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An evaluation of key challenges of CO_2 transportation with a novel Subsea Shuttle Tanker

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Abstract. Recently, a novel Subsea Shuttle Tanker (SST) concept has been proposed to transport carbon dioxide (CO_2) from ports to offshore oil and gas fields for either permanent storage or enhanced oil recovery (EOR). SST is a large autonomous underwater vehicle that travels at a constant water depth away from waves. SST has some key advantages over subsea pipelines and tanker ships when employed at marginal fields. It enables carbon storage in marginal fields which do not have sufficient volumes to justify pipelines. Further, in contrast to ships, SST does not require the use of a permanently installed riser base. This paper will evaluate the key challenges of using such vessel for CO_2 transportation. It discusses the most important properties such as thermodynamic properties, purity, and hydrate formation of CO_2 at different vessel-transportation states in relation to cargo sizing, material selection, and energy consumption.

Keywords: Subsea Shuttle Tanker; Carbon Capture and Storage; CO_2 Transportation

1. Introduction

The most critical agreement adopted in Conference of the Parties 2021 (COP 21) is a legally binding international treaty on climate changes to control the global mean temperature increase within 2 °C above pre-industrial levels by limiting this value to 1.5 °C before mid-century [1]. To achieve this target, tremendous effort from all parties is required. The Intergovernmental Panel on Climate Change (IPCC) indicates that the global CO_2 emission should be reduced by 50 - 85% from 2000's 28.2 Gt/yr level [2]. However, the world is slipping further away from the target. Tollefson [3] reports that the annual emission has grown in 2019 to 35.9 Gt/yr, though there is a slight reduction in 2020 (33.6 Gt/yr) due to the lower economic activity related to the Covid pandemic.

Carbon Capture and Storage (CCS) is one of many approaches to mitigate climate change. It enables the reduction of CO_2 emission from fossil fuels which will in the foreseeable future still contribute substantially to the global energy mix as this is required to preserve our current way of living [4]. In the CCS process, CO_2 is captured at various sources, processed, and then transported to selected storage sites. It is finally injected into the reservoir for Enhanced Oil Recovery (EOR) [4] or permanent storage [5]. During the transportation, different tools are used depending on the EOR/storage location. CO_2 can be transported by pipelines, trucks, and railway if the geological formation for storage is onshore. Subsea pipelines and ships can be used for transportation of CO_2 to be injected at offshore fields.

Recently, a novel Subsea Shuttle Tanker (SST) concept was proposed to be an alternative to pipelines and tanker ships for offshore CO_2 transportation [6]. It aims to be an enabler for the CCS utilisation of marginal field. It has some key advantages over the above-mentioned conventional methods. First, it

can be applied to small fields without sufficient CO_2 storage capacities to economically justify subsea pipeline installation. Second, in contrast to tanker ships, SST does not require the use of a permanently installed riser base [7]. Third, SST operates underwater and is not exposed to wind and waves, i.e., it is weather-independent. Fourth, SST travels at a slow speed to minimise drag resistance and consequently it has a low energy consumption, i.e., lower carbon footprint compared to pipelines and ships [6]. Last, the SST is designed to be fully autonomous. This increases safety and reduces marine operations costs when compared to a conventionally manned vessel.

Using SSTs for CO_2 transportation was first proposed by Equinor in two research disclosures [8][9]. Xing et al. [7] went on to discuss the most important design considerations of an SST system for liquid CO_2 transportation. Recently, a 164 m SST conceptual baseline design was developed by University of Stavanger (UiS) and presented in Ma et al. [6] (illustrated in Figure 1). In Xing et al. [7] and Ma et al. [6], discussions on design issues related to the CO_2 transportation aspect of SST were made. This paper continues these discussions by performing an initial evaluation of key challenges faced by UiS SST such as CO_2 thermodynamic properties, CO_2 purity, cargo tanks sizing, material selection, energy consumption, and CO_2 hydrate formation. The objective of this paper is to provide insights on managing and reducing the high levels of uncertainties associated with the CO_2 transportation aspect of SST.
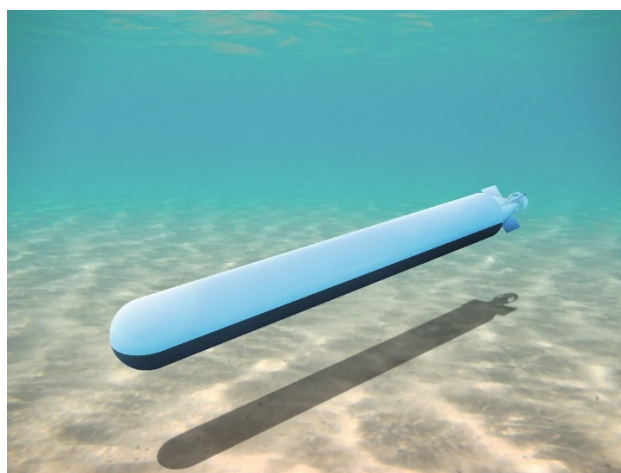
Figure 1. The UiS baseline SST.

