FOREWORD

The decision to conduct this study came in the early days of the Global Centre for Maritime Decarbonisation (GCMD). While ammonia as an alternative marine fuel was already being discussed at that time, it wasn't known whether, where, or how ammonia bunkering could be carried out safely.

The team at GCMD thus saw this study as a no-regrets move to identify the configurations and associated risks for ammonia bunkering, to assess whether these risks could be mitigated, and if so, to highlight measures for an eventual pilot. Learnings from this study would also inform and shape the development of standards for the safe transfer of ammonia during breakbulk and bunkering operations and a competency framework to prepare seafarers and operators to handle ammonia as a bunker fuel.

Quantitative Risk Assessment (QRA) required the identification of a suitable location for ammonia bunkering. Using 43 criteria across 5 categories, DNV Maritime Advisory and Surbana Jurong shortlisted two sites in Singapore where pilots involving cross-dock breakbulk and shore-to-ship bunkering could take place with minimal upfront investment. The study also looked at ship-to-ship breakbulk and bunkering at Raffles Reserve Anchorage as a third site.

Hazard Identification (HAZID) and coarse QRA were conducted at these three sites. The 400 operational and locational risks that were identified across shore and sea bunkering sites were found to be low or mitigable. Due to commercial sensitivities, we have chosen not to identify the selected land sites or publicise associated site-specific findings in this public report; these details will be released at a later stage. Central to this public report are the HAZID and coarse QRA for breakbulk and bunkering at anchorage.

This study is not meant to be exhaustive or definitive, it is meant to pave the way for GCMD's pilot to demonstrate ammonia transfer in the port waters of Singapore. Other sites that may be suitable for ammonia bunkering pilots with additional infrastructure buildout were not part of this study.

A guidebook detailing custody transfer requirements, bunkering procedures, and safety precautions, as well as a competency framework to train personnel, was developed based on the findings of this study and is part of this public report.

With this study completed, GCMD aims to conduct a proxy pilot involving the first ship-to-ship transfer of ammonia in the port waters of Singapore by end of 2023, subject to regulatory approval, to build stakeholder confidence and user competence for an eventual bunkering exercise when ammonia-fuelled ships become available.

In view of this, the competency framework has been developed into a curriculum in partnership with the Singapore Maritime Academy. The first training course that includes handling of ammonia under the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) took place in March 2023, and registration is open for the next course run.

Concurrently, we are working with Oil Spill Response Limited to develop emergency response procedures. We are submitting the report as a draft technical reference to the Standards Development Organisation of the Singapore Standards Council's Chemical Standards Committee (CSC) to help guide the safe transfer of ammonia during breakbulk and bunkering operations locally. And we have initiated discussions with organisations, such as the Oil Companies International Marine Forum, the Society for Gas as a Marine Fuel, the Society of Gas Tankers and Terminal Operators, to help shape standards for safe ammonia bunkering internationally.

The completion of this study in nine months is a testament to the immense support of willing partners across the stakeholder value chain in the maritime community. We thank the 22 Study Partners who generously contributed their knowledge and experience, and the 130 members of the Industry Consultation and Alignment Panel who provided feedback on the initial draft of this public report. We are also grateful to the numerous regulatory agencies whose inputs helped refine our analysis.

Progress is incremental. We see this report as a critical step, of many still to come, in readying the maritime ecosystem for ammonia bunkering. And it is by starting now and working together that we can successfully navigate the complexities of the energy transition.

Professor Lynn Loo
Chief Executive Officer
The Global Centre for Maritime Decarbonisation
27 April 2023

Disclaimer:
This report is for informational purposes only and was developed based on the best available knowledge, bearing in mind the commercial sensitivities of our 22 Study Partners who had graciously shared the necessary data needed for the study, and the more than 130 Industry Consultation and Alignment Panel (iCAP) members who had provided valuable feedback. The Global Centre for Maritime Decarbonisation (GCMD) makes no representation or warranty, express or implied. The report should be taken as a basis for considerations by interested parties intending to carry out ammonia bunkering, and not as a definitive recommendation.

EXECUTIVE SUMMARY

1.1 Overview

The Global Centre for Maritime Decarbonisation (GCMD) is supporting international shipping to meet or exceed the International Maritime Organization's (IMO) 2030 and 2050 goals of reducing its greenhouse gas emissions. As part of this effort, one of GCMD's focus is to identify and help close technical and operational gaps in the adoption of alternative fuels, such as green ammonia.

