The Northern Lights facility – west of Bergen, Norway. (Credit: Equinor)

Will CO_2 transport and storage limit blue fuel availability for the maritime industry?

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

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Executive summary

Blue ammonia is an attractive alternative fuel for the maritime industry, due to its potential to scale up quickly using existing technologies and its low production costs compared with other low-emission fuels. Like conventional, gray ammonia, blue ammonia is produced from natural gas, but carbon capture and storage (CCS) is used to capture, transport, and permanently sequester the CO_2 byproduct, thereby yielding a fuel with low well-to-wake emissions.

Carbon storage is an established technique where captured CO_2 from industry is transported to a long-term storage location. Several sites have been in operation for decades. However, the volumes of CO_2 currently stored are small relative to the expected demands for the energy transition. As a result, carbon storage availability will need to increase significantly for blue ammonia to be a viable option for decarbonizing the maritime industry.

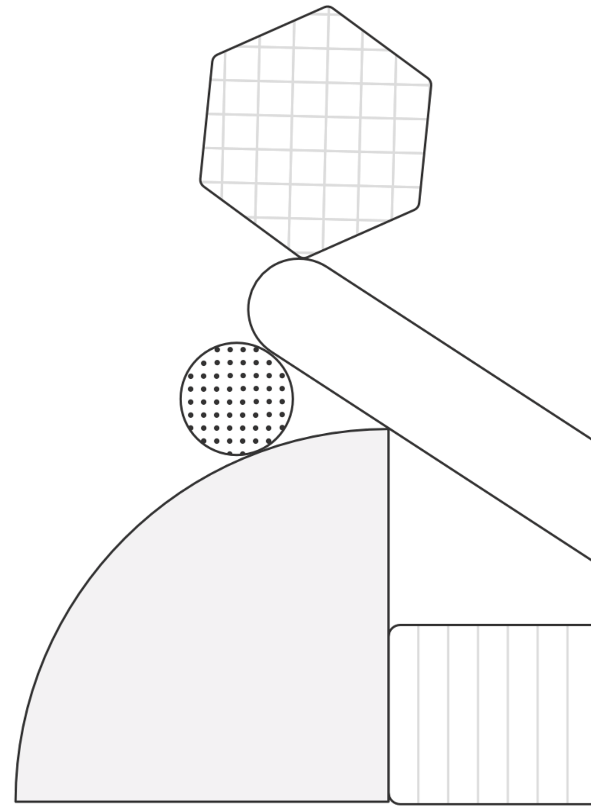
To find out more about the global potential for carbon storage, we analyzed whether potential carbon storage in CCS networks can meet the expected demands from blue ammonia production for maritime in the context of the wider demand for CCS from other industries. We also studied potential constraints on CCS and blue ammonia availability, including industry ramp-up plans, equipment supply, public policy, permitting time, infrastructure costs, operating costs, and cross-sectoral competition.

Our findings showed that global CO_2 transport and storage capacity is expected to expand dramatically over the next few years. As a result, CO_2 storage capacity will not prevent blue fuel availability from meeting the anticipated demand from the maritime industry by 2030. Most of the expansion in CO_2 storage by 2030 is likely to come from regional hub projects serving multiple industries and emitter sites, rather than single sites with individually dedicated storage. This arrangement is beneficial, as it allows the infrastructure development costs to be shared and drives down the cost per tonne of CO_2 storage.

Regulatory barriers to increasing CO_2 storage appear to be surmountable on a global scale. Several countries expected to be key to large-scale blue fuel production have already established supportive national policies and incentives for CCS. Characterization, permitting, planning, and construction of new CO_2 storage sites can take several years, resulting in a time delay in establishing new capacity. Nevertheless, areas with established oil and gas production generally have well-characterized geology, which can help to reduce the characterization and permitting times.

We expect blue fuel production locations to be concentrated in areas with access to low-cost natural gas and CO_2 storage. As a result, we analyzed the suitability for blue fuel production of each of the major gas exporting countries/regions and identified several countries/regions most suitable for blue fuel production. We also estimated likely production costs for blue ammonia in each of these regions, which range from 480 to 600 USD/t, excluding the impact of tax incentives.

Overall, our analysis indicates that CO_2 storage capacity is unlikely to constrain the availability of blue ammonia for shipping by 2030.

