Pipeline Interconnection	$0	$10,561	$2,958	$0	$13,519	$1,352	$0	$2,974	$17,846
	Subtotal	**$21,961**	**$23,109**	**$7,555**	**$0**	**$52,625**	**$5,262**	**$0**	**$11,577**	**$69,465**
2	CO_2 BOG System									
2.1	BOG Compressor	$0	$5	$6	$0	$11	$1	$0	$2	$14
2.2	Heat Exchangers	$10	$78	$46	$0	$134	$13	$0	$30	$178
2.3	Refrigeration System	$723	$70	$69	$0	$862	$86	$0	$190	$1,138
2.4	BOG Knockout Vessel	$34	$68	$26	$0	$128	$13	$0	$28	$170
	Subtotal	**$768**	**$220**	**$147**	**$0**	**$1,136**	**$114**	**$0**	**$250**	**$1,499**
3	MEA Receiving and Reclaiming									
3.1	Spent Solvent Intermediate Storage	$62	$39	$22	$0	$124	$12	$0	$27	$163
3.2	Caustic Injection	$5	$6	$10	$0	$21	$2	$0	$5	$28
3.3	Solvent Reclaimer	$328	$98	$74	$0	$500	$50	$0	$110	$660
3.4	Solvent Concentrator	$151	$176	$95	$0	$422	$42	$0	$93	$557
3.5	Reclaimed Solvent Storage	$53	$72	$43	$0	$168	$17	$0	$37	$222
3.5	Intermediate Waste Storage	$17	$46	$30	$0	$92	$9	$0	$20	$122
	Subtotal	**$616**	**$437**	**$273**	**$0**	**$1,326**	**$133**	**$0**	**$292**	**$1,751**
4	Service Water & Miscellaneous BOP Systems									
4.1	Service Water Piping	$0	$2	$3	$0	$4	$0	$0	$1	$6
4.2	Wastewater Piping	$0	$2	$3	$0	$4	$0	$0	$1	$6
4.3	Plant / Instrument Air System	$275	$475	$281	$0	$1,031	$103	$0	$227	$1,361
	Subtotal	**$275**	**$478**	**$286**	**$0**	**$1,039**	**$104**	**$0**	**$229**	**$1,372**
5	Accessory Electric Plant									
5.1	Substation	$74	$54	$58	$0	$187	$19	$0	$41	$246
5.2	Switchgear & Motor Control	$926	$0	$37	$0	$963	$96	$0	$212	$1,271
5.3	Wire & Cable	$0	$69	$14	$0	$83	$8	$0	$18	$110
5.4	Grounding & Electrical Trenching	$12	$18	$30	$0	$60	$6	$0	$13	$79
5.5	Standby Equipment	$435	$0	$869	$0	$1,304	$130	$0	$287	$1,721
5.6	Electrical Foundations	$0	$3	$2	$0	$5	$0	$0	$1	$6
5.7	Misc. Electrical	$102	$62	$40	$0	$203	$20	$0	$45	$268
	Subtotal	**$1,548**	**$206**	**$1,051**	**$0**	**$2,804**	**$280**	**$0**	**$617**	**$3,702**