In January 2022, GCMD commissioned a study to define the safety and operations envelops under which ammonia bunkering pilots can be carried out in the port waters of Singapore, the world's largest bunkering hub and second largest container port.

DNV Maritime Advisory (DNV) was appointed to undertake this study. Supported by Surbana Jurong (SJ) and the Singapore Maritime Academy (SMA), this study aims to establish the basis to execute a pilot that would eventually enable the bunkering of ammonia with industry wide applicability. The DNV-led consortium consulted extensively with a GCMD-curated group of 22 study partners and obtained feedback from more than 130 Industry and Consultation Alignment Panel (iCAP) members. The consortium also had discussions with relevant regulators to help refine their analyses. The scope of the study includes:

1. Forecasting ammonia marine fuel demand to establish capacity needs in Singapore
2. Analysing and recommending feasible operating concepts for an ammonia bunkering pilot
3. Screening, evaluating, and selecting suitable sites for an ammonia bunkering pilot
4. Identifying hazards and key risks and establishing mitigation protocols for the pilot
5. Estimating total capital expenditure (CAPEX) for an ammonia bunkering pilot
6. Compiling an ammonia bunkering safety study guidebook for ammonia bunkering pilots

1.2 Ammonia bunker demand forecast in Singapore

Demand for ammonia impacts ammonia storage capacity calculations (throughput assessment), regulatory considerations, and infrastructural needs. To forecast the ammonia bunker demand in Singapore, the DNV-led consortium applied a comprehensive bottom-up and top-down approach that accounts for the probability of vessels adopting ammonia as fuel, its potential share in a ship's total energy consumption, carbon taxes, fleet growth, energy prices.

Three scenarios (optimistic, pessimistic, and realistic) were developed based on past global bunker consumption data and anticipated market conditions. The realistic scenario has ammonia comprising 10% of all marine fuels bunkered in Singapore in 2035, and rising to 37% in 2050. Given that Singapore's demand for conventional marine fuels was consistently 20% of the global marine fuel demand from 2012–2021, this study assumes Singapore's demand for ammonia as a fuel will reach a corresponding 20% of global demand for ammonia by 2045.

This projection corresponds to a total ammonia marine fuel demand of approximately 50 million tonnes (MT) by 2050 in Singapore, and a significant corresponding increase in the number of bunker vessels, port infrastructure, and storage capacity required in that same period. Therefore, regulators should consider developing a regulatory framework enabling the growth of an ammonia bunkering ecosystem and encouraging private sector investment from fuel suppliers, bunker operators, storage facility operators, and shipowners. This regulatory framework should be developed without delay, considering the time required for infrastructure buildout and competency development, and operational readiness of the bunkering ecosystem given the safety concerns around handling ammonia as a bunker fuel.

1.3 Concept selection

Ammonia must be safely transferred from producers to marine fuel suppliers, and eventually to vessels powered by ammonia bunker fuel. Based on DNV's ammonia bunker demand forecast, the consortium performed detailed technical analyses on the following modes of ammonia transfer:

1. Ship-to-ship (STS) breakbulk at an anchorage or jetty-based location
2. Shore-to-ship (SHTS) breakbulk at a jetty-based location
3. STS bunkering at an anchorage or jetty-based location
4. SHTS bunkering at a jetty-based location
5. Truck-to-ship bunkering at a jetty-based location