2. CO_2 properties

2.1. Thermodynamic properties
The purity or quality of the CO_2 has critical impact on the cargo tank design of the SST since impurities can cause erosion and increase the risk of hydrate formation. This property is largely affected by the thermodynamic properties which can be shown via a phase diagram as presented in Figure 2. Depending on the pressure and temperature combination, CO_2 can exist in four phases: solid phase, liquid phase, vapor phase, and supercritical phase. The triple point (5.1 bar, 56 °C) is where CO_2 exists simultaneously in vapor, liquid, and solid phase. CO_2 turns into supercritical phase when the pressure and temperature increase beyond the critical point (74 bar, 32 °C).

Figure 2. CO_2 phase diagram.
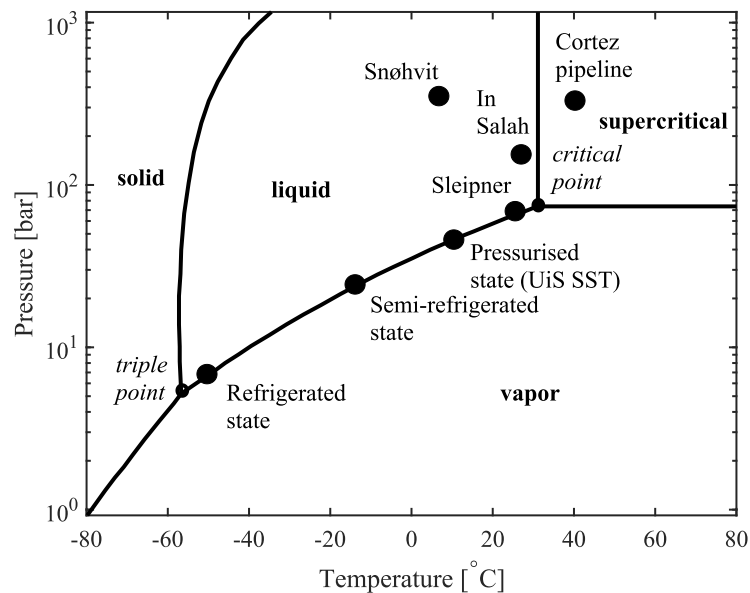
As presented in Figure 2, the state of CO_2 varies between different transportation methods. Pipelines transport CO_2 in a high-pressure, high-temperature supercritical phase. In contrast, ships carry CO_2 as a saturated liquid. In this condition, CO_2 is constantly boiling and as a result the pressure and temperature will be naturally maintained at a setpoint. Such cargo may be carried under one of the three states along the saturation line: refrigerated state (7 bar, -55 °C), semi-refrigerated state (15 bar, -30 °C), or pressurised state (45 bar, 10 °C) [10][11]. The selection of the transportation state depends on the vessel size. Larger vessels such as Very Large Gas Carriers (VLGC) can transport CO_2 liquid at a refrigerated state since the design and construction cost of large pressure vessels with high pressure capacities is uneconomical. Therefore, refrigeration is used for very large CO_2 carriers with capacities over 20,000 m^3 [12]. For smaller ships around 10,000 m^3 capacity, semi-refrigeration is more attractive. Since the scale of current offshore CCS projects are not very large, many CO_2 carriers are designed to transport semi-refrigerated CO_2, e.g., the Northern Light project CO_2 carrier [13] and Kokubun's CO_2 carrier [10]. The UiS SST [6] transports CO_2 as a pressurised liquid which means CO_2 can be transported at environmental temperature of 0 to 20 °C, i.e., no refrigeration is required. However, the cargo tanks need to be designed to handle higher pressures of 40 to 60 bar. For information, Figure 2 also presents the CO_2 wellhead injection states. At Snøhvit, In Salah, and Sleipner fields, CO_2 is injected at an intermediate-temperature and high-pressure state (10 - 30 °C, > 80 bar) (data from [13][14]).

