CO_2 offloading alternatives and guidelines

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Preface

This publication presents some of the findings from the second work package (WP2) of the research project EverLoNG[6], which aims to expedite the adoption of ship-based carbon capture technology on commercial vessels. The EverLoNG project is part of the Accelerating CCS Technologies (ACT) program [1], which seeks to promote the emergence of CCUS through transnational funding, targeted research, and innovation. The EverLoNG project is supported by several organizations, including the Federal Ministry for Economic Affairs and Climate Action (Germany), the Research Council of Norway, the Ministry of Economic Affairs and Climate Policy (Netherlands), the Department for Business, Energy & Industrial Strategy (UK), and the U.S. Department of Energy, all of whom have provided funding for this project.

Disclaimer

Executive summary

Ship-Based Carbon Capture (SBCC) is proposed as an alternative to decarbonize the maritime sector, as compared to zero-emission fuels (ammonia, hydrogen). A ship with on-board CO_2 capture and its ports of call requires more distinct integration than what is common today.

Ports are a vital part of the required stakeholders involved for implementing a successful CO_2 capture onboard LNG fuelled ships worldwide. The EverLoNG concept covers absorption-based CO_2 capture by MEA and further CO_2 purification, liquefaction, and storage onboard. Upon arrival at port the CO_2 must be unloaded to the port which then must have relevant infrastructure to receive, process and transport the CO_2 to the desired end-customer which potentially could be a pipeline, truck transport, ship transport or rail transport to permanent storage or for further utilization purposes, reference to Figure 3.

The size of receival facilities at a port must be designed according to the expected volumes of CO_2 and amine. Currently, this number is highly uncertain because onboard CO_2 capture as an emission reduction technology for the shipping industry is in its early development and to what degree this technology will be rolled out is highly uncertain.

By choosing the amine-based absorption technology for onboard CO_2 capture the degraded amine must be offloaded at port when required. The port facilities must both include amine reclaiming process and be able to source fresh or regenerated amine for loading the ship CO_2 system when at port. The disposal of non-regenerable amine must be facilitated at the port facilities for intermediate storage and further transport to a disposal facility away from the port.

Port selection for CO_2 receival, processing and transport to end customer should be based upon several criteria as geographical location, ship travel routes, existing pipelines in the area which can be used for CO_2 transport and vicinity to permanent storage and/or CO_2 utilization customers.

Ship offloading alternatives are primarily container swap or gas transfer in cryogenic, flexible hoses/loading arms. These methods are described in this report, but it should be mentioned that the recommended methods are case specific and varies with volume, space available and temperature of the CO_2. CO_2 can be stored in gas cylinders both as gas and liquid. Cylinders can be connected in a sheet which is skid framed and able to be transported as a container on a truck or offloaded from a ship to port.

Skid mounted storage tanks can be placed onboard in a let-down area and manually hooked up to the CO_2 feeding line from liquefaction plant. When the tank is full, the CO_2 will be directed to a similar tank which is connected in parallel or offloaded at port. Both container swap with either containerized gas sheets or skid framed storage tanks are feasible. The CO_2 may also be pumped from the permanent onboard storage tanks by pumps to the port receiving facilities.

Currently, there are no guidelines on the logistics of CO_2 and solvent receival from the ship to the port and the loading of reclaimed or fresh solvent from the port to the ship. These challenges must be solved before a larger port network of CO_2 receival- and solvent reclaiming facilities can be organized.

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Introduction

CO_2 emissions from maritime transport represent around 3 % of total anthropogenic CO_2 emissions and the numbers are growing continuously[1][2]. It is assumed to increase 50 – 250 % during next 30 years with the industrial growth while the climate target (1.5 °C - 2 °C, according to the Paris Agreement) requires 50 – 85 % reductions across all economic sectors. The maritime sector has pledged to reach net zero emissions by 2050 [16]. Ship-Based Carbon Capture (SBCC) may be a low-cost alternative to decarbonize the maritime sector, as compared to zero-emission fuels (ammonia, hydrogen). The objective of the ACT ''EverLoNG'' project is to accelerate the implementation of the SBCC technology. A graphical representation of the EverLoNG project and its' scope is shown in Figure 1.