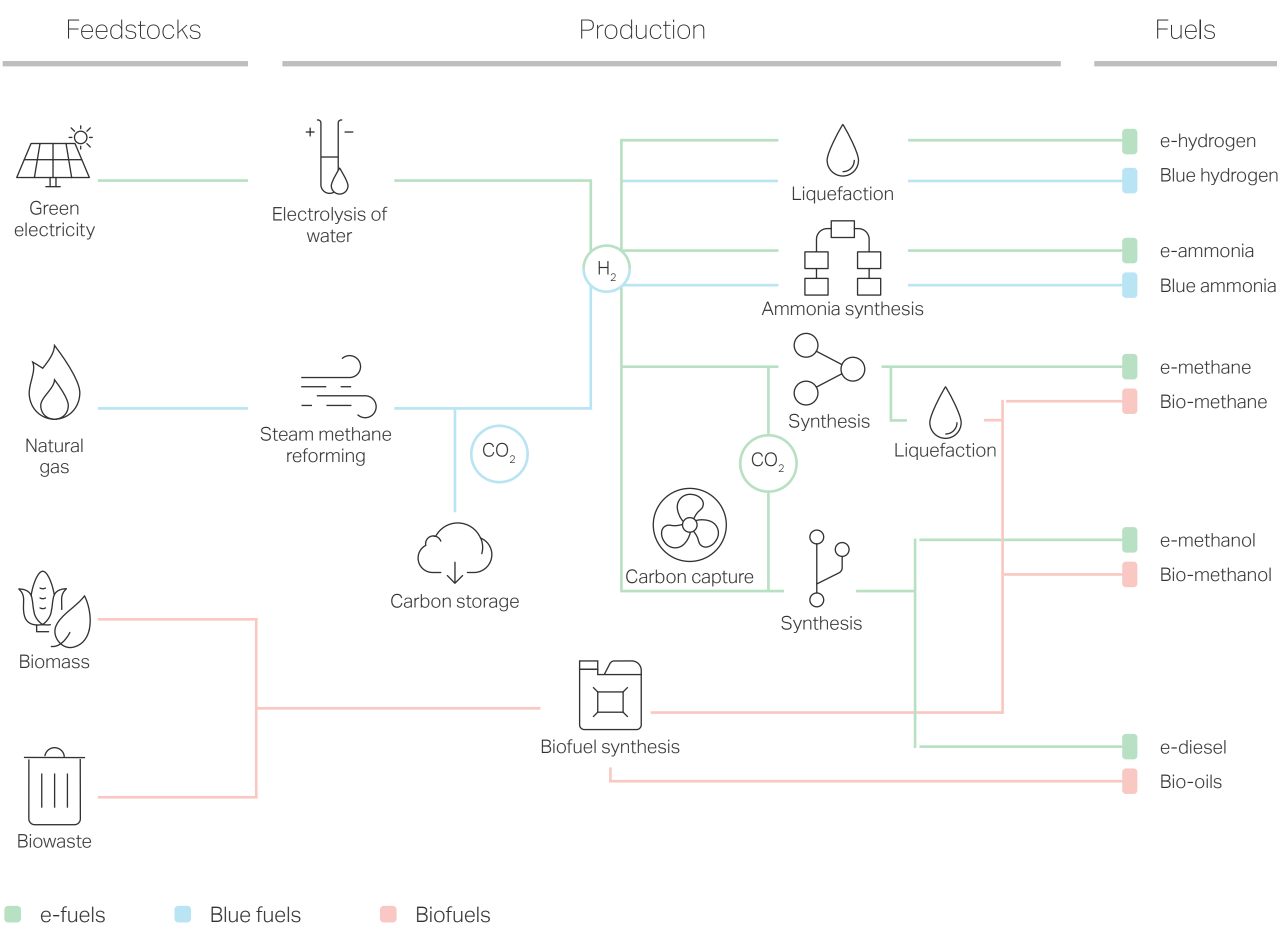


1. Introduction

The maritime industry will only be able to decarbonize if ships transition to alternative fuels with lower greenhouse gas emissions than today's carbon-based fuels. Critically, the industry must begin this fuel transition within the current decade to establish the necessary momentum to decarbonize by 2050. Therefore, for the next several years, new-build ships should be prepared to use low-emission fuels, since these ships will remain in operation by the 2050 target. However, as future alternative supply chains are currently uncertain, investments in ships that can sail on alternative fuels are risky. Therefore, the year 2030 serves as a relevant milestone for the assessment of fuel availability.

De-risking the emerging supply chain for alternative fuels would de-risk investments in alternative fuel-ready ships and accelerate decarbonization. However, some alternative fuels (Figure 1) may be limited in the near term by cost and scalability, limiting their impact on decarbonization.[1] For example, until renewable electricity costs reduce, unsubsidized e-fuels will be too costly for most of the maritime industry. Meanwhile, biofuels could achieve lower production costs, but they may lack the ability to quickly reach the necessary scale for multiple reasons, including limited biomass supplies, demand from multiple sectors, and the relatively small capacities of biofuel plants means hundreds of new plants would be required in a short time.