Table 25: Capital Cost Estimate– Continued

	Case:	EverLoNG Ship-Board Carbon Capture (SBCC) - Onshore Facility								
	Cost Base:	2023, $/1,000								
Acct No.	Item / Description	Equip. Cost	Material Cost	Labor		BEC	Eng'g CM, H.O. & Fee	Contingencies		TPC
				Direct	Indirect			Process	Project	
6	Instrumentation & Control									
6.1	CO_2 Receiving and Processing I&C Equipment	$2,084	$0	$62	$0	$2,146	$215	$0	$472	$2,832
6.2	CO_2 BOG I&C Equipment	$177	$0	$56	$0	$233	$23	$0	$51	$307
6.3	MEA Reclaiming I&C Equipment	$243	$0	$70	$0	$313	$31	$0	$69	$414
6.4	Distributed Control System / PLC	$188	$0	$7	$0	$196	$20	$0	$43	$259
6.5	Instrument Wiring & Tubing	$0	$2	$3	$0	$5	$1	$0	$1	$7
6.6	Other I&C	$0	$23	$9	$0	$32	$3	$0	$7	$42
	Subtotal	$2,693	$25	$207	$0	$2,925	$292	$0	$643	$3,861
6	Improvements to Site									
6.1	Site Preparation	$0	$0	$10	$0	$10	$1	$0	$2	$13
6.2	Site Improvements	$0	$0	$0	$0	$0	$0	$0	$0	$0
5.3	Foundations	$0	$403	$306	$0	$710	$71	$0	$156	$937
	Subtotal	$0	$403	$316	$0	$719	$72	$0	$158	$949
	TOTAL	$27,860	$24,879	$9,835	$0	$62,575	$6,257	$0	$13,766	$82,598

O&M Cost Estimate

Table 26 shows the O&M cost estimate for the Onshore Facility. Operating labor requirements per shift reflect labor requirements for the full Onshore Facility during the 4-day ship turnaround time. When there is no ship at port, it is assumed that only one operator is required for the BOG system. This is accounted for in the annual operating labor cost estimate. Consumables consumption is denoted per hour when the respective facility is in operation. For example, caustic injection of 0.09 cubic meters per hour is only required during the 8 hours of spent solvent reclaiming time for a single ship. The dollar per tonne of CO_2 results are based on the product CO_2 flow to the pipeline.

Annual fixed operating costs are estimated at $3.3 million per year, or $59 per tonne of CO_2. Variable operating costs are estimated at $0.9 million per year, or $16 per tonne of CO_2. Electricity costs for the facility are estimated at $0.1 million per year, or $2.5 per tonne of CO_2. The total O&M cost estimate for the Onshore Facility is $4.4 million per year, or $78 per tonne of CO_2.

Table 26: O&M Cost Estimate

Case:	EverLoNG Ship-Board Carbon Capture (SBCC) - Onshore Facility					
Cost Base:	2023					
Product CO_2 Flow to Pipeline:	57,031 tonne/yr					
Capacity Factor:						
Onshore Facility	12.5%					
CO_2 Processing	1.6%					
BOG System	80.0%					
MEA Reclaiming	1.0%					
OPERATING & MAINTENANCE LABOR						
Operating Labor			Operating Labor Requirements per Shift			
Operating Labor Rate (base):	$48.55	$/hour	Skilled Operator		1	
Operating Labor Burden	30%	of base	Operator		2	
Labor O-H Charge Rate	25%	of labor	Foreman		1	
			Lab Techs, etc.		1	
				Total	5	
FIXED OPERATING COSTS						
					Annual Cost, $	$/tonne CO_2
Annual Operating Labor					$829,331	$14.54
Maintenance Labor					$528,630	$9.27
Administrative & Support Labor					$339,490	$5.95
Property Taxes and Insurance					$1,651,970	$28.97
Fixed Operating Costs Total					$3,349,421	$58.73
VARIABLE OPERATING COSTS						
					Annual Cost, $	$/tonne CO_2
Maintenance Material					$792,945	$13.90
Consumables	Consumption		Cost			
	Initial	Per Hour*	Per Unit	Initial Fill		
Caustic (30 wt.%), m^3	0.19	0.09	$348.63	$65	$3,049	$0.05
N_2 Refrigerant, m^3	500	0.001	$266.17	$133,083	$135,212	$2.4
BOG System Cooling Water, tonne	0.0	1.11	$0.03	$0.00	$247	$0.004
MEA Reclaiming Cooling Water, tonne	0.0	141	$0.03	$0.00	$409	$0.01
Reclaimer Waste Disposal, tonne	0.0	0.58	$50.37	$0.00	$2,672	$0.05
Subtotal				$133,148	$141,589	$2.5
Variable Operating Costs Total					$934,535	$16
ELECTRICITY COST						
	Consumption		Cost		Annual Cost. $	$/tonne CO_2
	Initial	Per Year	Per Unit	Initial Fill		
CO_2 Receiving & Processing, MWh	-	2,024	$53.70	-	$108,670	$1.91
BOG System, MWh	-	142	$53.70	-	$7,601	$0.13
MEA Reclaiming, MWh	-	432	$53.70	-	$23,191	$0.41
Net Electricity Import Cost Total					$139,462	$2.45
Notes:						
* Consumption per hour during respective facility operating hours						