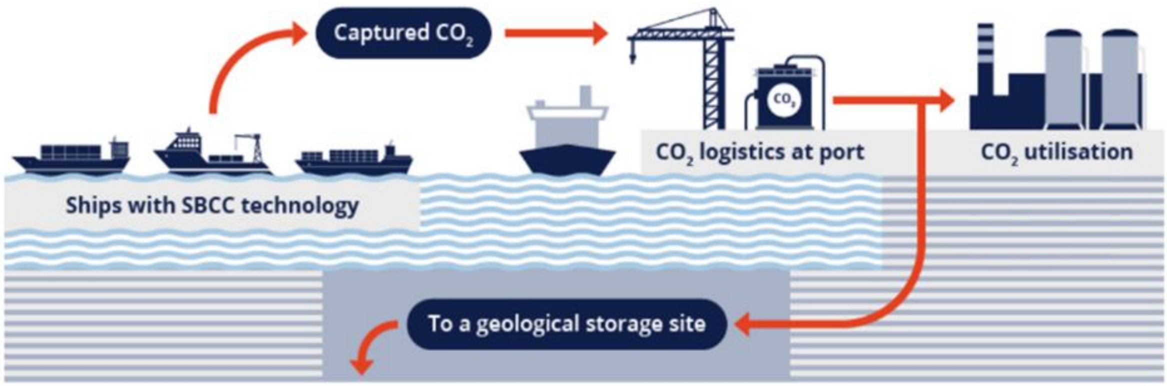

Figure 1: Graphical representation of the EverLoNG project and scope[6]

This report encompasses the CO_2 offloading alternatives and proposes a selection guideline.

This report does not cover the actual implementation of onboard CO_2 capture and handling of CO_2, the reader is referred to other EverLoNG project reports on details of the onboard implementation. This report covers the potential offloading alternatives at port that could be relevant for CO_2 captured onboard different types of ship. With that being said, the state of the CO_2 stored onboard the ship might have implications for type of offloading methods that can be considered, therefore a general discussion regarding the state of CO_2 is included.

State of CO_2

The CO_2 volumes which are captured from a vessel's exhaust gas will likely need to undergo some kind of handling before it is intermediately stored onboard, as it is unlikely that the CO_2 is stored in gaseous form at low pressure (using an MEA capture system, CO_2 is produced at ca. 2 bar and 40°C). The CO_2 is therefore expected to be compressed and maybe even undergo a liquefaction process. The CO_2 storage conditions onboard the ships directly impact the required storage volume of CO_2 as density vary with storage pressure, further it could also have implications for the offloading method at port. Storing and offloading CO_2 as a liquid is a proven technology today on dedicated CO_2 cargo ships where the purpose is to transport CO_2 from one location to another. In the case of SBCC, the conditions chosen for the intermediate storage might not be straight forward, as any conditioning requires additional equipment and energy consumption, thus impacting the cost of SBCC. Other factors that also might play a role in selecting the onboard storage conditions is HSE (health, safety, and environment) considerations, the CO_2 volumes generated during the voyage (storage volume needed), and space limitations.

Traditionally, CO_2 storage conditions have been referred to as low-, medium- and high pressure. Storing at high pressure, above 50 barg, is not considered as a viable short-term option compared to the medium- and low pressure (6 -15 barg) for purpose-built CO_2 carriers, however in the case of SBCC it could be reconsidered. The onboard storage pressure and temperature of the CO_2 carriers planed for operation in the Northern Lights project [4] is 15 barg and -26°C. The density of CO_2 increases when approaching the triple point, see Figure 2, and consequently, a pressure of 6 barg is interesting as the required CO_2 storage volume decreases with lowering the pressure. However, as there is not yet CO_2 carriers operating at 6 barg, both process control- and material aspects must be further investigated as there is a risk of dry ice formation and low temperature material issues when approaching the triple point for CO_2. The storage conditions, 6, 15, 50 barg implication on the storage volume needed is illustrated in Table 1. The temperature is the corresponding temperature of the CO_2 at the given pressure. The table also shows the density of CO_2 at atmospheric conditions for reference.

