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Role of CO_2 Carriers in Carbon Capture Utilization and Sequestration as A Part of Global Decarbonization Strategy

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Abstract: With the world gearing up to cut down carbon emissions to combat the greenhouse effect, a novel method has been introduced to collect and store co_2 after pressurizing and liquifying it. carbon sequestered will either be put to use in industries or will be buried deep underground. this concept is highly revered due to its pragmatism and simplicity and is broadly termed as "carbon capture, utilization and sequestration/ storage (ccus)". though it is clear how to capture, utilize and store liquified co_2 (lco_2), the modus operandi of transportation remains abstruse. though the technical feasibility of this method is still under debate, many shipping companies have set forth to construct liquified co_2 (lco_2) tankers. ongoing studies are focused on finding the best methods to transport co_2 by retrofitting lng ships to better equip them for storing and transporting co_2. this paper takes a systematic approach to review the development of lco_2 tankers. it discusses the trail of development, major challenges and limitations, technological gaps, and future prospects. it also looks over the economic and ecological aspects of such an endeavor. the paper has also taken care not to be oblivious to other options at hand, including pipelines and railways. it briefly explains the above methods and further discusses their limitations.

Keywords: Carbon Capture Utilization and Sequestration (CCUS), Carbon Dioxide, Offloading, CO_2 Liquefaction, Internal refrigeration, IMO

I. INTRODUCTION

The phenomenon of global warming was identified by the Swedish scientist Svante Arrhenius as early as 1896. In a follow-up study, Guy Callender identified the role of carbon dioxide (CO_2) in the game in 1938. But it took the general public (and the scientific community in particular) six decades to identify the threat it posed to nature and human life. Since then, global warming always managed to stay on top of the priority list and continues to be at the forefront of a greater part of the research. Yet it doesn't cede the rise of global $_{CO2}$ concentration, which surged at an alarming rate of 2ppm yearly since 1980 [1]. Though the number may seem insignificant, its cumulative consequences lead to a yearly increase in global temperature of 0.18°C.

As per International Maritime Organization (IMO), shipping releases over 940 million tonnes of CO_2 annually, which is roughly 2.5% of global Green House Gas (GHG) emissions. With pressure mounting up for reducing emissions, the shipping industry is also involved in the crossfire. Understanding the seriousness of the issue, IMO has responsibly stepped up to shoulder its share of responsibility and proposed its aim to cut down the emissions by 2050 to half of that in 2008 [2]. It has devised a multi-faceted approach to tackle the problem. Their solutions range from practical steps (deterring ships to carry empty containers) to conventional steps (reducing the speed of ships, using renewable energy sources) to revolutionary ideas (carbon capturing utilization and sequestration, electricity powered ships) that seem far-fetched with the current technological developments.

Carbon capture, utilization, and sequestration (CCUS) is a self-explanatory term. It refers to this simple idea, where atmospheric CO_2 is captured, liquefied, and transported to various industries which make use of it. The liquefied CO_2 can also be stored in offshore sites such as oil rigs, where it can be put to use for productive works, like enhanced oil recovery (EOR), or can be stored in depleted wells, coal bed seems, and saline aquifers as a measure to reduce the CO_2 content in the atmosphere. Amidst all the latest R&D in reducing carbon emissions, CCUS stands out as it is not substantiating emission reduction but emission control. Albeit this, it is the only currently available method to remove bulk amounts of CO_2 from the atmosphere as of now.

CO_2 transportation is predominant, especially in the food and beverages industry and ships are developed solely for this purpose (shuttle tankers). But the full-fledged use of ships for the purpose is still debated. Due to the longevity and availability of technology, pipelines remain the first choice for many. In 2005, Intergovernmental Panel on Climate Change (IPCC) introduced a report on the cost-effectiveness of CO_2.

It introduced a comparison between pipelines, which showed that it was cheaper to use ships for transfer for distances more than 1000km. It is not always necessary to have ships built specifically for CO_2 transit. LNG/LPG tankers can be retrofitted to facilitate this.

A rough analysis of the costs of different processes in CCUS chain is given below (Fig.1) (for transporting 25kT).

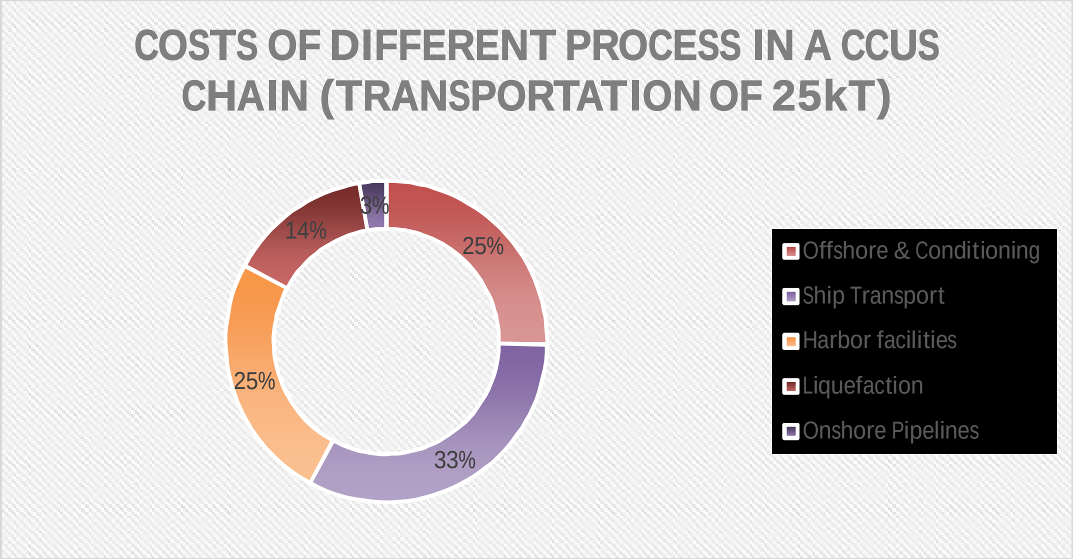


Figure1. Costs of different process in a CCUS chain (considering a transportation of 25kT)

This paper is a literature review on the development of CCUS technology. It also discusses the prospects and challenges from this perspective.