Table 27 and 28 show the variable O&M costs for the CO_2 Plant and MEA Reclamation Plant at an annual cost and a dollar per tonne of CO_2 and dollar per tonne of MEA, respectively. The dollar per tonne of CO_2 result considers the product CO_2 flow to the pipeline. The dollar per tonne of MEA result considers the amount of MEA in the spent solvent that is offloaded from the ship. The total variable operating costs for the CO_2 Plant alone are $0.3 million per year, or $4 per tonne of CO_2. The total variable operating costs for the MEA Reclamation Plant alone are $29 thousand per year, or $213 per tonne of MEA.

Table 27: Variable O&M Costs – for CO_2 processing Plant

Case:	Everlong Ship-Board Carbon Capture (SBCC) – CO_2 Plant					
Cost Base:	2023					
Product CO_2 Flow to Pipeline:	57,031 tonne/yr					
Capacity Factor:						
CO_2 Processing	1.6%					
BOG System	80.0%					
VARIABLE OPERATING COSTS						
Consumables	Consumption		Cost		Annual Cost, $	$/tonne CO_2
	Initial	Per Hour*	Per Unit	Initial Fill		
N_2 Refrigerant, m^3	500	0.0011	$266.17	$133,083	$135,212	$2.4
BOG System Cooling Water, tonne	0.00	1.11	$0.03	$0.00	$247	$0.004
Subtotal					**$135,460**	**$2.4**
ELECTRICITY COST						
	Consumption		Cost		Annual Cost. $	$/tonne CO_2
	Initial	Per Year	Per Unit	Initial Fill		
CO_2 Receiving & Processing, MWh	-	2,024	$53.7	-	$108,670	$1.91
BOG System, MWh	-	141.5	$53.7	-	$7,601	$0.13
Net Electricity Import Cost Total					**$116,271**	**$2.04**
Notes:						
* Consumption per hour during respective facility operating hours						

Table 28: Variable O&M Costs –MEA Reclamation Plant

Case:	EverLoNG Ship-Board Carbon Capture (SBCC) - MEA Reclamation Plant					
Cost Base:	2023					
MEA Offloaded from Ship to MEA Reclamation Plant:	138 tonne/yr					
Capacity Factor:						
MEA Reclaiming	1.0%					
VARIABLE OPERATING COSTS						
Consumables	Consumption		Cost		Annual Cost, $	$/tonne MEA
	Initial	Per Hour*	Per Unit	Initial Fill		
Caustic (30 wt.%), m^3	0.19	0.09	$349	$65.40	$3,049	$22
MEA Reclaiming Cooling Water, tonne	0.00	141	$0.03	$0.00	$409	$3.0
Reclaimer Waste Disposal, tonne	0.00	0.58	$50	$0.00	$2,672	$19
Subtotal					$6,130	$45
ELECTRICITY COST						
	Consumption		Cost		Annual Cost, $	$/tonne MEA
	Initial	Per Year	Per Unit	Initial Fill		
MEA Reclaiming Electricity, MWh	-	432	$53.70	-	$23,191	$168.47
Net Electricity Import Cost Total					$23,191	$168.47
Notes:						
* Consumption per hour during respective facility operating hours						

Owner's Cost Estimate

Owner's costs for the Onshore Facility are shown in Table 29. For consumables inventory capital, only N_2 refrigerant for the BOG system is assumed to be stored on-site. Total owner's costs for the Onshore Facility are estimated at $14 million. TOC and TASC are estimated at $96 million and $105 million, respectively.