Figure 1: Alternative fuel pathways in shipping.[1]



Utilizing the blue ammonia fuel pathway (Figure 1) could overcome the current limitations faced by alternative fuels and de-risk investments in onboard technology, therefore accelerating maritime decarbonization. Unlike other alternative fuels, the technology readiness level for producing blue ammonia is high, the energy feedstock price has been low historically, and plant capacities are already high enough to enable economic scaling. Conventional ammonia plants with a production capacity of one million tonnes p.a. are in operation today. Multiple blue ammonia plants of this capacity are now being developed, with a large expansion in blue ammonia production capacity expected over the next 5 to 10 years.[2] Therefore, if ships can be built ready for propulsion by ammonia, then blue ammonia presents an opportunity for a lower-cost and quicker-scaling fuel than most alternatives.

Blue ammonia is a candidate as a low-emission fuel because it has the potential to generate low life cycle emissions. Ammonia is already carbon-free and produces no carbon dioxide emissions when combusted. However, possible N_2O emissions must be addressed.[3] Meanwhile, GHG emissions from production are reduced in the blue ammonia pathway because most of the fossil feedstock carbon can be captured as CO_2 and then permanently sequestered.

There is an existing synergy between ammonia production and CO_2 storage. All conventional ammonia plants remove CO_2 to protect the ammonia reaction catalyst, so the CO_2 in the process stream is captured with a high efficiency (>99%).[4] However, in conventional ammonia plants, approximately 35% of a conventional plant's CO_2 is produced outside the process stream and is therefore not captured economically today. Blue ammonia plants can address this using autothermal reforming technology (ATR), which is an existing solution that integrates most of the produced CO_2 in a common process stream, thereby achieving an overall capture rate of 95% or more.

Despite these favorable supply perspectives, there is one potential supply chain gap that needs to be assessed for blue ammonia to be a viable option for the maritime industry: the current global capacity of CO_2 transport and storage would not be sufficient to provide for our maritime decarbonization targets of 2030.

To attempt to answer the question 'Will CO_2 storage limit blue fuel availability for the maritime industry?,' we researched cost structures, planned projects, market drivers, regional policies, and barriers to scaling. The project was a collaboration between the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) and our strategic partners: bp, CF Industries, Equinor, Sumitomo Corporation, NYK, and TotalEnergies. The Environmental Defense Fund (EDF), a knowledge partner to MMMCZCS, and Global CCS Institute also contributed to the project. This position paper summarizes the results of the project research.

Our project partners:

2. How much storage capacity could be available to meet 2030 maritime requirements?

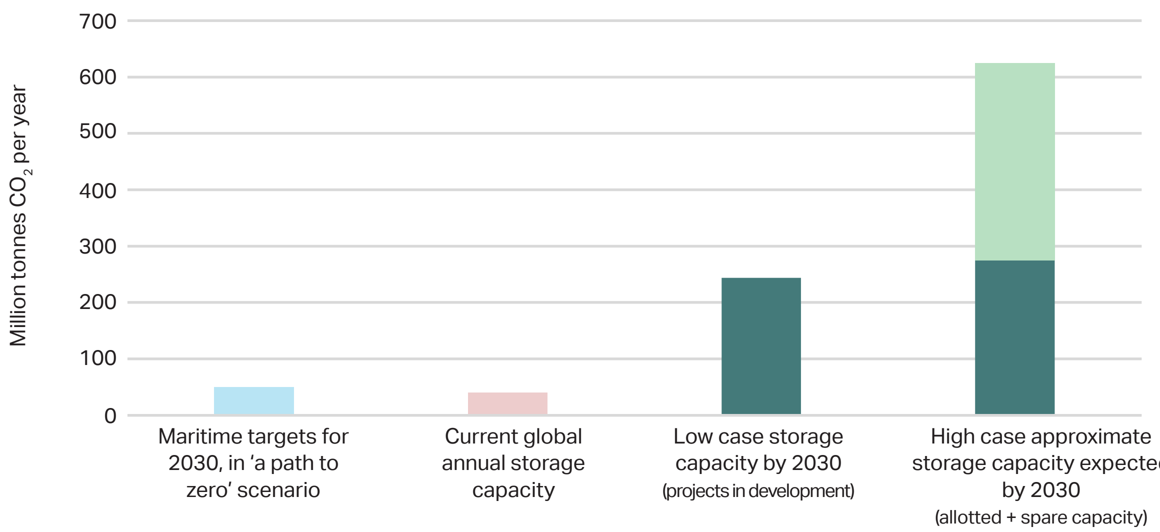
To establish whether the shipping industry could have adequate CO_2 storage available by 2030, we selected a benchmark demand scenario of 34 million tonnes of blue ammonia per year. This corresponds to the blue ammonia demand in our Navigate Path to Zero 2022.[1] The required capacity would change depending on if slower or faster decarbonization is targeted or if other alternative fuels sufficiently penetrate the maritime fuel mix.[5] For this amount of blue ammonia, the required CO_2 storage would also be approximately 50 million tonnes per year. Notably, there is already a gap in supply. Producing 34 million tonnes of blue ammonia production would consume more than the current global annual CO_2 storage, which stands at approximately 40 million tonnes per year.[6]