The main processes in CO_2 transportation are presented in Figure 3. It envisioned that transporting CO_2 in refrigerated, semi-refrigerated, and pressurised states provide different challenges to SST. In the refrigerated and semi-refrigerated states, liquefication and heating systems are required to transport CO_2 at a low temperature at the port and offloading destination, respectively. During the offloading at the wellhead, inter-heaters and compressors are required to bring the temperature from sub -20 °C to above 10 °C and boost the pressure from approximately 10 bar to above 80 bar. In this process, boil-off gas is generated and must be re-captured using re-liquefaction systems. On the contrary, transporting CO_2 as a pressurised liquid (UiS SST) is more cost- and energy-efficient. At the port, CO_2 does not need to be conditioned before loading. Further, since the saturated liquid CO_2 can passively regulate its pressure and temperature with the environment, no cost-intensive re-liquefaction system is needed. At the wellhead, the liquid CO_2 which is at approximately 40 - 60 bars can also be injected directly using a single stage booster pump into the reservoir [6].
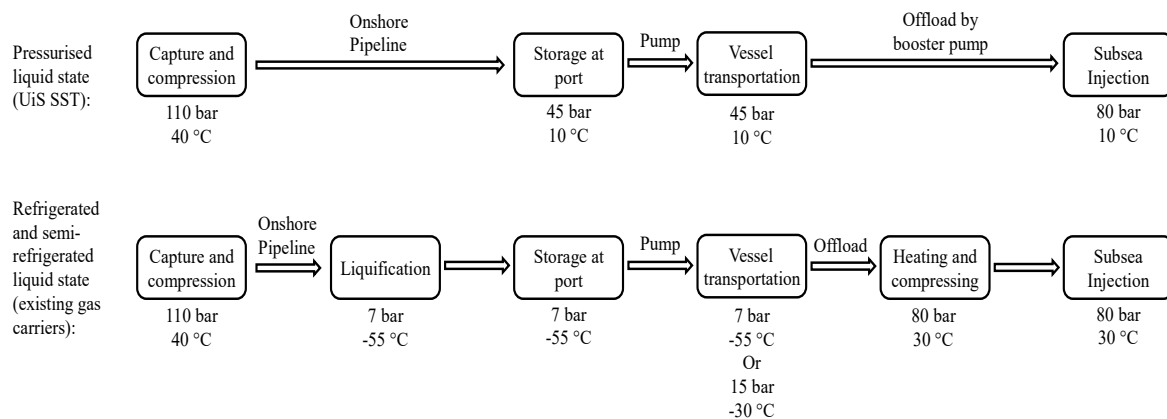
Figure 3. Main processes in CO_2 transportation.

2.2. CO_2 Impurities

Fossil fuel combustion is the dominant human-activity-related CO_2 source. It contributes 92.4% of the total CO_2 emission in the US in 2008 [15]. Within this, electricity generation and transportation accounts for 34.5% and 32.6% of the total emission, respectively. The other main components apart from CO_2 include N_2, H_2O, and O_2 [4]. Besides, sulphur oxides SO_x, hydrogen sulphide (H_2S), and nitrogen oxides NO_x are also very common contents in typical carbon sources like coal-fired power plants [16]. The amounts and types of contaminants in the captured CO_2 vary significantly with the carbon source as well as capture and separation technology [4]. As an example, Figure 4 presents the purities of the captured CO_2 from three different combustion methods. Table 1 shows the CO_2 impurity limits in several CCS projects together with SST's design limits. It lists the reference values provided from the projects Northern Lights [13], Dynamis, Schwarze Pumpe Oxyfeul pilot [17], and a cement plant from ICF International [15]. It is common to have a purity level above 95%; in Northern Lights, Schwarze Pumpe, and ICF, the CO_2 concentration is higher than 99.9%. However, these high purity levels may not be necessary for most transportation, storage, or EOR purposes. The purity levels can be optimised to reduce the energy consumption and purification cost [17]. Therefore, it is attractive to identify an optimal purity level required for SST. On the other hand, a high level of impurity in liquid CO_2 can lead to higher pressure requirements applied on the cargo tanks to avoid the risk for hydrate formation and corrosion. Besides, impurities also constitute volume and affect the compressibility of CO_2 which reduces cargo tank carrying capacities [7].