Table 29: Owner's Cost Estimate

Description	$/1,000
Pre-Production Costs	
6 Months All Labor	$849
1 Month Maintenance Materials	$66
1 Month Non-Fuel Consumables	$63
1 Month Waste Disposal	$21
2% of TPC	$1,652
Total	$2,651
Inventory Capital	
60-day supply of non-fuel consumables at 100% CF	$28
0.5% of TPC (spare parts)	$413
Total	$441
Other Costs	
Initial Cost for Catalyst and Chemicals	$133
Land	$0.0
Other Owner's Costs	$8,260
Financing Costs	$2,230
Total	$10,623
Total Owner's Costs	$13,715
Total Plant Cost	$82,598
Total Overnight Costs (TOC)	$96,314
TASC Multiplier (IOU, 32-year)	1.093
Total As-Spent Cost (TASC)	$105,271

Cost of CO_2 Capture

Table 30 shows the cost of CO_2 capture (COC) for the EverLoNG Onshore Facility. The total COC (excluding T&S) is calculated as $208 per tonne of CO_2. When CO_2 T&S costs are included, the total COC is increased to $222 per tonne of CO_2. As shown in Table 30, capital investment recovery costs are the largest contributor to the total cost of capture (63%), primarily due to the high capital costs for the CO_2 storage tanks, 25-kilometer export pipeline, and low capacity factor 12.5%. Fixed and variable costs account for 28% and 8% of the total COC excluding T&S, respectively. Electricity costs account for 1% of the total COC, excluding T&S.

Table 30: Cost of CO_2 Capture Summary

Component	Cost of CO_2 Capture, $/tonne CO_2
Capital	$130.50
Fixed	$58.73
Variable	$16.39
Electricity	$2.45
Total (excluding T&S)	**$208.06**
CO_2 T&S	$14.25
Total (including T&S)	**$222.31**

2.4.3 Sensitivity Study for Higher Ship Arrival Frequency

We also conducted a sensitivity analysis regarding the impact on costs for the EverLoNG Onshore Facility with more frequent ship arrivals. With a ship turnaround time of 4 days, the maximum frequency of ship arrivals to the facility is every 4 days. This equates to 91 ship arrivals per year which will offload CO_2 and spent solvent at the Onshore Facility. This increases the overall capacity factor for the onshore system to 99.8%. With a CO_2 processing time of 12 hours and spent solvent processing time of 8 hours, the capacity factors for the CO_2 Plant and MEA Reclamation Plant are 12.5% and 8.3%, respectively.

With ship arrivals every 4 days to the Onshore Facility, the BOG system does not need to be run for CO_2 reliquification, so the capacity factor for the BOG system in this case is zero. However, the capital costs for the BOG system are still included in the estimate, since this system would be required at the facility for operation before the maximum ship arrival frequency is reached.

The High Frequency Ship Arrival Case uses the same design and capital cost basis defined in Sections 1 and 2 except for those parameters shown in Table 31 in red.

Table 31: Sensitivity Case Design Parameters

Parameter	Unit	High Ship Frequency Case	Base Case
Online Time			
Ship Turnaround Time	days	4	4
No. Ship Arrivals Per Year	ships/year	91	11
CO_2 Processing Time	hours/ship	12	12
MEA Reclaiming Time	hours/ship	8	8
Capacity Factor			
Onshore Facility Capacity Factor	%	99.8	12.5
CO_2 Processing Plant CF	%	12.5	1.6
BOG System CF	%	0.0	80
MEA Reclamation Plant CF	%	8.3	1
CO_2 and Solvent Quantity			
Product CO_2 Flow to Pipeline	tonne/year	456,250	57,031
MEA Offloaded from Ship to MEA Reclamation Plant	tonne/year	1,139	138

Sensitivity Case – Capital Cost Estimate

The capital costs for the Sensitivity Case are equal to the capital costs of the Base Case. It is expected that with ship arrivals every 4 days, the BOG system will no longer need to be operating. However, the BOG system will still be required at the facility, so the capital costs for the BOG system are still included in the Sensitivity Case.