The long-term theoretical global resources for CO_2 storage are exceedingly large. Following the third annual assessment cycle of global CO_2 storage resources,[7] completed in March 2022, the total estimated resource stands at 13,954 billion tonnes of CO_2, more storage capacity than humanity would ever need. Furthermore, 4.1% (577 billion tonnes) of these storage resources have been proven technically with subsurface data such as well and seismic surveys, which is also sufficient to meet storage needs.

Despite the very large potential for CO_2 storage, not all of the volumes can be utilized with existing infrastructure. Therefore, the more relevant consideration for near-term storage is the planned capacity by Engineering, Procurement, and Construction companies (EPCs). There has been dramatic growth in planned CO_2 transport and storage capacity during 2021 and 2022, with planned CO_2 storage projects approaching one billion tonnes per year.[8] Of these project announcements, according to intelligence from project participants, more than 600 million tonnes per year are planned to be in operation by 2030. The Global CCS Institute[6] reported that as of September 2022 there were 244 million tonnes per year of CO_2 storage in development, with approximately 110 million tonnes per year in either construction or advanced development.

As depicted in Figure 2, this planned capacity would be more than sufficient for shipping alone, but the forecast supply is not without risk. Not only must the new CO_2 storage be shared across industries, but potential supply chain risks could inhibit achieving these infrastructure capacities within the timeframe. In this work, we assessed these factors with consideration for specific regions, regulatory barriers, equipment supply, and cost structures. The results are outlined in the following sections.

Figure 2: Comparison of Capacities for CO_2 Storage: 2030 requirements, currently existing, and planned for 2030 (million tonnes CO_2/year).



3. Will CO_2 storage be available in the most favorable regions for blue fuel production?

The most critical factors in determining the favorability of siting new blue fuel production plants are:

- Availability of low-cost natural gas feedstock
- Sufficient reserves of gas to ensure supply through plant lifetime
- Proximity to CO_2 storage site (or easy access via transport)
- Access to port for export
- Stable investment environment
- Supportive investment environment for CCS (e.g., tax credits or grants)
- Credible regulatory regime

Analyzing which regions could meet these critical factors yielded five regions of interest: North America, the Arabian Gulf, Norway, Australia, and Southeast Asia. Note that there is a good correlation between areas of oil and natural gas production and areas with favorable geological conditions for CO_2 storage, as indicated in Figure 3. These areas also benefit from having well-characterized geology due to extensive oil and natural gas exploration.