II. PROPERTIES OF CO_2 TO BE CONSIDERED FOR SHIPPING

For a safe and economic transit of CO_2, a thorough understanding of its thermal, chemical, and physical properties

A. Density

From the voyage point of view, the maximum density of CO_2 (at the triple point) provides the best stability and effectively utilizes the cargo capacity. It is noted that at subzero temperatures, a change in pressure (up to 5 MPa) has little effect on the density of CO_2. The presence of non-condensable impurities, however, reduces the density of CO_2 (this owes to the fact that most such impurities have higher molar volume than CO_2). Barring the fact that it takes up valuable storage space, this also increases injection pressure.

B. Solubility In Water

The presence of water can cause hydrate formation and corrosion in the equipment used. It is noted that solubility increases with higher temperature and pressure. Though the temperature of liquid CO_2 is well below to support solvation, the pressure aids it to mix with CO_2. The melding increases if CO_2 is in a liquid state. The presence of impurities such as CH4, N2, or O2 is proven to reduce the dissolution of water.

Even more, the presence of trace impurities like SOx and NOx (<500ppm), has shown a significant reduction in the solvation. These conclusions are drawn as parts of general studies and do not specifically imply the application of CCUS. The lack of development of a proper thermodynamical model to identify these characteristics in accordance with the conditions for CCUS hinders further studies in this matter.

C. Maintaining Phase Equilibria

The CO_2 stored after liquefaction is an equilibrium - a constant phase change between gaseous and liquid CO_2 occurs. The equilibrium is dynamic, as the rate of evolution of gaseous CO_2 is equal to condensation to liquid CO_2. The storage tanks are designed in accordance with this equilibrium condition and it is necessary to maintain it. A deviation from this equilibrium can cause operational difficulties, and the worst-case scenario - leads to explosions and accidents.

The presence of small quantities of impurities can alter the pressure-temperature equilibria. The type of impurity also dictates the kind of change to be expected from the system. For instance, the presence of H2 and N2 (for even a minuscule amount of 0.5mol%) can cause the vapor pressure to surge by 30% while the presence of SO2 can cause a fall. The presence of N2 and O2 can increase the saturation pressure of liquid CO_2.

D. Composition Of The Atmospheric Co_2 Stream

The presence of impurities, as discussed earlier, has a great influence throughout the CCUS chain. Though the technology for capturing pure CO_2 is already available, the selection of these is highly regulated by economic and safety considerations. The presence of impurities like SO2 and H2S can increase the risk associated with transport as they may endanger human life - and so will be subjected to stronger restrictions. Chances of reaction between impurities and tank materials also have to be considered. Projects like ENCAP, DYNAMIS, IMPACT, CO_2QUEST, and CO_2Mix have helped to achieve a much-needed conclusion on the matter of CO_2 quality. The number of impurities that can be tolerated also depends on the final purpose of CO_2.

E. Shipping Considerations

Literature suggests shipping CO_2 at 0.7MPa and 223K. This conclusion is reached not based on a comprehensive techno-economic analysis, but it helps CO_2 to be transported in a high-density state and the operating conditions are kept near the triple point. Operating near the triple point demands additional expenditure to attenuate the chances of freezing.

III. OVERVIEW OF THE DEVELOPMENT OF CCUS FACILITIES

To implement CCUS on a full scale, several supplements have to be made in the infrastructure of ports to facilitate temporary storage. Similarly, ships have to be either retrofitted or supplanted to ensure a smooth transit between source and sink occurs. The technological gap happens to sodden this progress to a great extent. Though numerous studies were conducted on cutting down emissions in ships, not much of an improvement is made in this aspect. Even the proponents of CCUS remain sceptical whether the competency of ships can match that of the pipelines. This reluctance can be explained due to the fact that components like storage facilities and liquefaction plants form a whopping 80% of the total cost incurred [3]. As per the Shipping UK Cost Estimation study (2018), pipelines suit to transport larger volumes to shorter distances, while shipping is suited to transport smaller volumes to longer distances [4]. Another reason is the perception of CO_2 as a waste product, and not as a commodity of commercial value. Exploring the commercial prospects of CO_2 will change this notion. Yet another reason, which must be quite obvious by now, is the underdeveloped technology [5].

CO_2 transport using ships is nothing new - it had been used for the past 30 years on a smaller scale, in the food and brewery industry. This was done under 1.4-1.7 MPa and 238-243 K. Challenge awaits in the form of legal frameworks (both national and international), inadequate infrastructure, and immature technology when we try to reproduce the same on a larger scale. For instance, the European Union Emissions Trading System (EU ETS) proposes CO_2 shipping as an activity contributing to GHG emissions - thus leashing its leap by cutting the financial incentives it ought to receive [6]. The London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter or the London protocol, which also aims to prevent the "export of wastes and other matter for the purpose of ocean dumping" attacks the modus operandi and puts it under their crossfire [7].

The first ever ship to be built for the purpose of CO_2 transport is "Corral Carbonic", with a capacity of 600t in 1999. Around the same time, Mitsubishi Heavy Industries started its work in this field. Currently, Yara Gerda had undertaken and successfully completed the project to build four CO_2 carriers - through which they aim to dispose of 400,000 tonnes of $_{CO2}$ annually. A CCUS capturing project in Dongguan Taiyangzhou IGCC, switched from pipelines to ships in 2003 - making it a milestone in the green trends of the shipping industry advocated worldwide by corresponding organizations. Another breakthrough comes as a part of two projects - named Korea CCUS-1 and Korea CCUS-2, constructed under the conglomerates of two Australian companies Santos and CO_2CRC, and South Korean organizations SKE&S, Korea Trade Insurance Corporation and Korea-CCUS Association (K-CCUS) have selected shipping as their means to transfer.

Liquefaction of CO_2 is necessary for the transit of ships. Along with technologies to capture CO_2 from the atmosphere, CO_2 liquefaction plants are also constructed. Depending on the refrigerant and technologies available, this can be achieved by either an open or closed refrigeration system. In a closed refrigeration system (also called an external refrigeration system), CO_2 is compressed and then cooled with the help of external refrigerants (like R134a, and ammonia).

In an open refrigeration system (also called an internal refrigeration system), CO_2 is compressed beyond the required pressure and is then allowed to expand in a single stage or multiple stages (Fig. 2).