2.2.1. *Free water.* The most undesirable impurity in liquid CO_2 is free water (H_2O). Free water causes hydrate formation and can under suitable environments lead to corrosion since it easily reacts with majority of acid gas components. Figure 5 presents the study from Visser et al. [20] which documented the solubility of water in CO_2 in different pressures and temperatures. The solubility of water in CO_2 is low at low pressures and temperatures. This indicates that transporting CO_2 in refrigerated or semi-refrigerated condition would place higher requirements on the purity level, since less H_2O can dissolve in CO_2 and more of free H_2O would appear. In contrast, the SST transports CO_2 liquid in pressurised conditions which have CO_2 solubilities higher than 2000 ppm. In the authors' knowledge, the value of 2000 ppm is higher than the requirements defined in many CCS projects including the ones presented in Table 1. This means no free H_2O would appear if the SST is utilised on these projects.
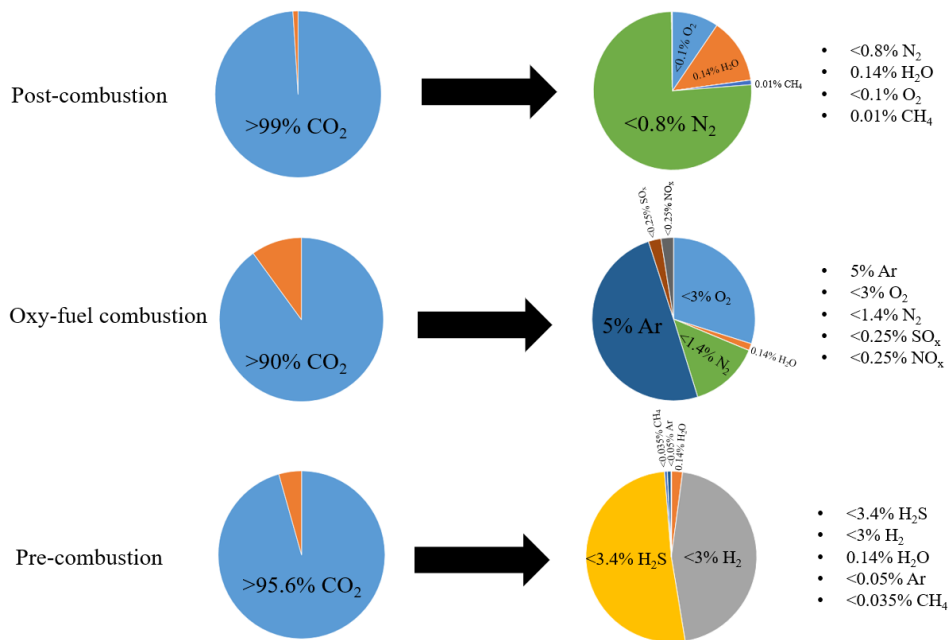
Figure 4. Expected levels of impurities from different CCS methods [4].

Table 1. CO_2 impurity levels in different projects.