Sensitivity Case – O&M Cost Estimate

Table 32 shows the O&M cost estimate for the Sensitivity Case. Annual fixed operating costs are estimated at $5.8 million per year, or $13 per tonne of CO_2. Variable operating costs are estimated at $0.8 million per year, or $1.8 per tonne of CO_2. Electricity costs for the facility are estimated at $1 million per year, or $2.3 per tonne of CO_2. The total O&M cost estimate for the Onshore Facility is $7.7 million per year, or $17 per tonne of CO_2.

Table 32: Sensitivity Case – O&M Cost Estimate

Case:	EverLoNG Ship-Board Carbon Capture (SBCC) – Onshore Facility					
Cost Base:	2023					
Product CO_2 Flow to Pipeline:	456,250 tonne/yr					
Capacity Factor:						
Onshore Facility	99.7%					
CO2 Processing	12.5%					
BOG System	0.0%					
MEA Reclaiming	8.3%					
OPERATING & MAINTENANCE LABOR						
Operating Labor				Operating Labor Requirements per Shift		
Operating Labor Rate (base):	$48.55	$/hour		Skilled Operator	1	
Operating Labor Burden	30%	of base		Operator	2	
Labor O-H Charge Rate	25%	of labor		Foreman	1	
				Lab Techs, etc.	1	
				Total	5	
FIXED OPERATING COSTS						
					Annual Cost, $	$/tonne CO_2
Annual Operating Labor					$2,764,437	$6.06
Maintenance Labor					$528,630	$1.16
Administrative & Support Labor					$823,267	$1.80
Property Taxes and Insurance					$1,651,970	$3.62
Fixed Operating Costs Total					$5,768,304	$12.64
VARIABLE OPERATING COSTS						
					Annual Cost, $	$/tonne CO_2
Maintenance Material					$792,945	$1.74
Consumables	Consumption		Cost			
	Initial	Per Hour*	Per Unit	Initial Fill		
Caustic (30 wt.%), m^3	0.19	0.09	$348.63	$65	$23,936	$0.05
MEA Reclaiming Cooling Water, tonne	0.0	141	$0.03	$0.00	$3,270	$0.01
Reclaimer Waste Disposal, tonne	0.0	0.58	$50.37	$0.00	$21,374	$0.05
Subtotal				$65	$48,580	$0.1
Variable Operating Costs Total					$841,526	$1.8
ELECTRICITY COST						
	Consumption		Cost		Annual Cost, $	$/tonne CO_2
	Initial	Per Year	Per Unit	Initial Fill		
CO_2 Receiving & Processing, MWh	-	16,189	$53.70	-	$869,360	$1.91
MEA Reclaiming, MWh	-	3455	$53.70	-	$185,528	$0.41
Net Electricity Import Cost Total					$1,054,887	$2.31

Notes:

* Consumption per hour during respective facility operating hours

Table 33 and 34 show the variable O&M costs for the CO_2 Plant and MEA Reclamation Plant at an annual cost and a dollar per tonne of CO_2 and dollar per tonne of MEA, respectively, for the Sensitivity Case.

The total variable operating costs for the CO_2 Plant alone are $0.9 million per year, or $2 per tonne of CO_2. This only considers the electricity cost for running the CO_2 processing system, since consumables and electricity for the BOG system are not required for the High Frequency Ship Arrival Case. The total variable operating costs for the MEA Reclamation Plant alone are $0.2 million per year, or $206 per tonne of MEA.