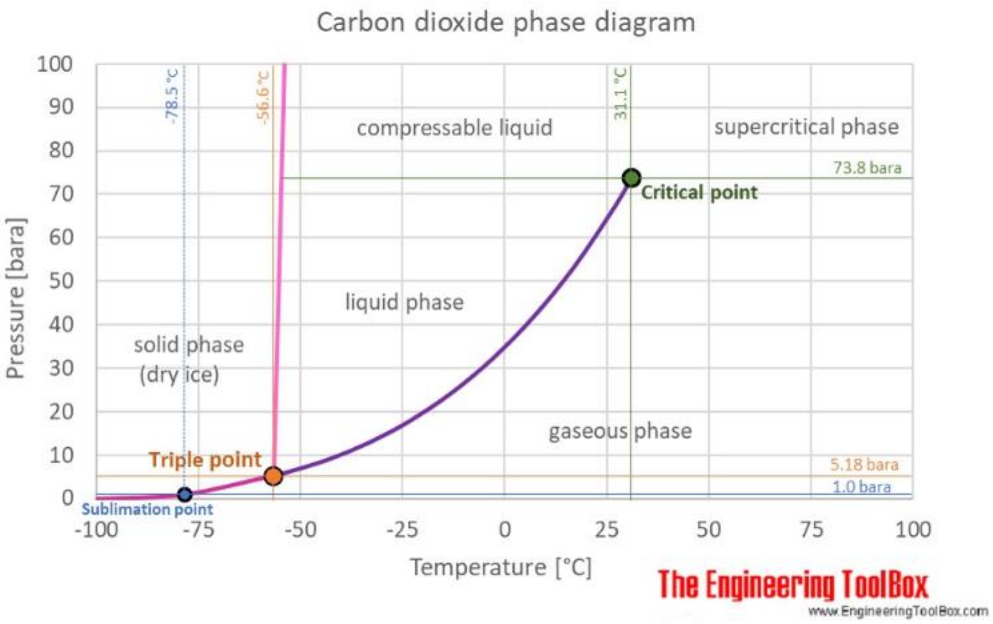

Figure 2: CO_2 phase diagram [5] (©The Engineering Toolbox

Table 1: The effect of the state of CO_2 on the onboard storage density [15]

CO_2 pressure, barg	CO_2 temperature, °C	CO_2 density, kg/m^3
1	15	160
6	-49	1150
15	-26	1058
50	14	155

There have been published several articles about the preferred CO_2 storage pressure and temperature during ship transport. However, the volumes considered in these studies have been larger[7], [8], [9] compared to the volumes applicable for SBCC.

When determining the pressure of CO_2 on board, several important factors need to be considered. One of these considerations is the risk of dry ice formation if the pressure drops below the triple point. To prevent this, it is crucial to maintain the pressure and temperature within the designated range, which encompasses the design pressure and the triple point. The CO2LOS III (2021-2022) project conducted a study [17] that covered both low (6 barg) and medium pressure (10 barg). The findings indicate that the risk of reaching the triple point is higher at low pressure. However, this risk can potentially be managed by implementing measures such as shutoff valves. Additionally, low-pressure conditions are associated with lower temperatures, which may increase the risk of freezing in the surroundings. Even with low water content, the risk of hydrate formation is also higher at low pressure. In the event of an unintended release of liquid CO_2 into the atmosphere, the consequences are similar regardless of the pressure conditions.

Regarding liquefaction alone, the [17] paper gives that medium pressure option is less energy-intensive and does not pose any anticipated material challenges. However, the cost of intermediate storage is higher for medium pressure compared to low pressure due to the requirement for increased wall thickness.

Port operation and integration

A ship with on-board CO_2 capture and its ports of call requires more distinct integration than what is common today. The current infrastructure includes:

- Cargo handling - often the main purpose of calling the port
- Other services like:
    - Water and electricity supply
    - Waste removal (residues, oily mixtures, garbage, and sewage)
    - Bunkering
    - Service

When a ship equipped with SBCC completes a journey and reaches a port, it needs to off-load the stored CO_2 (besides the normal operations of cargo off-loading, bunkering, etc.). This means that the port needs a CO_2 off-loading 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.

In case of onboard CO_2 capture with an amine-based absorbent, it is expected that both the captured CO_2 and amine for reclaiming need to be received and handled at the port of call.