| Component	North Lights (Various sources)	Dynamis (Hydrogen production)	Schwarze (PowerICF plant)	(Cement plant)	UiS SST
Carbon dioxide, CO_2	>99.9%	>95.5%	>99.9%	99.8%	>95.5%
Water, H_2O	30 ppm	500 ppm	<5 ppmv	640 ppmv	500 ppm
Sulphur oxides, SO_x	10 ppm	100 ppm	1.3 ppmv	<0.1 ppmv	100 ppm
Nitrogen oxides, NO_x	10 ppm	100 ppm	3-10 ppmv	0.86 ppmv	100 ppm
Hydrogen sulphide, H_2S	9 ppm	200 ppm	-	-	200 ppm
Carbon monoxide, CO	100 ppm	200 ppm	<2 ppmv	1.2 ppmv	200 ppm
Oxygen, O_2	10 ppm	Aquifer <4 vol% EOR 100-1000 ppm	<0.001 vol%	35 ppmv	Aquifer <4 vol% EOR 100-1000 ppm
CH_4	-	Aquifer <4 vol% EOR <2 vol%	-	0.026 ppmv	Aquifer <4 vol% EOR <2 vol%
Amines, RNH_3	10 ppm	non-considerable gases <4 vol%	-	-	non-considerable gases <4 vol%
Ammonia, NH_3	10 ppm		-	-	
Hydrogen, H_2	50 ppm		-	-	
Formaldehyde, HCHO	20 ppm		-	-	
Acetaldehyde, CH_3CHO	20 ppm		-	-	
Dinitrogen & Argon, N_2 & Ar	-		<0.01% vol%	904 ppmv	
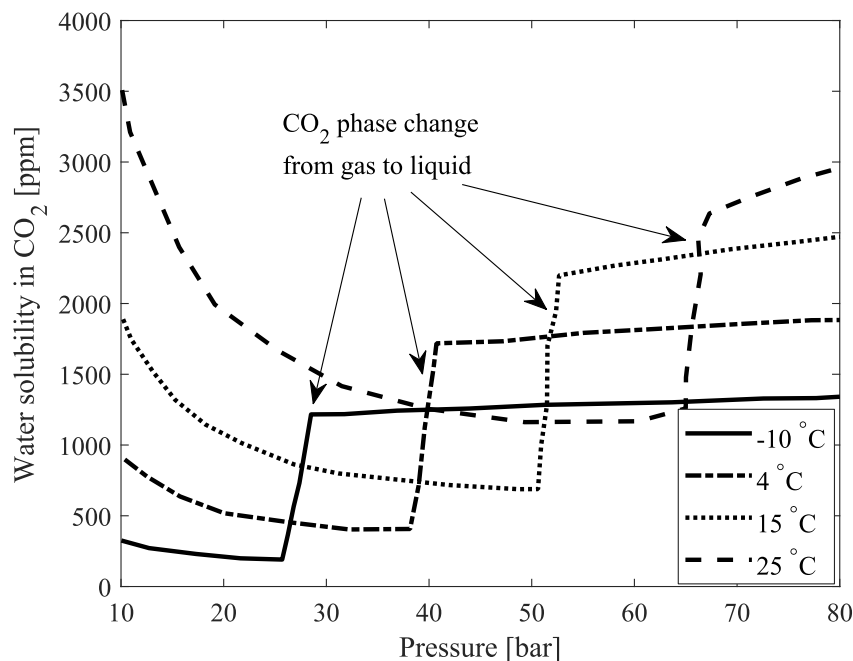
Figure 5. Solubility of H_2O in CO_2.

2.2.2. SO_x and NO_x. Projects like Dynamis placed limits on these gases as they are toxic to humans. It is postulated that no limits on these gases are required for SST as it is an unmanned vessel. However, more detailed investigations in this are required as SO_2 and NO_2 may cause negative effect on water solubility and therefore can increase the risk of hydrate formation. This was shown in a study performed by Ahmad and Gersen [21]. However, this study was performed at pressures of 90 - 120 bar and temperatures of 10 - 45 °C which are outside of SST's operating region.

2.2.3. Other impurities. The *SST* places limits other impurities like CH_4, N_2, and amines to mitigate hydrate formation since these impurities reduce the solubility of H_2O [22].

3. Cargo tank design

3.1. Sizing
Current CO_2 carriers transport liquid CO_2 in the semi-refrigerated state [10][12][13][23][24][25]. This results in lower pressures of about 6 to 22 bar at -50 to -15 °C and allows the use of large cargo tanks of up to volumes of 4000 m^3. For example, Northern Lights project [13] uses a 7500 m^3 gas carrier with two 3750 m^3 type-C storage tanks. This is also similar for LPG carriers that transport semi-frigerated LPG. For example, the typical size range for a type-C LPG tank is between 4000 m^3 to 22,000 m^3 [26]. No VLGCs are yet used for refrigerated CO_2 transportation, but they have been utilised for LNG. LNG carriers carry refrigerated LNG at 1 to 2 bars at -165 °C and utilise cargo tanks of volumes up to 20,000 m^3.

The SST transports liquid CO_2 at environmental temperature which leads to higher pressures of 40 to 60 bars and therefore requires a more demanding burst pressure design. For thin-walled cylinder-shaped pressure vessels, the burst failure is dominated by the yielding of the material. Following Barlow's formula, the internal pressure that a thin-walled cylinder-shaped pressure vessel can withstand is calculated as $p = 2 \cdot SF \cdot \sigma_y t / D_o$, where σ_y is the yield stress, t is the wall thickness, D_o is the external diameter of the cylinder, and SF is the safety factor. Xing et al. [8] used this method to estimate the internal pressure capacity of the SST cargo tanks when stainless steel 304 (yield strength $\sigma_y = 207$ MPa) is applied. A safety factor $SF=0.72$ is used. The results, i.e., internal pressure capacities are presented in Table 2 for different vessel diameters and wall thicknesses. As observed in Table 2, the *W/V* ratios

are the same for all cases. This is because *W/L* and *V/L* are directional proportional to (diameter)^2. This means designing larger cargo tanks does not save structural weight or increase cargo capacity. However, the bending and welding of thicker plates can be more complex. For this reason, the UiS SST uses several smaller tanks instead of a single large tank. Seven 5 m diameter main cargo tanks and six 2.5 m diameter auxiliary cargo tanks are used. The volumes are 1931 m^3 and 483 m^3, respectively which are much smaller than the semi-refrigerated cargo tanks discussed above. However, the cargo weight still constitutes a large portion (53%) of the SST's total weight [6]. For reference, surface tanker ships have about 80% [7].