Table 33: Sensitivity Case – Variable O&M Costs, CO_2 Plant

Case:	Everlong Ship-Board Carbon Capture (SBCC) – CO_2 Plant					
Cost Base:	2023					
Product CO_2 Flow to Pipeline:	456,250 tonne/yr					
Capacity Factor:						
CO_2 Processing	12.5%					
BOG System	0.0%					
VARIABLE OPERATING COSTS						
Consumables	Consumption		Cost		Annual Cost, $	$/tonne CO_2
	Initial	Per Hour*	Per Unit	Initial Fill		
N_2 Refrigerant, m^3	0.00	0.000	$0.00	$0.00	$0.0	$0.0
BOG System Cooling Water, tonne	0.00	0.00	$0.00	$0.00	$0.0	$0.0
Subtotal					$0.0	$0.0
ELECTRICITY COST						
	Consumption		Cost		Annual Cost, $	$/tonne CO_2
	Initial	Per Year	Per Unit	Initial Fill		
CO_2 Receiving & Processing, MWh	-	16,189	$53.7	-	$869,360	$1.91
BOG System, MWh	-	0.0	$0.0	-	$0.0	$0.00
Net Electricity Import Cost Total					$869,360	$1.91
Notes:						
* Consumption per hour during respective facility operating hours						

Table 34: Sensitivity Case – Variable O&M Costs, MEA Reclamation Plant

Case:	EverLoNG Ship-Board Carbon Capture (SBCC) – MEA Reclamation Plant					
Cost Base:	2023					
MEA Offloaded from Ship to MEA Reclamation Plant:	1,139 tonne/yr					
Capacity Factor:						
MEA Reclaiming	8.3%					
VARIABLE OPERATING COSTS						
Consumables	Consumption		Cost		Annual Cost, $	$/tonne MEA
	Initial	Per Hour*	Per Unit	Initial Fill		
Caustic (30 wt.%), m^3	0.19	0.09	$349	$65.40	$23,936	$21
MEA Reclaiming Cooling Water, tonne	0.00	141	$0.03	$0.00	$3,270	$2.9
Reclaimer Waste Disposal, tonne	0.00	0.58	$50	$0.00	$21,374	$19
Subtotal					$48,580	$43
ELECTRICITY COST						
	Consumption		Cost		Annual Cost, $	$/tonne MEA
	Initial	Per Year	Per Unit	Initial Fill		
MEA Reclaiming Electricity, MWh	-	3,455	$53.70	-	$185,528	$163
Net Electricity Import Cost Total					$185,528	$163
Notes:						
* Consumption per hour during respective facility operating hours						

Sensitivity Case – Owner's Cost Estimate

Table 35 shows the owner's cost estimate for the Sensitivity Case. Total owner's costs for the Onshore Facility are estimated at $15 million. TOC and TASC are estimated at $97 million and $106 million, respectively.

Table 35: Sensitivity Case – Owner's Cost Estimate

Description	$/1,000
Pre-Production Costs	
6 Months All Labor	$2,058
1 Month Maintenance Materials	$66
1 Month Non-Fuel Consumables	$49
1 Month Waste Disposal	$21
2% of TPC	$1,652
Total	**$3,846**
Inventory Capital	
60-day supply of non-fuel consumables at 100% CF	$0.0
0.5% of TPC (spare parts)	$413
Total	**$413**
Other Costs	
Initial Cost for Catalyst and Chemicals	$0.07
Land	$0.00
Other Owner's Costs	$8,260
Financing Costs	$2,230
Total	**$10,490**
Total Owner's Costs	**$14,749**
Total Plant Cost	**$82,598**
Total Overnight Costs (TOC)	**$97,348**
TASC Multiplier (IOU, 32 year)	1.093
Total As-Spent Cost (TASC)	**$106,401**

Sensitivity Case – Cost of CO_2 Capture

Table 36 shows the COC comparison for the High Frequency Ship Arrival Sensitivity Case and the Base Case. For the High Frequency Case, the total COC (excluding T&S) is calculated as $33.29 per tonne of CO_2. This represents an 84% decrease from the Base Case. When CO_2 T&S costs are included, the total COC is increased to $47.54 per tonne of CO_2, which is a 79% decrease from the Base Case.

Table 36: Cost of CO_2 Capture Comparison

Component	Cost of CO_2 Capture, $/tonne CO_2	
	High Ship Frequency Case	Base Case
Capital	$16.49	$130.50
Fixed	$12.64	$58.73
Variable	$1.84	$16.39
Electricity	$2.31	$2.45
Total (excluding T&S)	**$33.29**	**$208.06**
CO_2 T&S	$14.25	$14.25
Total (including T&S)	**$47.54**	**$222.31**

Conclusion

We carried out a detailed testing to quantity the MEA concentration, CO_2 loading, and MEA degradation. We also developed the process design package and cost estimate for the Onshore Facility for the EverLoNG project.