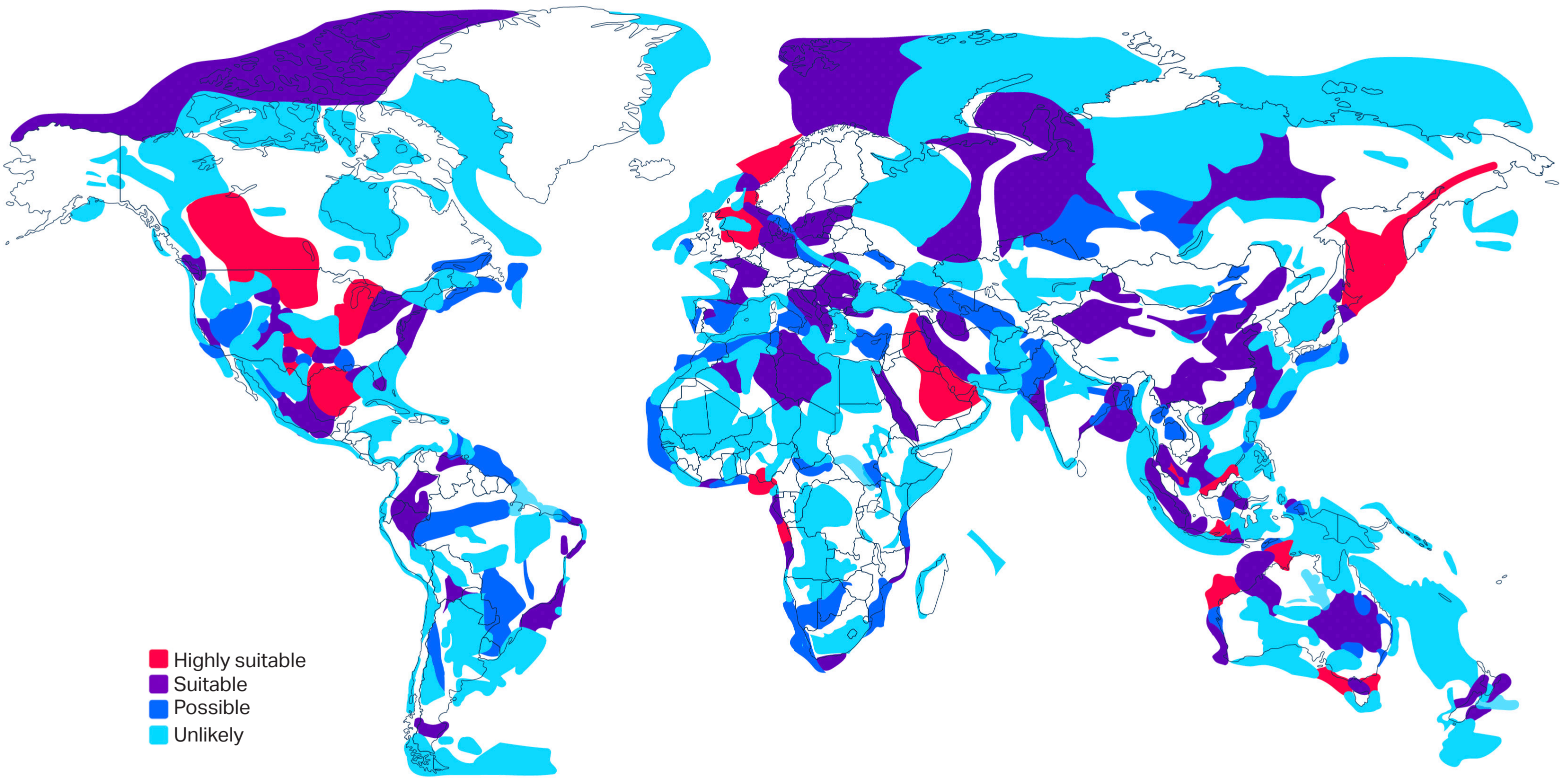
North America has extensive areas suitable for geological storage and well-established existing CCS infrastructure. Additionally, there is a large-scale supply of competitively priced gas production and highly supportive tax incentives for CCS.

The Arabian Gulf also benefits from large gas reserves, low-cost gas, and extensive areas suitable for geological CO_2 storage. It also has three operational CCS facilities,[6] with plans to expand CO_2 storage significantly in the next few years and new blue fuel production projects in development. This region also benefits from relatively easy access to key Asian markets.

Norway and Australia also have large gas production, favorable conditions for CO_2 storage, and some established CCS capability, with some planned blue fuel production capacity.

Malaysia and Indonesia are additional locations that we identified as potentially satisfying the most critical factors listed above. These countries are looking to establish CCS capability in the next few years, to complement their natural gas production with the potential for blue fuel production. Both countries have announced that regulatory regimes for CCS are under development, and plans for new CCS facilities are currently in development, including the retrofit of CCS to an existing ammonia plant in Indonesia.

Figure 3: Suitable geological storage regions for CO_2 storage.[6]



4. Will regulation and political barriers limit the scale-up of CO_2 storage?

Several of the countries identified above have established supportive national policies and incentives for CCS.

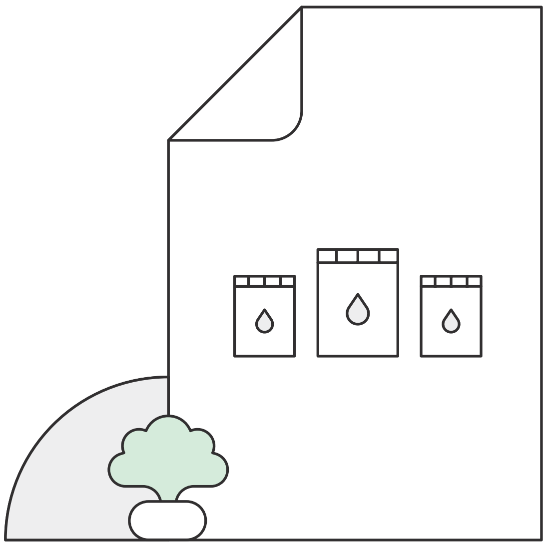
In the USA, the Infrastructure Investment and Jobs Act[9] provides over 12 billion USD for CCS[6] and related activities, including 2.5 billion USD for carbon storage validation and 8 billion USD for hydrogen hubs,[10] including blue hydrogen. Even more significantly, the Inflation Reduction Act[11] increased the value of the 45Q tax credit for each tonne of geologically stored CO_2 from 50 USD to 85 USD, which can be claimed for the first 12 years of operation.[12] This is sufficient to make many CCS projects economically viable.