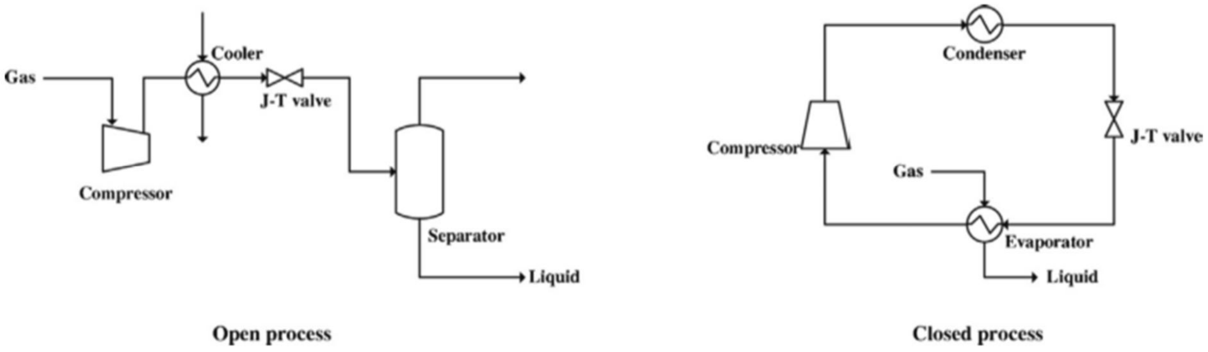


Figure 2. Open process and closed process (Source: A review of large-scale CO2 shipping and marine emissions management for carbon capture, utilisation and storage.)

The science of liquefaction of gases, due to its significance in many fields (including life-saving applications like oxygen cylinders), is rightly studied. To understand the properties of the gas and to develop optimal conditions for its transport via sea, studies on the liquefaction of CO_2 are scrutinized by various researchers. Studies by Nam et.al. [8] show that energy-efficient liquefaction occurs at 6 MPa and 295 K (This study is exclusively for ships. Conditions alter when the pipeline is considered.). Baroudi et. al. devised that 4.5 MPa and 283 K are the most cost-effective parameters (They justified this by stating that 5.5 MPa to 6.5 MPa requires higher capital) [9]. Yet another study by Seo et. al. suggests that 6.5 MPa and 298 K provide the optimum conditions in terms of energy intensity. Closed refrigeration systems are particularly advantageous when looking at low-pressure applications (~0.6 MPa). High-pressure application (above 1.5 MPa) demands open refrigeration systems. Kather and Engel proved that the energy efficiency of a closed system can be increased by converting it to a multi-stage process [10]. Optimal refrigerants corresponding to their number of stages are given in the table (Table 1).

Table 1 Optimal refrigerants to be used according to the number of stages

NO. OF STAGES	REFRIGERANT
1	Propene
2	Ammonia propane
3	Ammonia

The liquefaction is made expensive as the number of impurities present in captured CO_2 increases. In a study conducted by Deng and Skaugen, they compared the cost to liquefy CO_2 in pre-combustion gas from a coal-fired power plant and post-combustion gas from a cement plant [11]. They state that they have incurred an expenditure of an additional 34% for the former. The impure stream of gas can also increase the cost due to the increased safety considerations. In general, the presence of impurities affects the process if the final pressure is less than 3 MPa. The temperature of seawater also influences the layout of the liquefaction plant. With the average seawater temperature rising, the energy consumption by compressors also rises substantially.

The liquefied CO_2 is loaded onto ships for transferring them to the sink. The tank is generally filled between 72% - 98% of its maximum capacity [12]. Inside the tank, CO_2 forms an equilibrium between gaseous and liquid phases. A part of the total volume is deliberately left vacant to protect the ship from catastrophes that might occur due to the ingress of operational heat or sudden pressure spikes.

Boil-off gas (BOG) is generated during the voyage due to constant sloshing and/or heat ingress. Other factors that influence the rate of BOG formation are modus operandi, distance traveled, level of impurities, and tank design. The rate of BOG formation can be anywhere between 012% -015% (the conclusion is made by comparing the rate of BOG formation in a similar LPG and LNG carrier vessel). Researchers suggest the possibility of using reliquefication techniques similar to the ones used in LPG and LNG carriers to counter this problem.

Brayton cycle is used for the reliquefication - albeit their ersatz efficiency is considered, it is acclaimed due to the stability in sea conditions, ease of installations, minimal equipment, and compact design. After the transit, the cargo is discharged either at an onshore site or at an offshore site.

IV. COMPONENTS IN CCUS

To make CO_2 shipping economically feasible, a "clockwork" like relation is required between the source, components, ships, and the final sink. The general pathway of CO_2 from the source (capturing plant) to sink is shown in the below flowchart (Fig. 3).