Table 2. Internal pressure capacities for UiS SST

Diameter (m)	Wall thickness (mm)	Internal pressure capacity (bar)	Weight/length, *W/L* (kg/m)	Cargo volume/ length, *V/L* (m^3/m)	Ratio, *W/V*
0.5	7.5	45	92	0.20	471.02
1	15.1	45	370	0.79	471.02
1.5	22.6	45	832	1.77	471.02
2.5	37.7	45	2312	4.91	471.02
5	75.5	45	9248	49.64	471.02
10	151.0	45	36,993	78.54	471.02
15	226.4	45	83,235	176.71	471.02

3.2. Material selection

The UiS SST transports CO_2 at environmental temperatures which allows the use of highly weldable carbon steels which have poor brittle fracture properties at low temperatures. UiS SST uses SA-738 Grade B which is a high strength carbon steel broadly applied on welded pressure vessels subjected to moderate or low temperatures [6]. In contrast, due to the low service temperatures experienced by LNG and LPG carriers, DNV recommends the use of fine-grained carbon-manganese structural steels and nickel alloy steels [27]. Higher manganese and nickel content allow a lower design temperature. For semi-refrigerated CO_2 tanks, DNV grade VL 4-4 is a suitable candidate. It has a manganese content between 0.7-1.6%. This steel also has a high tensile strength between 490 and 610 MPa. This avoids the heavy structural design with thick plates. However, the lowest design temperature for carbon-manganese steels is -55 °C. This barely satisfies the fully refrigerated condition. When the temperature is below such value, nickel alloy steels are used. High nickel alloy steels are used in the refrigerated transportations as these steels have excellent strength and toughness at low temperature in both base metal and welding joints [28]. One potential candidate for fully refrigerated cargo tanks is VL 2.25Ni (-65 °C design temperature). These materials are more expensive and complex to weld compared to the carbon steel used in UiS SST.

4. SST operation

4.1. Energy consumption

In a typical CO_2 transportation by vessels, the energy consumption can be divided into three categories, (i) cargo processing, (ii) propulsion and (iii) pumping. The energy consumption related to cargo processing includes liquefication and cargo conditioning. The energy required for this is significant. This is because the boil-off gas liquification process requires multi-stage cooling and compression. However, since the UiS SST transport CO_2 in environmental conditions, it does not require any cargo processing. This means a huge amount of energy is saved. For example, Aspelund et. al. [23] conducted concept analysis for transporting CO_2 with a fully refrigerated 20,000 m^3 vessel, the specific energy consumption of ship transportation is 25 kWh/tonne CO_2 for a 1500 km round trip. As comparison,

energy consumption for using UiS SST for the same distance is listed as Table 3. The propulsion energy costs for UiS SST are calculated to be 289 kw at 6 knots speed and account for 40,139 kwh for 1500 km. The pumping energy consumption comes from the cargo and ballast pumps used during the loading and offloading process and is calculated to be 3900 kWh per trip [6]. As observed, the UiS SST transportation energy consumption is nearly 90% lower than the reference surface ship.

Table 3. SST energy consumption and comparison with ships.

Transportation method	SST environmental temperature [6]	Ship with refrigeration at -52 °C [23]
Propulsion	40,139 kWh	
Pumping	3900 kWh	
Other hotel loads	4861 kWh	
Total energy consumption	48,900 kWh	
Specific energy	3.19 kWh/tonne	25 kWh/tonne