The US Gulf Coast presents advantageous conditions for blue fuel production, including access to low-cost gas, established gas and CO_2 infrastructure, established ammonia production, and ready access to ports for exports. This has led to a high degree of activity in this region, making the US Gulf Coast the globally dominant area for new blue fuel production projects.[2]

Canada established a 2.6 billion CAD tax credit for CCS projects,[6] which makes grants of 50% available towards new CCS capture equipment and 37.5% towards transportation and storage equipment.[6] Under the Canadian output-based policy, if blue fuel plants sequester CO_2 with emissions below a threshold, they are eligible to receive tax credits for their reduced emissions.[13]

Regulation of CO_2 storage is established or under development in all the identified key regions. Both the USA and Canada have regulatory regimes in place for their established CCS facilities and CO_2 transport pipelines. Other countries that have established CO_2 storage licensing and government grants include Norway,[14,15,16] Denmark,[17,18,19] the Netherlands,[20,21,22] and the UK.[23,24,25] Other potential blue fuel-producing countries have made CCS a key part of the nationally determined contributions. Qatar,[26,27] United Arab Emirates (UAE),[28] and Saudi Arabia[29,30] have announced significant expansion plans for CCS. A recent report on opportunities for CCS in the Gulf Cooperation Council region[31] identified ten potential CCS hubs. Malaysia[32,33] and Indonesia[32,34,35] have both announced that regulatory regimes for CCS are under development.

Permitting of CO_2 storage sites can potentially slow the development of CO_2 storage. The time lag to develop new CO_2 storage projects is typically five or more years due to the need to fully characterize the storage site, obtain regulatory permits, and develop the engineering infrastructure. The process of obtaining storage permits can be lengthy as well. The US Environmental Protection Agency typically takes approximately 3–6 years to issue a new Class VI permit,[36] which is required for permanent CO_2 storage sites. However, the US Infrastructure Investment and Jobs Act has allocated resources to address this problem by expanding the federal Class VI permitting capability and allocating funding for states which take on primacy for Class VI permits. To date, only two US states have primacy for Class VI permits, but the Gulf Coast states of Louisiana and Texas have submitted applications for primacy and others are currently going through the process of taking on primacy for permitting.[36,37] Despite the risk of extended permitting time, areas with established oil and gas production generally have well-characterized geology, which can help to reduce the characterization and permitting time. Note that the projections for CO_2 storage in operation by 2030 reflect current expectations around permitting requirements. Overall, regulation and policy are generally favorable in the regions with the highest potential for supplying blue ammonia.



5. Will competition for CO_2 storage from other industries limit its availability for blue ammonia production?

The upcoming CO_2 storage capacity will need to be shared among industries. This cross-sector competition could limit the storage available to any single sector, such as shipping. However, it is apparent that the aggregate demand is translating into aggregate supply. Most of the expansion in CO_2 storage by 2030 is expected to come from regional CO_2 transport and storage hub projects, which serve multiple industries and capture sites, rather than serving single capture sites with dedicated storage.[6,8] These hub projects are beneficial for developing blue fuel projects. By reducing the cost per tonne of CO_2 storage, they make the construction of new blue fuel production more economically viable. In general, the presence of CO_2 capture from other industries will assist the development of blue fuel production, thereby improving the economics of CO_2 storage.