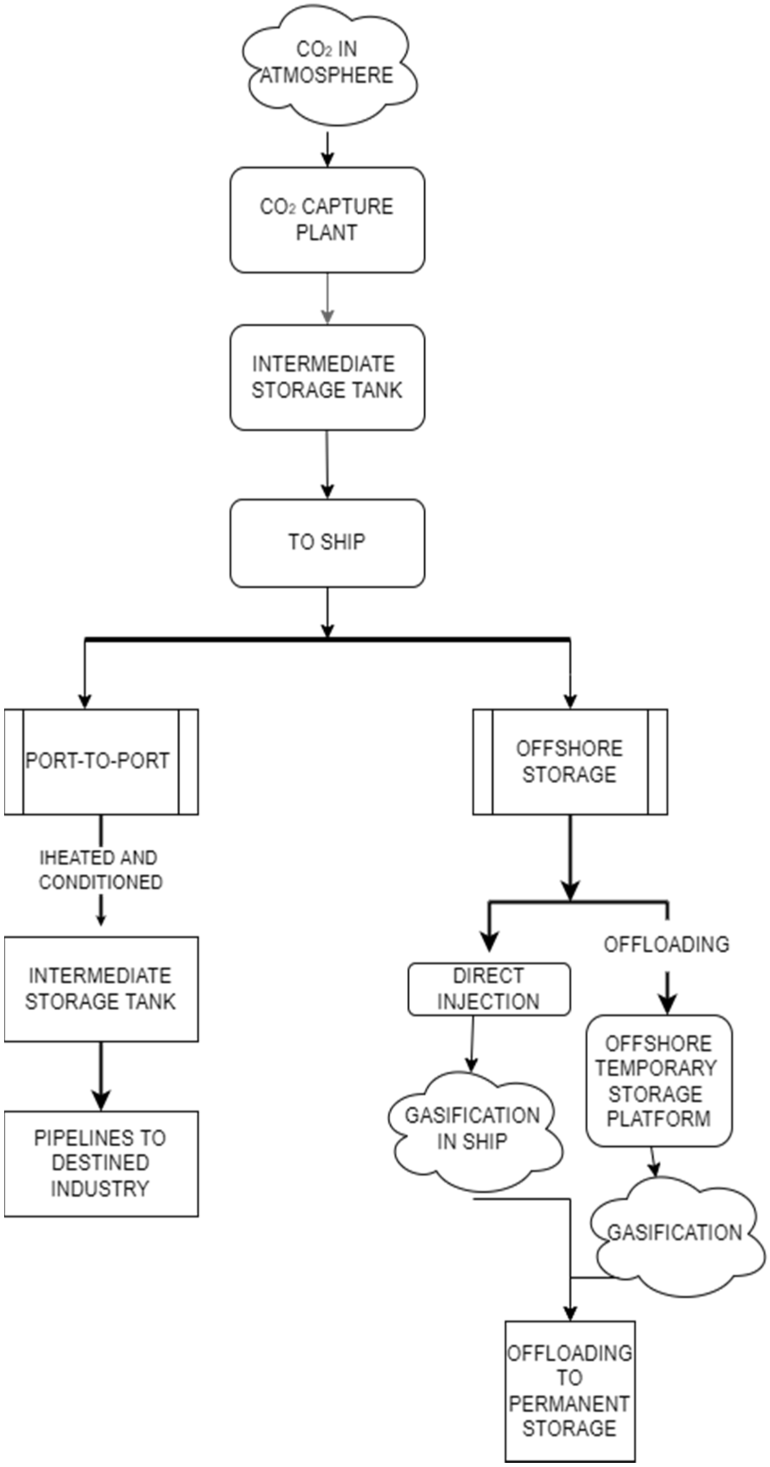


Figure 3. Flowchart of operations in CCUS

A. Dehydration

The CO_2 captured from the atmosphere has to be dehydrated primarily. It assures the protection of the machinery involved. Though multiple researchers were conducted, erudite are not yet to conclude a consensus. They agree that the maximum allowable water content in the system must be between 10-50ppm. The apparatus and chemicals involved in this process are difficult to collect as the sellers tend to keep them confidential. Generally, molecular sieve dehydration or Triethylene glycol (TEG) unit is used. The presence of impurities such as NOx, SOx, amines, and glycols can turn out to be detrimental to this system. So they have to be removed before admitting it to the dehydration unit. Table 2. shows the list of impurities and their perceived effects on the dehydration unit.

Table 2 Common impurities and their effect on TEG and molecular sieve units

Impurity	Effect on molecular sieve unit	Effect on TEG unit
NOx	Reduce lifespan	No effect
SOx	Reduce lifespan	No effect
Amines	Dust accumulation	Foaming
Glycol	Premature damage to the sieve system	No effect

B. Liquefaction

As explained earlier, liquefaction can be achieved by an open or closed refrigeration cycle. In a closed refrigeration cycle, external refrigerants such as ethane, propane, R134a, ammonia, or a combination of these are used. Generally, an open cycle is preferred when a large quantity of CO_2 is considered [13]. Depending upon the target pressure and temperature condition, the selection of refrigerant is done. Table 3 shows the pressure each refrigerant ought to achieve.

Table 3 Refrigerant and the pressure range it acts upon

Refrigerant	Pressure range
Propane	1.5 - 3.5 MPa
Ammonia	4.5 - 6.5 MPa
Ethane and propane	0.6 - 0.8 MPa
NH3	0.8MPa
NH3 - R134a	0.8MPa

Despite the use of different refrigeration cycles and refrigerants, all the processes try to constrain CO_2 at conditions at or near triple point because of its ease of transport, high density, and low storage costs. According to Nam [7], the process becomes most energy efficient at 6MPa and 295K.

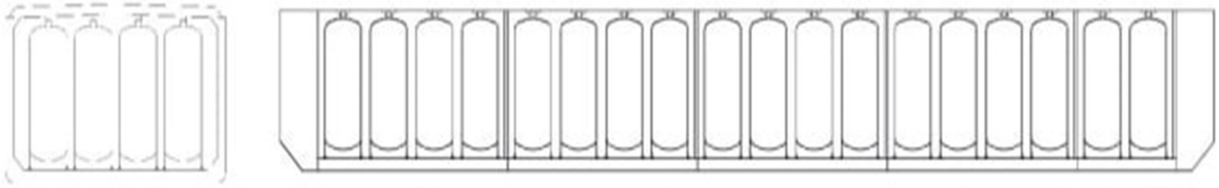
The location of the liquefaction plant is also scrutinized. Nam et. Al. [7] has developed a modelling tool that suggests that the plant should be situated in high-emitting regions and can be connected to low-emitting regions via pipelines.

C. Storage

The liquefied gas has to be stored in an intermediate storage tank before being loaded into a ship. CO_2 is stored in a bubble point. The tank is filled 72% - 98%, such that at any point CO_2 in the tank exists as a mixture of gas and liquid. This resolves issues caused by pressure spikes or ingress of heat. The size of the storage tank must be at least 1.5 times the size of the vessel. Tanks can be built in bi-lobate, spherical and cylindrical shapes – a spherical shape is preferred as it is the cheaper option. The thickness of walls depends on the pressure it is intended to be used. Literature suggests carbon steel for spherical tanks and 9% Ni steel for cylindrical tanks. More research ought to happen in the case of intermediate tanks - it is not just the economic factors we have to consider. A failure can result in the sudden expulsion of a large quantity of CO_2 into the atmosphere. This is detrimental to both the local ecosystem and humans alike. In case of non-availability of land onshore, one can install tanks in floating barges.

Floating Logistics Terminals (FLT) is an innovative method that can be of use. Currently, they are used to store LNG. These are cost-effective and easy to install (Fig. 4).

(a) A sketch of midship and section view of floating barge type temporary storage with capacity of 28,000 m3



(a) A sketch of midship and section view of floating barge type temporary storage with capacity of 110,000 m3

Figure4. Floating barge-type temporary storage (Source: The Engineer's guide to CO_2 transportation options)

D. *Loading*

Loading of CO_2 from intermediate tankers to ships can be done using mechanical arms or special hoses used for loading cryogenic liquids. Mechanical arms are preferred as they fail less frequently compared to hoses. Cargo is loaded using high-pressure, low-temperature pumps. It is suggested to fill the CO_2 in pressurized gas form and not liquid as this will hinder the formation of dry ice. To deter the build-up of pressure inside the vessel, CO_2 vapors have to be removed using a return line, connected parallelly to the supply line. The loading time can be reduced by increasing the flow rate of CO_2 - this helps to improve the economic characteristics of the process. While the option seems acceptable, it must be accompanied by an emergency release system to facilitate unplanned disconnection of the ship (due to emergencies like fire or rough weather) failure in the loading arm.