4.2. Hydrate formation

Hydrate formation in the cargo tanks should be carefully avoided. Operating the SST inside the hydrate formation zone may cause blockage and sealing issues in some of the critical systems [7], such as piping and seals. Figure 6 presents the hydrate phase equilibrium points of pure CO_2. As presented, hydrate formation is easier formed at very low temperatures of -40 to 0 °C. Therefore, transporting with refrigeration requires CO_2 liquid to be properly dried. On the contrary, when CO_2 is transported at environmental temperature (>8 °C), hydrate formation is unlikely to appear.
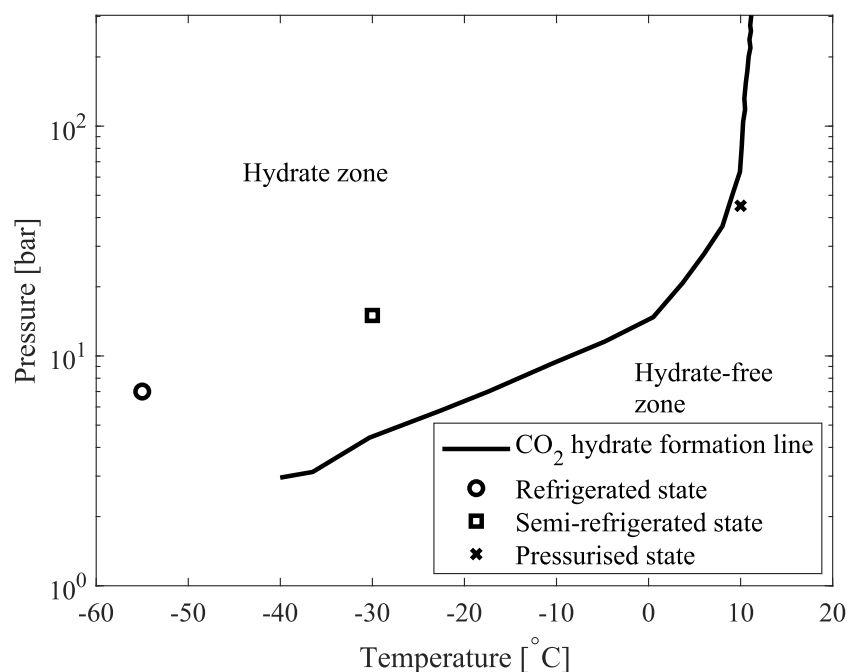

Figure 6 Hydrate formation zone of CO_2 and transportation states [29].

5. Conclusion

CO_2 may be transported by the SST as a saturated liquid under one of the 3 states: Refrigerated state (6 bar, -50 °C), semi-refrigerated state (22 bar, -10 °C), or pressurised state (45 bar, 10 °C). This evaluation discussed CO_2's key properties during transportation and SST operation, such as thermodynamic properties, purity captured from the source facility, and hydrate formation. This paper founded that transporting CO_2 under pressurised state at room temperature has a number of advantages. First, it can reduce energy consumption significantly by avoiding liquefication requirements. Second, using carbon steels can reduce the complexity of cargo tank welding and further reduce the manufacturing cost. Third, the solubility of water in CO_2 increases with temperature. Therefore, the risk of free water and corrosion can be mitigated. Last, the risk of hydrate formation is significantly lower when the CO_2 temperature is above 8 degree and therefore reduce risk of blockage in the piping and pumps. In addition, the authors also identified that there are still knowledge gaps to be bridged by future research such as the actual effects of saturated CO_2 liquid with different purity levels under various pressure and temperature conditions for SST.

References

[1]   UN 2015 *Adoption of the Paris agreement, United Nations Framework Convention on Climate Change* (Paris: 2015).

[2]   Edenhofer O, Madruga R, Sokona Y, et. al. 2012 *Renewable Energy Sources and Climate Change Mitigation—Special Report of the Intergovermental Panel on Climate Change* (New York: Cambridge University Press).

[3]   Tollefson J 2021 COVID curbed carbon emissions in 2020-but not by much, *Nature.* **589**, p 343.

[4]   Onyebuchi V E, Kolios A, Hanak D P, Biliyok C and Manovic V 2018 A systematic review of key challenges of CO_2 transport via pipelines, *Renewable and Sustainable Energy Rev.* **81**, 2563-2583.

[5]   Seigo S, Dohle S and Siegrist M 2014 Public perception of carbon capture and storage (CCS): A review, *Renewable and Sustainable Energy Rev.* **38**, 848-863.

[6]   Ma Y, Xing Y, Ong M C and Hemmingsen T 2021 Baseline design of a subsea shuttle tanker for liquid carbon dioxide transportation, submitted to *Ocean Eng.*

[7]   Xing Y, Ong M C, Hemmingsen T, Ellingsen K E and Reinås L 2021 Design considerations of a subsea shuttle tanker system for liquid carbon dioxide transportation, *J. Offshore Mech. Arct. Eng.* **143**(4), 045001.