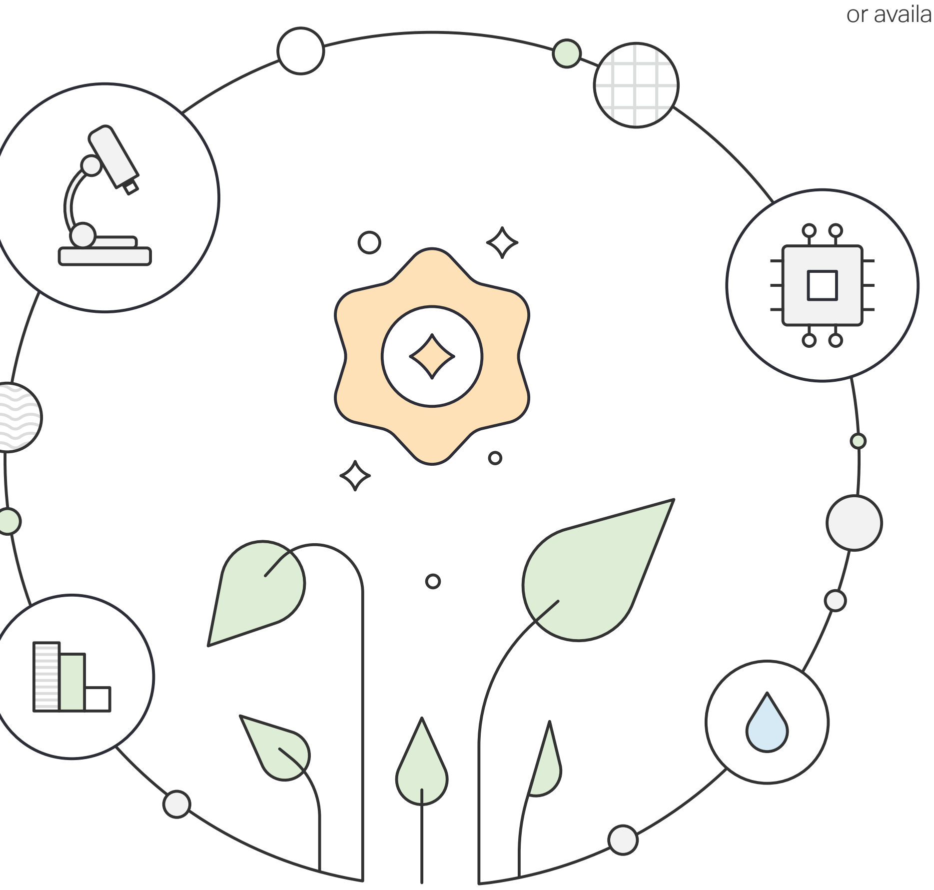
A further positive aspect is that many of the planned hubs are being developed with capacity that exceeds the requirements of currently planned capture plants,[8] allowing for additional capture plants, such as new blue ammonia production plants, to be connected in the future. Some of the hubs expected to be most relevant for blue ammonia production include the Permian basin and Houston Ship Channel (USA), Alberta (Canada), Ras Laffan (Qatar), Al Reyada (UAE), Jubail (Saudi Arabia) and Kasawari (Malaysia).

Blue ammonia plants will have the advantage of lower capture costs than most other industries. Since the cost of CO_2 capture is often the most prohibitive cost component for other sectors to implement CCS, a lower capture cost greatly reduces the risk of cross-sector competition for CO_2 storage. All standard existing ammonia plants already capture approximately two thirds of their total CO_2 generation as a high-purity CO_2, stream. capture takes place from a clean, high-pressure process stream containing around 18% CO_2[4] which is simpler and more economic than flue gas capture. This relative ease of capture, combined with the fact that CO_2 capture is built-in as a necessary cost, makes ammonia production a significant low-cost commercial source of CO_2, which is demanded by other industries such as food and beverage. Upcoming blue ammonia plants seeking to achieve 90-98% capture will implement ATR or add additional flue gas capture to a SMR. Plants designed for ATR will incur only marginal additional costs to large-scale plants and will not make CO_2 capture less economical. Therefore, ammonia plants will likely emerge as first-movers in the upcoming demand for storage.

6. Will supply chain constraints limit the availability of CO_2 storage?

The expected scale-up of CCS capacity in the next few years will demand engineering and construction capacity, labor, and specialized equipment such as high-pressure CO_2 compressors. From industry insights directly from our project partners, we explored whether these factors could limit CSS scale-up.

We found that the engineering and construction contracting companies involved in developing CCS infrastructure are, in general, those already involved with oil and gas and similar large infrastructure projects. All the main engineering contractors are aware of the potential growth in the CCS industry, and they are expanding their capabilities in this area.



There will be significant labor requirements for the construction of capture plants and CO_2 transport and storage infrastructure. As with engineering and construction companies, the technology and equipment required for CCS are similar to those of the existing oil and gas industry. As a result, for countries with existing skilled labor pools serving the oil and gas industries, minimal retraining is likely to be required for the construction of CCS projects.