E. *Offloading*

After the voyage, CO_2 can be unloaded at its destination. It can either be an offshore site - which is deemed as the final destination or it can be an onshore site, which can be treated as a regular port-to-port transit. In the latter scenario, offloading and transferring it to the designated site is done via pipelines.

The technology for the process is already developed and is widely used in the food and ammonia industries. The types of machinery in use for the system share similarities with the one used in offloading other gaseous cargo such as LNG and LPG. But offloading at offshore sites throws a challenge as the technology is not yet developed. The selection of machinery for the process is expected to have an impact on vessel design. An advisable model is building an auxiliary platform, similar to intermediate storage. The platform serves as the base for several equipment and as a site for temporary storage. Though this comes at a higher CAPEX, it will ensure a continuous discharge, regardless of the condition of the weather. It will also reduce the time for offloading by 5 times (it will take up to 50 hours in the absence of temporary offshore storage). Perchance availability of space occurs, and the very same FPSO can be used to install the temporary storage platform.

F. *Injection System*

Another model is the direct injection system, where cargo is discharged to a riser buoy. In such a system, the CO_2 in the vessel has to be heated to 273K to prevent hydrate formation [14], pressurized to ~30MPa, and conditioned before injection within the vessel. The use of seawater for heating can be followed, but weather variations may affect the process. So, it is advised to have a system that makes use of waste heat for the process. The ship's engine can give the energy for injection. The injection process must be continued throughout, as sudden cessations can result in the formation of dry ice.

V. A COMPARATIVE STUDY BETWEEN SHIPS, ROADS, RAILWAYS, AND PIPELINES FOR THE TRANSPORTATION OF CO_2

CO_2 transportation includes gaseous transport, liquid transport, dense-phase transport, supercritical transport, and solid transport. All except the last one is acceptable for long-distance, large-scale transportation [15].

A. Pipelines

CO_2 lines are considered the best option for transporting a large amount of CO_2 over a short distance (250km). The main deterring factor is the high initial investment and limited adaptability. Transportation cost for CO_2 transport using pipelines is low.Phase transportation is very critical since temperature, pressure, and impurities have a great impact. Pipeline transportation ensures a continuous flow (i.e., it is a steady flow from source to sink) while other modes require intermediate storage sites [16]. To ensure a continuous flow, compressed gas is fed to the pipeline system – which increases the expenditure as distance increases. In order to maintain the supercritical phase throughout the line, a pump-based system is recommended for regulating the pressure. CO_2 is compressed and recompressed at specific points in the pipelines – just like an amplifier in an electric circuit – which increases its energy consumption. The terrain through which the pipelines traverse also causes variation in pressure.

Other arguments against the model are

1) that the construction of the pipeline and other supporting facilities can cause damage to the local environment
2) underground pipeline leaks can be detrimental to soil and underground water bodies.
3) Cause depletion of oxygen level
4) Harmful to aquatic organisms

B. Roads

Roads are a flexible and reliable method of small-scale CO_2 transportation. An average truck can transport 18 tonnes of liquid CO_2 [17]. For an economic operation, the distance between the source and sink must be below 320km. To maintain temperature and reduce evaporative loss, the container needs to be well insulated. Trucks find their applications in transporting CO_2 for loading in ships and to reach areas where pipelines and ships cannot.

C. Railways

Rail cars are used for point-to-point transfer and could be used as potential temporary transport solutions on CCUS projects until additional transport options such as pipelines or high-capacity transport ships are developed. Operating expenses are associated with shipping and labor for loading and unloading rail cars.[18]. It is a cheaper option than the road. These types of transport systems do not get affected by weather or traffic conditionsBoth the source and the sink sites have to be near the rail line. Railway Transport is not asflexible as shipping or truck. It also doesn't provide a continuous supply.

D. Ships

CO_2 transport with the ship is the best method to transport CO_2 from the source to near the coast and offshore storage site. They offer greater flexibility than pipelines. From various economic studies, it is made clear that for longer distances (>1000 km), ships are most suited. Shipping can be used in countries where the implementation of pipelines is not possible due to the possibility of natural calamities [19].

VI. ENVIRONMENTAL ASSESSMENT

A. Shipping Emissions And Control Measures

The emissions from the several types of machinery onboard a ship including the main engine, boilers, and incinerators contain up to 450 different compounds - whose detrimental effects reach out to global levels. The use of residual fuels (e.g., HFO) in shipping owing to its low cost takes up the blame for increasing air pollution significantly [20]. he effect of these activities within a range of 400km from the nearest land causes severe deterioration of the local environment [21]. On a related note, an intriguing yet concerning study unveiled the influence of aerosols generated from the ship engine exhaust on storm intensification and increased lightning in the north-eastern Indian Ocean and the South China Sea [22]. With the raising concerns, IMO has heightened its focus on curbing emissions. In 2008, IMO initiated two new actions to address emissions from ships -the Ship Energy Efficiency Management Plan (SEEMP) and the Energy Efficiency Design Index (EEDI). Under it, the following parameters are checked and suggestions were put forth:

1) *Alternative fuels:* Heavy Fuel Oil - has very high life cycle emissions, but is still considered favorable for shipping. Switching to alternative fuels will result in the reduction of carbon emissions [23]. Some of the challenges concerning this are the availability of bunkering infrastructure and the engine modifications needed [24]. Liquified natural gas is a promising alternative with its negligible sulphur content and high hydrogen to carbon ratio than diesel fuels. It has 20 to 30% lower CO_2 emissions [25]. There are about 251 LNG-propelled vessels in operation worldwide as of 1 January 2020. Biofuels are another genre of alternatives. These are classified as first-generation biofuels such as hydrotreated vegetable oil (HVO), straight vegetable oil (SVO), fatty acid methyl ester (FAME), etc., and second-generation biofuels such as pyrolysis oil, lignocellulosic ethanol (LC Ethanol, Fischer- Tropsch diesel (FT-Diesel), etc.

B. Energy Efficiency

The EEDI is employed to reduce fuel consumption and increase energy efficiency by making necessary changes in the design of the ship's propulsion systems, hull design, design speed, etc.