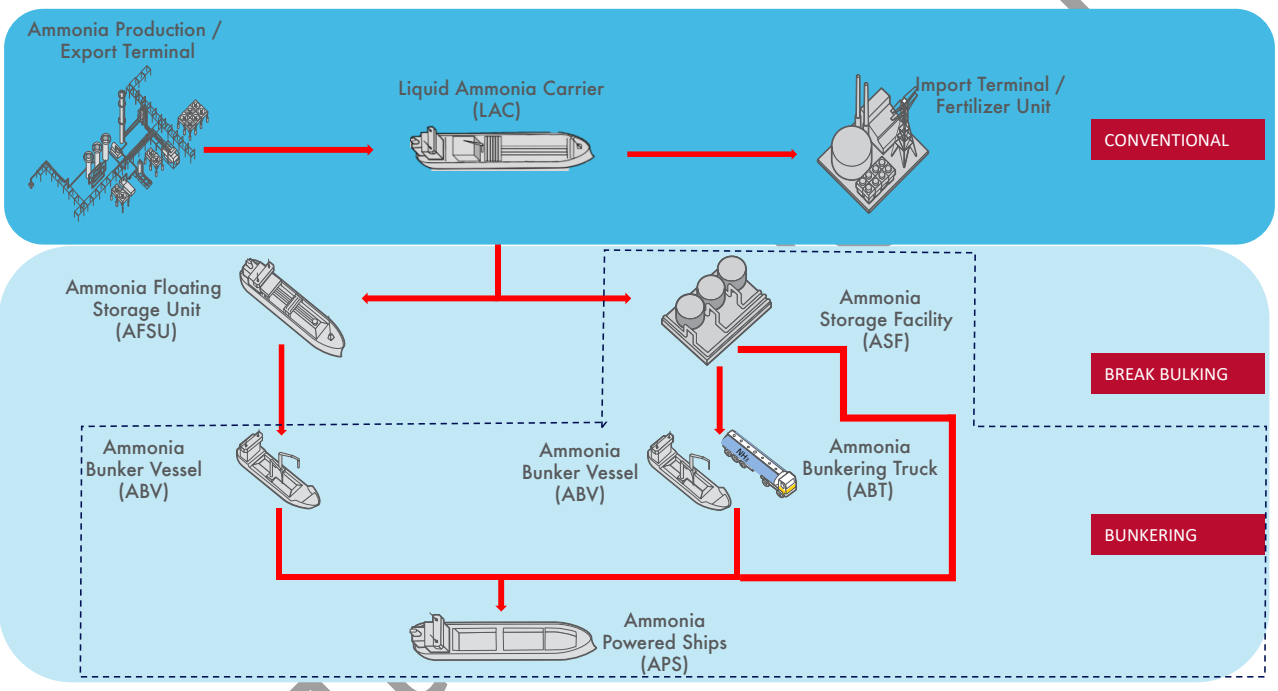

Figure 1.1 Concept for ammonia bunkering operations

Two feasible operational concepts were shortlisted for breakbulk, or fuel transfer between sources of supply or storage. Additionally, four technically feasible concepts were shortlisted for bunkering operations that involve transferring ammonia to vessels. Of the above six shortlisted operational concepts, there are five operating models the industry could pursue, the following four concepts are recommended as part of GCMD's pilot to demonstrate transfer of ammonia as a marine fuel.

1. Concept 1 - Liquid Ammonia Carrier (LAC) to Ammonia Bunker Vessel (ABV) / LAC, i.e., STS, at a breakbulk terminal in Singapore (Terminal A)
2. Concept 2 - LAC to ABV, i.e., STS, breakbulk activity at anchorage
3. Concept 3 - ABV to Ammonia Powered Ship (APS), i.e., STS, bunkering at anchorage
4. Concept 4 - Ammonia Shore Facility (ASF) to APS i.e., SHTS, bunkering at a tank terminal in Singapore (Terminal D)

These operating models include transfers from ships supplying liquid ammonia to ammonia bunkering vessels at jetty-based locations and anchorages, transfers from smaller ammonia bunkering vessels to ships that are powered by ammonia, and transfers from shore-based ammonia storage facilities to ships powered by ammonia.

1.4 Site selection study

To pilot concepts 2 and 3, the Raffles Reserve Anchorage was identified. To determine suitable land-based sites for piloting concepts 1 and 4, a detailed three-step analysis was carried out:

1. **Site screening:** Shortlist of potential sites based on a set of conditions required or beneficial for the development of ammonia transfer pilots
2. **Site evaluation:** Quantitative evaluation based on a penalty system to rank potential sites and shortlisting the two most suitable ones for pilot concept development
3. **Validation:** Alignment with relevant stakeholders to verify the suitability of these sites for the intended pilot, subject to regulatory approvals

Seven potential land-based sites, Terminals A to E and Port A and Port B, were initially identified with the help of industry stakeholders. Thereafter, these sites were evaluated quantitatively using 43 criteria across five categories (Marine, Land, Health Safety & Environment (HSE), Accessibility & Constructability). Ultimately, a jetty-based facility and a tank terminal (both based in Jurong Island in Singapore) were deemed more appropriate than the other sites for the purposes of this pilot contingent on further upfront investment requirements. The identified sites are designated in this report as Terminal A and Terminal D. Both facilities are sheltered, close to major navigation channels, equipped with adequate jetty and sea space for ship manoeuvrability. No potential disruptions to current operations were identified.