Further the CO_2 which is being offloaded from ships in port may have different CO_2 quality depending on several factors such as engine and fuel type, onboard CO_2 capture and conditioning technology and performance, and storage and shore transfer conditions. The CO_2 processing facility located at the port side should be able to handle CO_2 volumes with a certain quality variation

Equipment on board the ship for handling captured CO_2

Several equipment is needed onboard the ship in addition to the capture facility. The CO_2 needs to be liquefied to be transported further, and if impurities should be removed, that will be done in cooperation with the liquefaction. The volume of CO_2 decreases a lot when pressurized, so for the storage and transport part it is beneficial to increase pressure at the ship. Below the liquefaction facilities and onboard storage are presented.

Liquefaction

There are two main methods for liquefying CO_2:

1. Internal cooling loop – here CO_2 is compressed to 70 barg and decompressed to transport pressure

2. External cooling loop – the CO_2 is compressed to transport pressure and cooled with an external cooling loop, e.g. by using NH_3 as refrigerant. The cold NH_3 is achieved through compression and decompression in a conventional refrigeration loop.

Both options require compressors and cooling and leads up to store the CO_2 in pressurized tanks.

To maintain pressure in the ship's tanks, they are not completely emptied during discharge. The remaining volume of CO_2 in the tanks, known as the "heel," consists mostly of gaseous CO_2. As the ship's tanks are filled with liquid during loading, this gas is compressed, increasing the pressure in the tanks. To prevent such pressure increase, the gas is sent through a gas return line to the liquefaction during loading. The heel volume is higher when the pressure is 15 barg compared to 6 barg.

Another aspect of the liquefaction process is the quality requirements that the CO_2 stream must meet. One of the important impurities for intermediate storage is water consumption. The liquefaction plant will include a drying section to be sure that no free water will be entering the storage tanks onboard.

From a transportation pressure perspective, it is not expected that impurities will significantly impact the choice of transport pressure or method, but the liquefaction and pretreatment processes will have influence on the vessels and equipment needed further in the transport chain. If the ship does not have a liquefaction process onboard, the storage of CO_2 requires much more space, and the offloading part will be affected. In our further analysis of different offloading alternatives, a liquefaction facility onboard the ship is assumed.

Intermediate storage onboard the ship

The intermediate storage of the captured CO_2 onboard the ship may involve large spherical, horizontal, or vertical insulated vessels or containers. They should be organised to utilize the available area for CO_2 storage at the ship.

For container ships, it might be best to store the captured CO_2 in container sized vessels, to make it feasible to offload the CO_2 in the container and then the container is replaced by an empty container. Then the offloading process goes rather fast and does not require extra equipment like loading arms/ hoses in addition to the main cargo handling. After the container is offloaded, the CO_2 can be transported in the same container to further handling either by trucks, railways lorries or other ships.

For other ships that do not handle their cargo in containers, other storage vessels are more convenient, as the container alternative requires most likely a very large number of containers.

Ship Cargo offloading alternatives.

When it comes to ship offloading, there are several alternatives available depending on the specific needs and circumstances. Here are a few common methods:

Crane Offloading: This is a traditional method where cranes are used to lift cargo from the ship and transfer it to the port. Cranes can be operated from the port's infrastructure or mounted on specialized vessels known as floating cranes.

Conveyor Systems: Conveyor systems are often employed in ports to transfer bulk cargo such as grain, coal, or ore. These systems use belts or other mechanisms to move the cargo from the ship's hold to the storage facility on the shore.

Forklifts and Reach Stackers: In cases where the cargo is containerized, forklifts and reach stackers are commonly used. They can efficiently handle shipping containers, moving them from the ship to the port or vice versa.

Pneumatic Systems: For certain types of dry bulk cargo, such as cement or grain, pneumatic systems can be employed. These systems use air pressure to suck the cargo from the ship's hold through pipes and transfer it to the storage facility.

Ro-Ro (Roll-on/Roll-off): Ro-Ro vessels are designed to transport vehicles, machinery, and other wheeled cargo. The ship has ramps that allow the cargo to be rolled on and off the vessel, eliminating the need for cranes or other lifting equipment.

Self-Unloading Ships: Some specialized ships, particularly in the bulk cargo industry, are equipped with conveyor systems or unloaders that can discharge the cargo directly to the port. These self-unloading ships are commonly used for transporting commodities like coal, iron ore, or grain.

It's worth noting that the choice of ship offloading method depends on factors such as the type of cargo, the port infrastructure, the available equipment, cost considerations, and efficiency requirements. Different ports and industries may prefer specific alternatives based on their unique circumstances.