1) *Concept And Speed:* The ships' energy efficiency is heavily dependent on their size, speed, and design of the beam and draught. With modern construction and maintenance, it is possible to extend the lifetime of ships to more than 30 years. Thus, retrofitting capabilities must be addressed at the design stage itself to ensure flexibility in operations. Although reduced speeds result in lesser emissions, the global uptake of speed reduction may be impractical as it may require regulations to be made which might be counterintuitive and hard to enforce.
2) *Hull Design:* By optimizing the hull design, hull resistance can be reduced and the propulsive efficiency improved. Hull design can be optimized by increasing the vessel size, changing hull shapes, hull coating, using resistance reduction devices, and lubrication.
3) *Power And Propulsion Systems:* Energy efficiency in propulsion engines can be improved by upgrading old engines, replacing them, and using exhaust gas heat recovery systems such as steam or electricity generation systems, etc.
4) *Fleet Management, Logistics, And Incentives:* By using the right kind of ship according to the size of the cargo, distance to be covered, and nature of the cargo, the efficiency of the shipping chain can be improved as a whole. Indeed, it will lead to improved energy efficiency. Also, carefully planned voyages, reduced wait times, and quicker turnaround times in port can lead to significant energy savings.
5) *Voyage Optimization:* By considering various factors such as weather, current, wave data, etc. It is possible to find the best route possible between the source and sink to optimize the voyage. This optimization helps to reduce fuel consumption and emissions.
6) *Energy Management:* Energy management is essential to restrict onboard energy consumption. Energy is required for propulsion, auxiliary operations, and sustenance of the crew.to reduce energy consumption, proper maintenance work should be carried out on all systems to ensure that maximum efficiency is achieved.

C. Renewable Energy Sources

Renewable energy can be generated on board ships or onshore to power ships while at berth (also called cold ironing). For instance, annual emissions can be reduced in the range of 5-10% by extracting wind power in various ways such as kites, sails, and Flettner-type rotor sails. Fuel cells can be used to shoulder a part of the energy supplied by generators.

D. Using CCUS Onboard Ship

The gaseous CO_2 in exhaust gases can be captured using various technologies such as the use of membranes, absorption processes, and solvents [26]. But the current CCUS methods used on shore cannot be used onboard due to the increase in power consumption and large footprint.

VII. CHALLENGES AHEAD

This session discusses the broad range of challenges that have to be overcome to transform CCUS into a reality. It mainly deals with technical challenges but also discusses economical and legislative barricades briefly.

A. Economic challenges

The source of CO_2 emission varies widely - ranging from a normal household to a multi-billion corporate industry. With changing sources, the condition of CO_2 streams will also change. Hence a decentralized, dynamic approach should be taken, which makes the process arduous.

CCUS is considered an economic uncertainty because of the large CAPEX and OPEX as well as the financial uncertainty it throws in front. The land resources that are to be dedicated to the complex infrastructure to contain the cargo will take up valuable space, and that too will be taken from locations near ports.

Captured CO_2 is often undervalued. As per Paris Agreement, the average global CO_2 price must range between \$40-\$80 /t by 2020. Treating captured CO_2 as a global commodity and lifting the sanctions will help to reduce the financial burden.

B. Legislative Challenges

Conventional norms tend to see CO_2 as a waste/ by-product that threatens the integrity of life on earth rather than a viable commodity of commercial value. Several international conventions have promulgated legal frameworks that impede the development of CCUS.

The London protocol (1996) regards CO_2 as a harmful waste and "prevents export of wastes to other countries for dumping"(A 2019 regulation strives to make amendments to this, thus providing hope for the future of CCUS). Several regional laws (centered in Europe) such as the CCS directive and ETS directive also strive to control CCUS activities. The former addresses only pipelines and is irrelevant to the study. The latter promotes only CO_2 transmitted by pipelines, essentially handicapping the CCUS. Several national laws are also formed based on these. Norwegian National Law enforces the ETS scheme, hence barricading the implementation of shipping in CCUS.

C. Selection Of Materials

The selection of materials primarily depends on two criteria - temperature and dehydration. Carbon steel can be used when a low water level is present in the stream, but stainless steel is preferred when the water content is more (to prevent corrosion). The system can also be manufactured with alternating materials when additional components that help dehydration (like coolers, and scrubbers) are fitted in the line. It must be noted that the presence of impurities will continue to have its effects on the equipment (for instance, the presence of H2S cause the formation of a thin layer of iron sulfide which coats inside the pipeline and reduces the heat transfer).

The operational temperature range of the system also significantly influences the selection of materials. Generally, the activities happen between 223K - 261K. Carbon steel treated for low-temperature and high-temperature operation can suffice the requirement. The use of 5% Ni steel and stainless-steel alloys can increase the cost of the project to such a level that it can even render the entire operation economically infeasible.

The use of non-metallic polymers is also explored [27]. PTFE, EPDM, and FKM are suitable for liquid CO_2 environments. The use of polymers as seals for the equipment is also studied. Materials such as chloroprene, polyethylene, and Fluro-elastomers show cracking under depressurization. The lack of research on the behavior of seals at the triple point of CO_2 makes further studies in accordance with the operation of CCUS obscure.

D. Boil-Off Gas Regeneration

The motion of the vessel and heat ingress cause boil-off gas (BOG) generation. A boil-off rate of 012%-0.15% is acceptable. The re-liquefaction BOG is done by external refrigeration (Brayton cycle). The reliquefication process is similar to that used in LNG tankers.

E. Countering Hydrate Formation

The presence of water can lead to the formation of hydrates - which will cause slag formation and corrosion, on solvation with CO_2. H2 increases the liquefaction pressure of the mixture - which means it will cause water to evaporate on depressurization and bond with gaseous CO_2, which will accelerate the hydrate formations. In case of leakages, the interaction of CO_2 causes hydrate formation and pH change.

F. Safety

The scientific, as well as legislative communities, were keen on safety considerations for both humans as well as the ecosystem as a whole. UK's health and safety executive issued an analysis of the dangers of CO_2 systems, with CCUS in particular. Technical faults such as (the formation of dry ice, failure of loading arms, etc.) have to be dealt with. Grounding or sinking of ships is a major concern, as it is capable of releasing the entire CO_2 in bulk. Due to the lack of available models and commercial implementation, the devastation of such a tragedy cannot be known, but the results will be unprecedented.