[8]   Equinor Energy 2019 *RD662093 Subsea Shuttle System.*

[9]   Ellingsen K E, Ravndal O, Reinas R, Hansen J H, Marra F, Myhre E, Dupuy P M and Sveberg K 2020 *RD677082 Subsea Shuttle System.*

[10]   Kokubun N, Ko K and Ozaki M 2013 Cargo Conditions of CO_2 in Shuttle Transport by Ship, *Energy Procedia.* **37**, 3160–3167.

[11]   Metz B, Davidson O, De Coninck H C, Loos M and Meyer L 2005 *IPCC Special Report on Carbon Dioxide Capture and Storage* (New York: Cambridge University Press).

[12]   Yoo B Y, Choi D K, Kim H J, Moon Y S, Na H S and Lee S G 2013 Development of CO2 terminal and CO2 carrier for future commercialized CCS market, *Int. J. Greenhouse Gas Control.* **12**, 323-332.

[13]   Equinor 2019 *Northern Lights - Receiving and Permanent Storage of CO2.* (Technical report EL001).

[14]   Eiken O, Ringrose, P, Hermanrud C, Nazarian B, Torp T A and Høier L 2011 Lessons learned from 14 years of CCS operations: Sleipner, In Salah and Snøhvit, *Energy Procedia.* **4**, 5541–5548.

[15]   EPA 2021 *Inventory of U.S. Greenhouse Gas Emissions and Sinks.* (Technical report: 430-R-21-005).

[16]   Lee J Y, Keener T C and Yang Y J 2009 Potential Flue Gas Impurities in carbon dioxide streams separated from coal-fired power plants. *J. Air Waste Manage. Assoc.* **59**(6), 725–732.

[17]   Porter R T J, Fairweather M, Pourkashanian M and Woolley R M 2015 The range and level of impurities in CO2 streams from different carbon capture sources, *Int. J. Greenhouse Gas Control.* **36**, 161–174.

[18]   Directorate-General for Climate Action 2012 Guidance document 2, characterisation of the

storage complex, CO2 stream composition, monitoring and corrective measures, *Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide*.

[19] Thomas D C and Benson S M 2005 *Carbon Dioxide Capture for Storage in Deep Geologic Formations-Results from the CO2 Capture Project: Vol 2-Geologic Storage of Carbon Dioxide with Monitoring and Verification.* (Oxford: Elsevier).

[20] De Visser E, Hendriks C, Barrio M, Mølnvik M J, De Koeijer G, Liljemark S and Le Gallo Y 2008 Dynamis CO_2 quality recommendations. *Int. J. Greenhouse Gas Control*. **2**(4), 478–484.

[21] Ahmad M and Gersen S 2014 Water solubility in CO2 mixtures: Experimental and modelling investigation, *Energy Procedia* **63**, 2402-2411.

[22] Xiang Y, Wang Z, Yang X, Li Z and Ni W 2012 The upper limit of moisture content for supercritical CO_2 pipeline transport. *J. Supercrit. Fluids*. **67**, 14-21.

[23] Aspelund A, Mølnvik M J and De Koeijer G 2006 Ship transport of CO2: Technical solutions and analysis of costs, energy utilization, exergy efficiency and CO2 emissions. *Chem. Eng. Res. Des.* **84**(9), 847–855.

[24] Zero Emissions Platform (ZEP) 2011 *The Costs of CO_2 Transport: Post-Demonstration CCS in the EU*. (Technical report).

[25] Brownsort P 2015 *Ship Transport of CO_2 for Enhanced Oil Recovery-Literature Survey*. (Techical Report).

[26] DNV-GL 2016 *Liquefied Gas Carriers with Independent Cylindrical Tanks of Type C.* (Class Guideline: DNVGL-CG-0135).

[27] DNV-GL 2019 *Rules for Classification, Ships, Part 2 Materials and Welding, Chapter 2 Metallic Materials*.

[28] Hoshino M, Saitoh N, Muraoka H and Saeki O 2004 Development of super-9% Ni steel plates with superior low-temperature toughness for LNG storage tanks, *Shinnittetsu Giho*, 17-20.

[29] Sun X, Wang Z, Sun B, and Wang W 2016 Research on hydrate formation rules in the formations for liquid CO2 fracturing, *J. Nat. Gas Sci. Eng.* **33**, 1390–1401.