CO_2 offloading

It can be challenging for the receiving ports to have infrastructure that can gather CO_2 from different ship types and sizes and with different cargo handling requirements. If the CO_2 is unloaded as a container or a transportable tank, it would be easier to offload and connect the container/tank with a distribution infrastructure for CO_2. If container swapping is used, the CO_2 can be offloaded with the same equipment as regular container transfer and will not affect the time for offloading or require large extra infrastructure. If CO_2 is pumped off the ship, different configurations are possible. The CO_2

can be offloaded by flexible hoses, or with fixed loading arms. These solutions are well known technologies and are in operation today for liquefied gases, including CO_2 [7].

Use of flexible hoses is the conventional method of conveying liquids between a terminal and a ship. To connect the hoses from the port to the vessel, a system to carry the hoses to the vessel is needed. A crane or derrick is normally used. The connection hoses-manifold requires manpower. A loading arm is a mechanical arm of articulated steel pieces that connects to the ship and loads/unloads it, while following the movements of the ship due to changing draft, tide, and wind. The cost for such arrangement might be higher and may not be as flexible to different ship sizes as the hoses might be.

Either way the CO_2 is unloaded, there is a need of infrastructure at the port side to receive the container or to receive the liquid CO_2 from the pipes or hoses. If the CO_2 is stored in tanks that are stationary on the ship, there will be a small volume of CO_2 left in the tank (called heel) to keep the low temperature after unloading.

Instead of offloading the captured CO_2 directly to a port, another option is to offload the CO_2 to a dedicated ship that collects CO_2 and amine from the ship outside the quay area. Then each port does not have to have equipment for receiving CO_2 and amine, and the dedicated CO_2 ship may collect CO_2 / amine from multiple ships before transporting the ship's cargo to a suitable port for offloading.

One of the main challenges of the port infrastructure is to be able to receive CO_2 from different kind of ships and not increasing the time the ship needed to have at the port. Today, several ports use bunkering ships that will come to the ship when loading or unloading cargo.

When the CO_2 has been offloaded from the ship, it must be stored in an intermediate storage tank and purification and conditioning activities may be needed to meet the end-user specifications. The CO_2 will be transferred to another intermediate storage tank downstream the purification facility. The risk of handling CO_2 must be addressed, and integrity of all processing equipment must comply with regulations fit for purpose [10].

Solvent loading and offloading

The solvent circulating in the onboard CO_2 capture plant will degrade over time which causes the efficiency of the solvent to be reduced. When the solvent has been degraded below a certain criterion the solvent must be regenerated. Solvent regeneration is normally achieved by a reclaiming process (e.g thermal reclaiming, ion exchange). The reclaiming processes need additional energy (heat or electricity) and chemicals (normally NaOH), and are a specialized operation, normally carried out by dedicated companies. Currently, it is suggested that the total solvent volume is unloaded to the port where the regeneration will take place. After the reclaiming process the regenerated solvent will be transported to an intermediate reclaimed solvent storage for subsequent loading onto vessels. Solvent which is not possible to regenerate should be considered as waste and removed from the port area to a proper disposal facility. Further, it is expected that fresh solvent supply is in place to ensure that the needed volumes are available for the vessels. At what interval the solvent needs to be sent for regeneration will vary from case to case. The detailed layout of the port side amine reclaiming unit will be provided at a later stage in the EverLoNG project.

The amine solvent can be loaded to the ships by liquid pumping in hoses or fixed piping solution. Another option is to provide amine in steel tanks which are lifted onboard the ships and further connected to the liquid transport system to the CO_2 capture facility.

The CO_2 conditioning process onboard the ship has a vital impact on several aspects of the CO_2 handling logistics chain. The required onboard storage volume of the captured CO_2 depends on the liquefaction process and consequently the CO_2 receival facilities at each port. A standardization for onboard storage conditions, ready for transfer to port should be implemented both with regards to storage pressure and the associated equilibrium temperature and not to forget the CO_2 purity. Material selection for storage tanks and levels of process controls will depend upon selected storage pressure. A condition monitoring system for CO_2 could be implemented at the port identifying any required purification of CO_2. Some of the offloaded CO_2 may not require further purification before transported to an end user.