Though most of the technologies used resonates with those used in handling LNP/LPG, a great advantage of CO_2 is that it is not explosive. Considerations of the impurities present should also be made.

Studies have suggested that the unloading system and the intermediate storage tanks present the highest risk. Developing an emergency shutdown device (ESD), particularly for CCUS operation can mitigate the risk [28]. ESDs will shut off the transmission of CO_2 during loading or unloading operations. An ESD contains fast-acting valves, loading arms with emergency release systems, and alarms.

G. Boiling Liquid Expanding Vapor Explosion (BLEVE)

The cracks or leaks in storage tanks or vessels can cause large expansion rates of gases [29]. The risk of BLEVE in low-pressure vessels (0.7 MPa, 223K) is considerably low compared to medium (I.5 MPa, 248K) and high-pressure vessels (4.5 MPa, 283K). Due to the non-flammability of CO_2, subsequent ignition and BOG formation are prevented. Thus, the BLEVE is referred to as BLEVE.

VIII. CURRENT CCUS FACILITIES AROUND THE GLOBE

CCUS has been implemented in USA and Canada from as early as the 1960s for carbon dioxide-enhanced oil recovery (EOR) (Fig. 5). The world's first large-scale CO_2-EOR facility, Scurry Area Canyon Reef Operating Committee (SACROC), came into existence on January 26, 1972, in Texas, USA. Between 1972 and 2009, the SACROC project captured and injected more than 175 million tonnes of natural CO_2.[30]

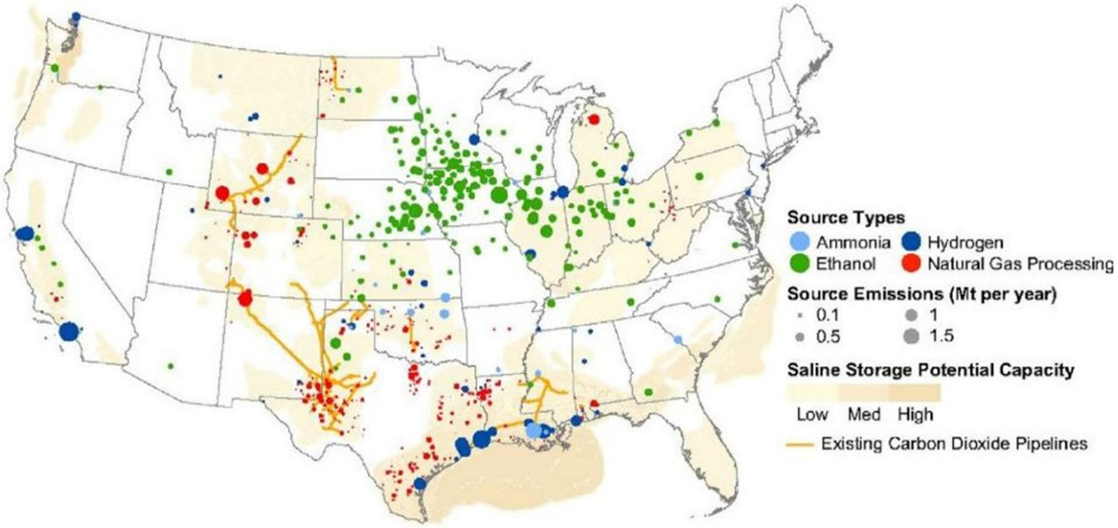


Figure5. Map showing CO_2 sources and existing pipelines in the USA (Source: Carbon capture and storage: History and the road ahead)

Though many such projects have been in operation for decades, all these employed pipelines or road transport as a means of transportation. This is largely attributed to the lack of ships capable of carrying CO_2 in bulk, to make it economical. As of 2018, only four ships are currently employed for transporting CO_2 from ammonia plants in northern Europe to coastal distribution terminals - which are used in food and beverage industries.[31]

The recent development where Japanese, Korean, and Chinese ventures focussing on ship-based transportation of CO_2 marks the beginning of a new era for the implementation of shipping in CCUS. The involvement of Korea and Japan paves an alternative path for countries that are geographically located far away from the sinks. For them, using pipelines is economically not feasible. Japanese shipping company NYK and Norwegian Knutsen Group have established a joint venture company or developing a liquified CO_2 marine transportation and storage business. Near the end of 2021, Japanese shipping firm MOL and Mitsubishi Shipbuilding Co. announced the completion of a study on multiple hull forms for a liquified CO_2 carrier.

Also, the world's largest Shipbuilder Hyundai Heavy Industries (HHI), and Korea Shipbuilding and Offshore Engineering Co. (KSOE) together unveiled a design for a new 40,000 cubic-meter liquified CO_2 Carrier in early 2021[32]. Figure 6 shows the current and proposed CCUS facilities globally.

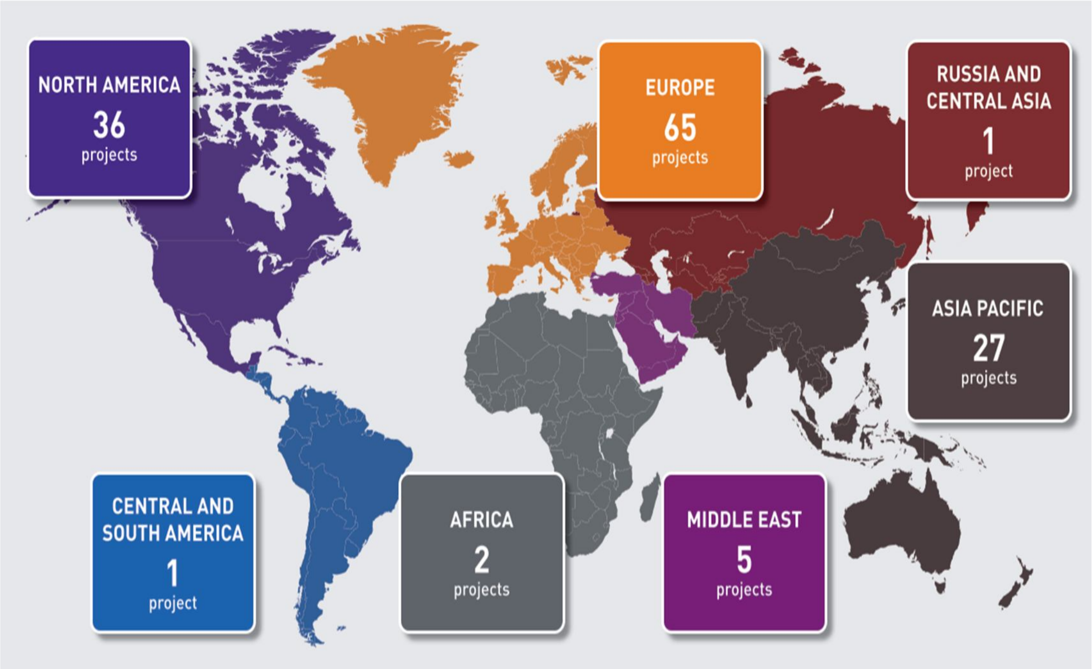


Figure 6. Map showing current and proposed CCUS facilities globally (Source: International Association of Oil and Gas Producers)