For MEA quantification, we analyzed MEA concentration, the net CO_2 loading, and impurities and degradation products in MEA. We received three batches of MEA samples from ship. The first and second samples were from the TotalEnergies campaign received in December 2023 and March 2024. The third sample was from the Sleipnir campaign, received in November 2024. For the first sample, we conducted ^{1}H NMR, to calculate the net MEA concentration. This was in the range of 18.2% (by weight) only. Since the pilot scale objective was to achieve an MEA concentration of 30 wt.%, an additional 170 g of pure MEA was added to the existing MEA-water mixture.

The MEA concentration for the TotalEnergies campaign gradually decreased from 30% to 26%, suggesting around 12% MEA degradation. Similarly, for the Sleipnir campaign, the MEA concentration reduced from 32% to 25%. Using ^{1}H and ^{13}C NMR, we also calculated the CO_2 loading for the MEA. With only carbamate, the net CO_2 loading for the rich sample was in the range of 0.4-0.45 mol_{CO2}/mol_{MEA}, while the lean sample was in the range of 0.18-0.25 mol_{CO2}/mol_{MEA}. These values suggest that the campaign results were as per our design parameters. Similarly, for the Sleipnir Campaign, the CO_2 loading was around 0.44 mol_{CO2}/mol_{MEA} for the rich sample and 18% for the lean sample with carbamate. We also conducted analytical experiments for the analysis of MEA samples after industrial CO_2 gas absorption and desorption. The analysis included ICP-OES to identify the metal ions and IC to identify inorganic impurities in the industrial sample, and GC-MS to identify degradation products. The major cation was in the form of sodium and was due to the use of NaOH for quenching the flue gas to adjust the pH. For anions, MEA oxidation was the major cause for the formation of formate, acetate, and oxalate, while NO_x in the flue gases resulted in nitrate salts. In degradation products, we identified HEPO as the major products, followed by OZD and acetamide for the TotalEnergies campaign, and similar results were seen in the Sleipnir campaign.

The Onshore Facility design includes CO_2 receiving and processing to pipeline export specifications as well as spent solvent receiving and reclaiming to treat spent MEA solvent from the SBCC system. The overall Onshore Facility design is based on several assumptions for the expected amount of CO_2 and spent solvent to be processed, as well as the frequency of ship arrivals to the port based on estimates made by the EverLoNG consortium. In reality, actual values may deviate from these assumptions. The design can be viewed as being conservative (i.e. oversized) to be able to handle variations in these assumptions, such as the ability to handle a higher number of ships per month than in the base case. The CO_2 Receiving and Processing Facility also considers that the CO_2 is offloaded from the ship in liquid form at 15 barg and -28 °C, and stored onshore in tanks with a design pressure and temperature of 22 barg and -45 °C. The overall cost for the Onshore Facility, excluding CO_2 T&S was 208 $/ton_{CO2}$, predominantly due to the lower capacity factor of 12.5%. The sensitivity case for more frequent ship arrivals resulted in a total cost of capture, excluding CO_2 T&S, of \$33/tonne$_{CO2}$, showing a significant decrease in the cost of CO_2 capture compared to the baseline case. This shows that the Onshore Facility is significantly more economic with several ship arrivals at the port compared to a single ship arriving every 32 days. The Onshore Facility design and cost results will be used with the results of other work packages to investigate the feasibility and costs for a full-chain ship-based carbon capture system.

Future work could consider designs to handle CO_2 from ships that is stored at different temperature and pressure conditions and how to integrate with the existing design. A large electrical load for the CO_2 export heating and for solvent reclaiming in an electric reboiler results from the current design. Future work should also investigate options for heat recovery or alternative heat sources to see the impact of alternative heat sources on plant design, costs, and life cycle CO_2 emissions.

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