Potentially, mixing of "dirty" CO_2 offloaded from the ship in intermediate storage tanks may impose challenges not foreseen yet. Different ships may have different fuel mix in the future together with individual CO_2 capture and liquefaction systems may result in a variety of CO_2 qualities received at the ports. Any undesired effects of CO_2 blending should be considered.

The degraded amine solution offloaded from ships at port may also have different quality and a proper condition monitoring system may divide the offloaded amine into two or more different treatment paths depending on the quality. Blending of different amine solutions and storage of such may also result in challenges with impurities and incompatible substances found in degraded amine.

In the future, there might be several solvents available in the market, and that poses a challenge on how the ports should be prepared to receive different kinds of solvents and be able to replace the solvents to the ship. This challenge has not been addressed in this report.

The solvent handling infrastructure will be investigated in report D.2.1.3.

Ports of the future

It is not foreseen to equip every port with CO_2 and amine receiving and processing facilities. There should be a selection of port locations relative to shipping routes and connection to CO_2 infrastructure. Permanent CO_2 storage in the port vicinity is preferrable as there are several CO_2 permanent storage locations planned worldwide. Use of existing pipelines may result in a more viable CO_2 distribution solution. There are several routes for utilizing of captured CO_2. However, there are challenges associated with bringing CO_2 into the industrial feedstock as: high energy demand, lack of established market, technology challenges and lack of a regulatory framework [11]. Potential CO_2 utilization customers nearby the port location is advantageous as some of the offloaded and processed CO_2 can be utilized in various industrial processes for making commercial products.

A drawing of the port's facilities that is needed for CO_2 and solvent handling is presented in Figure 3.

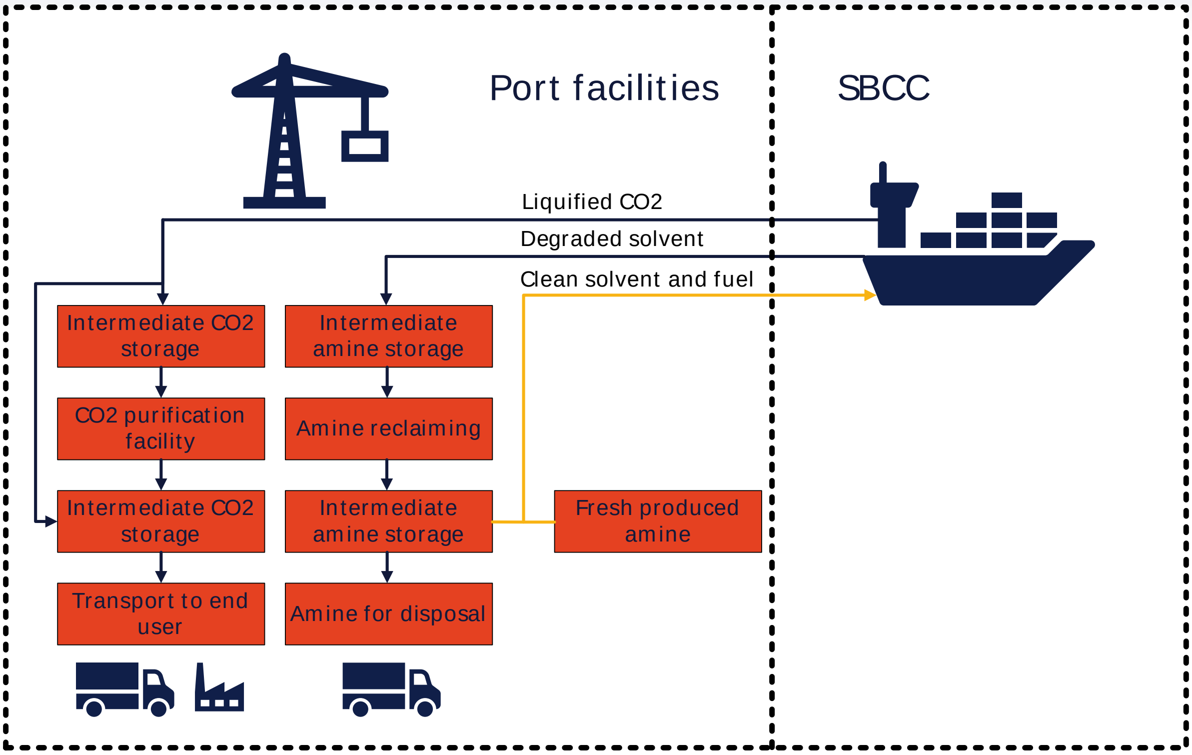

Figure 3: Proposed port infrastructure [6]

Port selection guideline

By introducing a CO_2 capture system onboard ship with use of amine solvent technology, certain port facilities and logistics must be implemented. There are several factors that should be in place in and around a port for establishing the required facilities for receiving, processing, storing and transport of CO_2 and solvent. One of the obvious facilities is a plan for further transport of the CO_2.