IX. DISCUSSIONS AND CONCLUSIONS

With pressure mounting to bring down GHG in the atmosphere, it is high time that each company should start to introspect, either individually or with their components in the supply chain or with their counterparts in the market, and present an amicable stratagem to bring down their emission in accordance with the limits set by respective agencies. The seriousness of the problem is comprehendible when banks start to take an organization's climate impact into account before providing them loans. Similarly, constraints from governments, which appear in the form of laws, sanctions, or even non-cooperation will chock both small and large businesses. While the leviathans can afford to allocate capital for R&D in cutting down their emissions, smaller businesses can invest a sum in CCUS companies. This allows them to spend their capital in accordance with their emission. Inadvertently, this also preaches corporates to take up more responsibility for their actions and consider their social obligations while planning. Utilization of captured carbon can highly boost the sector. Limited utilization of carbon causes a sense of uncertainty and decreases the investments flowing to the field.

Despite numerous technological gaps, the literature suggests that using LCO_2 carriers is one of the most favorable means of removing CO_2 from the atmosphere. It is cheaper than long-distance pipeline projects, has flexibility between source and sink, and presents less threat of accidents. It also allows to induct the development in one particular subsystem in the chain – for instance, the capacity of the carbon capturing facility can be improved independently of the ship's or cargo loading equipment's capacity, which is not possible in the case of pipelines. The major impediments in the way are the legal framework and operational challenges. Due to the lack of working projects, flawless data collection is challenged. Above all, capital expenditure is an indispensable factor that governs projects. Proper integration of different systems in the CCS chain and their active coordination is demanded for an economically profitable operation. Rightly addressing the challenges and developing a legal framework to bolster the projects is instrumental in reducing the global CO_2 content in the atmosphere.

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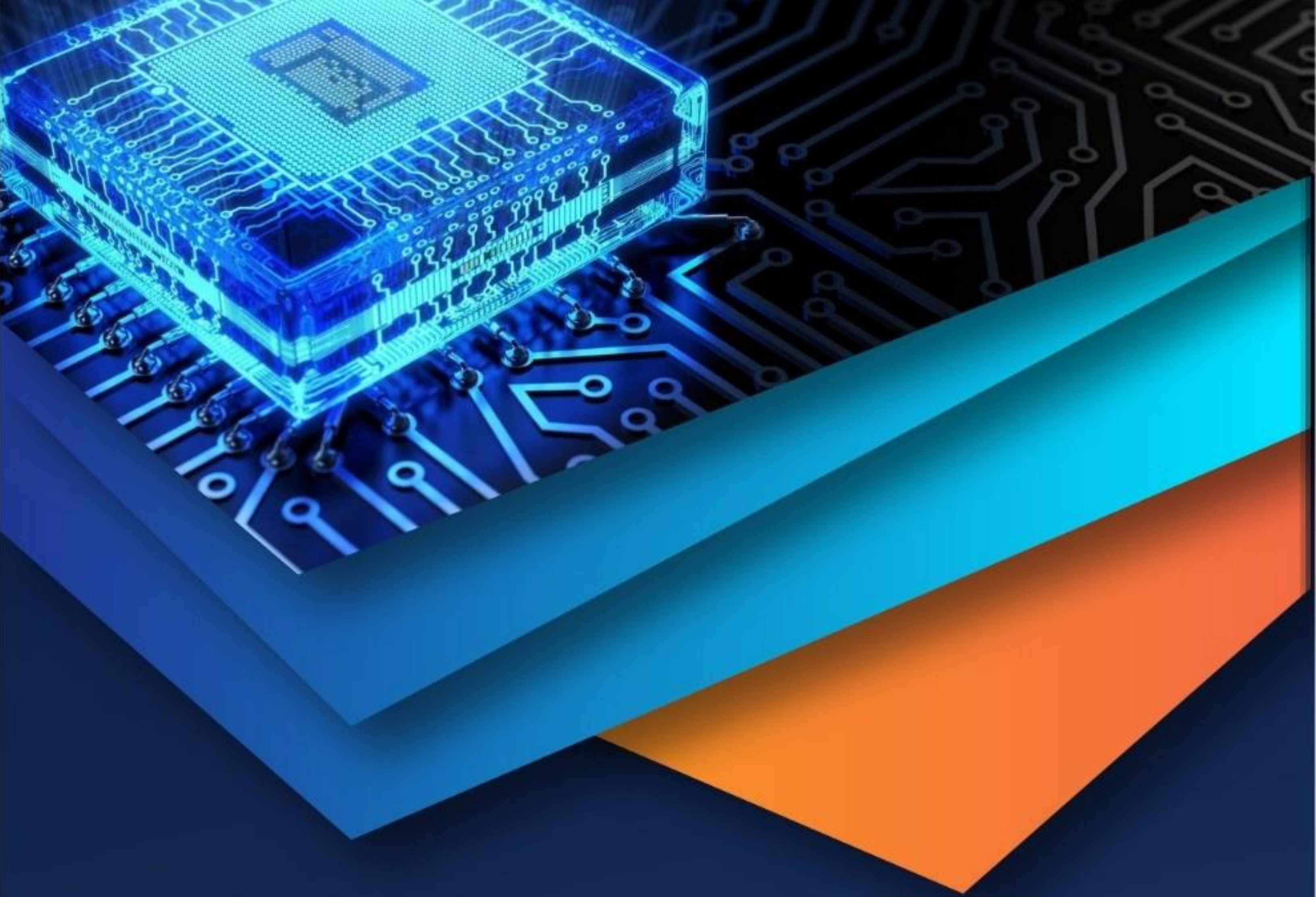

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