Further analysis was performed to determine the optimal combination of site and pilot concept, based on which the following combinations were selected, in addition to STS breakbulk and bunkering at Raffles Reserve Anchorage:

1. LAC to ABV / LAC, i.e., STS, breakbulk at Terminal A
2. ASF to APS i.e., SHTS, bunkering at Terminal D

Due to a lack of road access to the berth and restricted vehicle access near the storage tank area, neither site would be suitable for a truck-to-ship ammonia bunkering pilot. The tank-to-ship concept is thus assessed for pilot demonstration at Terminal D given an existing ammonia tank and supporting infrastructure, which would minimise impact on current operations and development cost. Terminal A is suitable for piloting the cross-dock breakbulk concept as it minimises the impact on current terminal operations and marine traffic.

1.5 Hazard identification and risk assessment

During the Hazard Identification (HAZID) exercise, about 400 potential risks were identified based on the four operating concepts and three selected sites (two land sites and one at anchorage). The majority of the potential risks were medium-risk and mitigable based on risk-ranking results. None of the risks identified were classified as high-risk.

A Coarse QRA was conducted to estimate the risk of injury or fatality according to the QRA Technical Guidance (Revision 9 November 2016). All four pilot concepts at the three selected sites meet the criteria set out by the Major Hazards Department's (MHD) under the Ministry of Manpower of the government of Singapore.

For a breakbulk pilot at anchorage, the safety zone ranges from 200 m to 320 m, subject to an "As Low as Reasonably Practicable" (ALARP) evaluation. For a bunkering pilot at anchorage, the safety zone ranges from 150 m to 320 m, subject to an ALARP evaluation. These values are to be taken as indicative and not absolute, as regulatory requirements for ammonia bunkering currently do not exist. Therefore, before the size of the safety zone is finalised, an ALARP evaluation by the owner/operator of the vessels should be carried out to determine "reasonableness".

The hazard identification and Coarse QRA were conducted based on pilot project requirements and do not reflect the hazards of full-scale commercial operations. Further studies will be required to address the safety of full-scale ammonia bunkering operations for the four concepts at three locations. The study is also based on the selected pilot models and available data, and risks must be reassessed for future changes to the concept design or operations.

Due to potential commercial sensitivities, the hazard identification and Coarse QRA for pilot concepts at Terminal A and Terminal D will not be made available at this stage. Nonetheless, assessments carried out for STS breakbulk and bunkering concepts at Raffles Reserve Anchorage have been included in this report to highlight the factors that have been taken into consideration for pilot concepts at Terminals A and D, with which the learnings can accelerate the operationalisation of pilots and trials.

1.6 Capital expenditure (CAPEX) estimates

Having shortlisted operating concepts, sites, and identified key mitigations required to manage risks, a Basis of Estimate (BoE) was developed. The land-side project cost was broken down into direct and indirect costs. Direct material costs include equipment, instrument, electrical, piping, and associated components. Indirect costs include construction, project management, third-party, and other preliminary costs. The cost estimate factored in costings of the relevant disciplines (for example, piping, civil, electrical, and instrumentation) and combined budgetary quotes from construction contractors, equipment suppliers (e.g., loading arms) based on Surbana Jurong's in-house cost data from similar projects.

Considering the early stage of this pilot project, a cost accuracy of approximately 40% is expected. Estimated costs are not disclosed as they are sensitive to the location of deployment, brownfield modifications, materials cost, procurement strategy, local taxes and other related parameters. However, based on the two pilot concepts at the identified land sites where the model was applied, the range of results illustrates the high dependency on the current infrastructure already invested. The cost estimates for the two land-side developments are on the order of SGD1 to SGD10 million; the differentiating primary cost drivers are the installation of mechanical equipment at Terminal A and the higher cost of project management and procurement services at Terminal D.

1.7 Guidebook for ammonia bunkering

Chapter 8 of this report is a guidebook applicable for vessels that are conducting ammonia transfers and bunkering pilots. The guidebook outlines the properties of ammonia, the requirements for custody transfer, the measuring of ammonia quantity and ammonia quality, etc. It also contains recommendations for pilot bunkering procedures and safety and competency requirements for personnel operating in the ammonia marine fuel ecosystem.

Leveraging its current experience with LNG bunkering and liquefied gas tanker courses, the Singapore Maritime Academy has included since March 2023 ammonia handling in their training courses related to alternative fuels, under the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) and other industry guidelines. This new course will be further enhanced in tandem with the development of ammonia-powered engines and vessels.

This report will be submitted as a draft technical reference to the Singapore Standards Council's Chemical Standards Committee (CSC) Technical Committee for Bunkering (Cryogenic and Gaseous Fuel) to ensure that the learnings from this GCMD study will benefit the drafting of guidelines, standards, and policies to bunker ammonia locally. This report will also be submitted to international standards development organisations at a future date to support the development of guidelines surrounding ammonia bunkering internationally.