There are several permanent injection and storage locations operating today with many years of experience [12]. However, these are not connected to the upstream chain of collecting CO_2 from various sources, process the CO_2, store, and transport CO_2 to the injection well location. In that respect, the Northern Lights project [13] paves the land for the future CCS industry as it covers the collection of CO_2 from emission sources and furthermore processing, storage, transport and injection of CO_2 in a permanent CO_2 storage reservoir.

There are networks of pipelines for distribution of hydrocarbons available [14]. These may serve as CO_2 transport pipelines instead. However, CO_2 is often transported at a considerable higher pressure compared to natural gas, therefore the integrity of existing pipelines must be addressed before repurposing could be considered.

The criteria for selection of a port to handle CO_2 from SBCC are currently unclear as there are no ports available with that equipment yet. We suggest that the main criterium for selection is to have a route or way to transport the CO_2 further into a logistic chain for CO_2 storage or use. The port should have available areas for all the extra infrastructure needed, either on land or on floating devices. In addition, the long-term plans for the ports and predictable routes of ships with CO_2 capture onboard is vital, as the investments are high.

As discussed, the preferable offloading technology is chosen by which type of ships that arrives to the port, and the volumes and transport solution from the port to storage or use. It is not possible to recommend one solution that fits all ports, as this is very site specific.

Recommendations and conclusion

Ports are a vital part of the required stakeholders involved for implementing a successful CO_2 capture onboard LNG fuelled ships worldwide. The EverLoNG concept covers absorption-based CO_2 capture by MEA and further purification, liquefaction, and storage onboard. Upon arrival at port the CO_2 must be unloaded to the port which then must have relevant infrastructure to receive, process and transport the CO_2 to the desired end customer which potentially could be a pipeline, truck transport, ship transport or rail transport to permanent storage or for further utilization purposes, reference to Figure 3.

The size of receival facilities at the port must be designed according to the expected ship sizes and number of arrivals per year. By choosing the amine-based absorption technology for onboard CO_2 capture, the degraded amine must be offloaded at port when required. The port facilities must both include amine reclaiming process and be able to source fresh and regenerated amine for loading the ship CO_2 system when at port. The disposal of non-regenerable amine must be facilitated at the port facilities for intermediate storage and further transport to a disposal facility away from the port.

Port selection for CO_2 receival, processing and transport to end customer should be based upon several criteria as geographical location, ship travel routes, existing pipelines in the area which can be used for CO_2 transport and vicinity to permanent storage and/or CO_2 utilization customers. Relevant regulative bodies should be involved in approval and standardization of both hardware and operational procedures for future CO_2 – storing, offloading and port processing.

Liquid CO_2 storage can be facilitated with permanent tank installations where CO_2 will be pumped to and from the storage tank(s) through process piping and/or flexible hoses. This concept is operational today both for CO_2 - and LNG transport. The CO_2 may be pumped directly to shore or via a bunkering ship that serves as a transit to the storage tanks in the port.

Skid mounted storage tanks can be placed onboard in a let-down area and manually hooked up to the CO_2 feeding line from liquefaction plant. When the tank is full, the CO_2 will be directed to a similar tank which is connected in parallel or offloaded at port or sea. CO_2 can alternatively be stored in cylinder vessels. Cylinder vessels can be connected in a sheet which again is skid framed and able to be transported as a container on a truck or offloaded from a ship to port.

Several different offloading alternatives has been introduced in this report. It shows that the ports have options on how the CO_2 could be transported, depending on the ship type, volumes of CO_2, size, and number of ships with SBCC annually. The infrastructure for further transport of CO_2 needs to be identified and ready before the port can receive CO_2 from the ships.

Acknowledgements

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