The suppliers of specialized CO_2 compressors for CCS are already seeing growth in demand, which can impact lead times. However, the suppliers are aware of the projected growth in demand. They have already formulated plans to increase production capacity.[38] A carbon capture, transport, and storage, supply chain deep dive assessment carried out for the US Department of Energy in 2022[39] found that

"CCS will not be a technology concept whose deployment is at risk to material or other supply chain constraints, but it does represent a considerable opportunity for the domestic workforce and manufacturing base." As a result, we concluded that supply chain constraints should not limit the scale-up or availability of CCS in the coming years.

7. What are the expected costs for CO_2 storage?

As with other alternative fuel pathways, such as e-fuels and biofuels, the ability to impact maritime decarbonization depends not only on ramp-up but also on the likelihood of achieving low costs. To better understand the cost structure of CO_2 transport and storage, we evaluated how costs vary by location, storage type, distance to storage, and transportation type.

Our analysis suggests that the expected CO_2 transport and storage costs for 2030 range from 22 USD/t to 55 USD/t.[40] This estimate applies to transport and storage, but it excludes compression and the cost of CO_2 capture. The cost of CO_2 capture usually contributes more to cost, but it is already integrated into ammonia plant design. A similar cost range for CO_2 transport and storage has also been reported by IRENA.[41]

The lower end of the cost range represents local onshore storage combined with pipeline transport. The higher end of the cost range represents offshore storage and offshore transport. Pipelines generally provide lower cost offshore transport than ship transport, especially for larger volumes and shorter distances. However, ship transport can be competitive against offshore pipelines over longer distances. Table 1 summarizes our assessment of CO_2 transport and storage costs in 2030 by region (USD/tCO_2).[40]

Note that the costs of storage are lower than the costs of CO_2 capture processes. While the costs of CO_2 storage can vary depending on location and circumstance, pipeline CO_2 transport is likely not at risk of diminishing the business case for blue ammonia.

Table 1: Summary of costs for various CO_2 transport and storage options.

	Transport cost (USD/tonne)			Storage (USD/tonne)	
	Onshore	Offshore	Ship	Onshore	Offshore
North America	10			12	20
Europe		15	35		20
Australia	6	25	35	17	
Asia		25	35	17	

8. What are the expected costs for blue ammonia production?

Having identified the most favorable regions for blue ammonia production (see Section 3), we calculated production cost estimates for new blue ammonia production. The cost is dominated by gas prices. Hence, blue ammonia production will be concentrated in regions with access to low-cost natural gas. We applied regional natural gas costs from 2021, thereby excluding the significant distortion that took place in the gas and ammonia markets during 2022. We then assumed designing for 95% CO_2 capture, and we used the regional CO_2 storage costs analyzed above (Section 7).

Our analysis indicated that production costs for new greenfield blue ammonia production would be 480-600 USD/t, prior to any tax incentives. Current tax incentives would give US producers a significant cost advantage at around 400 USD/t. These figures include the cost of capital, operational costs, and all costs associated with CO_2 capture and storage.

9. How fast is blue production expected to develop?

Blue ammonia projects are currently progressing, with around eight million tonnes per year[2] expected to be available by 2027 to 2028. Furthermore, new projects continue to be announced regularly. The upcoming supply growth reflects policy drivers, with existing ammonia producers recognizing that an emerging market for low-carbon ammonia will present a new market opportunity beyond the traditional driver of fertilizer to accommodate population growth.

Initial blue ammonia development projects aim to meet the announced Japanese and South Korean targets for co-firing ammonia in thermal power stations. Demand from shipping and as a low-carbon hydrogen carrier is an additional incentive. Both Japan[42] and South Korea[43,44] have ambitions to import three million tonnes per year of blue ammonia by 2030 to reduce CO_2 emissions. Both countries intend to increase this consumption significantly beyond 2030. Furthermore, MMMCZCS analyses[5] indicate a rapid expansion in demand for blue ammonia as a shipping fuel from the late 2020s.

The rate of development of further blue fuel production capacity beyond 2030 will be determined by how quickly the demand for blue fuels develops. The time lag to develop new blue ammonia projects is typically 4-5 years. Therefore, the shipping industry will need to demonstrate concrete steps to adopt ammonia as a fuel to encourage new investment decisions in blue fuel production.

10. Overall outlook & recommendations

Despite the current lack of global CO_2 storage capacity, there is significant momentum in developing both CCS and blue fuel production. Dramatic growth is expected over the next few years, so even if a proportion of the planned projects become delayed or canceled, our analysis indicates that CO_2 storage is highly unlikely to constrain the availability of blue ammonia for shipping by 2030. Blue ammonia is expected to become available in significant quantities by 2027, with the potential for significant scale-up in production over subsequent years.

11. Project team

This report was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners.

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The Northern Lights facility – west of Bergen, Norway. (Credit: Equinor)

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