Gateway to Green

Assessing port readiness for green hydrogen transition in India

Report / June 2025

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Indian Ports Association (IPA) was formed and registered in Delhi in 1966 under the Societies Registration Act, 1860 primarily to foster the growth and development of all Major Ports. Over the years, IPA has consolidated its activities and grown strength by strength and is considered to be a think tank for the Major Ports with the ultimate goal of integrating the maritime sector.

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Foreword

We stand at the cusp of an extraordinary transformation in global energy systems, and our ports are poised to be the catalysts of this revolutionary change. The emergence of green hydrogen represents not just an alternative fuel source, but also a fundamental reimagining of how we power our world, and India's ports are ready to lead this historic transition. The convergence of India's abundant renewable energy resources, strategic maritime position, and robust industrial capabilities presents us with an unprecedented opportunity. Our ports are evolving from traditional transit points into dynamic green hydrogen hubs, positioned to serve as the backbone of a new global energy economy. This isn't just about adapting to change — it's about driving it.

The potential before us is immense. Our eastern ports — V.O. Chidambaranar and Paradip — are strategically positioned to become powerhouses in the burgeoning East Asian market. Meanwhile, our western giants — Deendayal, Jawaharlal Nehru Port Authority (JNPA), Mumbai, and Cochin — are poised to meet Europe's growing appetite for clean energy. This geographic advantage, combined with our rapidly expanding industrial capacity, positions India to become not just a participant, but a leader in the global green hydrogen revolution. Vision without action remains merely a dream. We are committed to making substantial investments in cutting-edge infrastructure — from advanced storage facilities to state-of-the-art pipelines and refuelling stations. This infrastructure will handle not just green hydrogen, but also its derivatives like green ammonia, creating a comprehensive ecosystem that supports the entire value chain.

The transformation of our ports into green hydrogen hubs represents more than an infrastructure upgrade — it's a bold statement about India's role in shaping the future of global energy. We're not just building facilities; we're creating centres of excellence that will drive innovation, attract investment, and set new global standards for sustainable maritime operations. This report lays out our roadmap for this ambitious journey. It's a testament to our commitment to innovation, sustainability, and global leadership in the green hydrogen economy. The path ahead is clear, and the time to act is now. Together, we will transform our ports into beacons of sustainable energy, driving economic growth while contributing to global decarbonisation goals. The future of energy is green, and India's ports will be at the heart of this transformation. Join us as we embark on this exciting journey to reshape the global energy landscape.

Shri Vikas Narwal, IAS

Managing Director, Indian Ports Association

Executive Summary

Green hydrogen will play a critical role in reaching India's 2070 net-zero goal, offering energy security and economic opportunities. Promoting green hydrogen technology and infrastructure is one of the key elements of India's long-term low-carbon growth strategy.[1]

With green hydrogen and its derivatives termed as alternative fuels for the maritime sector and exports becoming an integral part of the green hydrogen economy, infrastructure readiness is essential to scaling India's green hydrogen ecosystem and seizing the opportunities it presents. India's ports can be the conduit for this shift. They have an opportunity to evolve from being mere transit points for goods to become dynamic ecosystems at the forefront of the global energy transition. The synergy between ports and the green hydrogen value chain, in particular, offers India an opportunity to accelerate its clean energy transition. Ports provide strategic advantages for green hydrogen hubs and trade, while green hydrogen boosts ports' role in decarbonisation, unlocking revenue opportunities like bunkering and refuelling.

"Ports provide strategic advantages for green hydrogen hubs and trade, while green hydrogen boosts ports' role in decarbonisation, unlocking revenue opportunities like bunkering and refuelling."

A common user infrastructure (CUI) framework will be fundamental in establishing green hydrogen facilities,[i] enabling ports to become central hubs. Emerging port hubs could serve both domestic and export markets, leveraging their proximity to industrial clusters such as fertiliser producers and refineries, presence of existing infrastructures like storage and distribution systems, access to international trade, and the captive demand from shipping and logistics operations. However, ports will need to address significant challenges, including high costs for green hydrogen and ammonia, limited pre-existing investment and business models, uncertain demand, and complexities in land acquisition and permitting.

Acknowledging these challenges, this study examines six key Indian ports — Deendayal in Gujarat, V.O. Chidambaranar (VOC) in Tamil Nadu, Paradip in Odisha, Cochin in Kerala, and Mumbai and Jawaharlal Nehru Port Authority (JNPA) in Maharashtra — to explore both the potential for repurposing existing infrastructure and the development of new assets. It assesses the suitability of repurposing gas pipelines

i. Common user infrastructure (CUI) refers to shared facilities or systems designed to be used by multiple entities or stakeholders.

and transforming liquefied natural gas (LNG) import terminals, if needed, to complement the new infrastructure that will be required to support the green hydrogen transition.

Additionally, the study outlines the new infrastructure and investment requirements needed to meet future demand for green hydrogen and ammonia at these ports while assessing the global competitiveness of the green hydrogen-based derivatives such as ammonia produced in the vicinity of these ports.

Key insights from this report with respect to port readiness for green hydrogen transition fall under three categories: a) prospects for leveraging existing infrastructure; b) investment in new infrastructure; and c) securing exports and bunkering opportunities.

Existing infrastructure, if necessary and available, can be repurposed to complement the development of new infrastructure at the ports.

To support green hydrogen projects, developing a new hydrogen pipeline network is essential. But high costs — 70%–80% from materials, labour, and construction — and challenges like securing rights of way make repurposing underutilised pipelines appealing. Decisions on blending (to be applied judiciously while mitigating associated risks; see **Box 2**, page 27) repurposing hydrogen-ready pipelines, or new construction depend on factors such as pipeline diameter, pressure, and urban proximity, and the ability to leverage existing infrastructure.

Similarly, India's LNG import terminals could be retrofitted to handle the export of green hydrogen derivatives such as ammonia. Clear cost advantage arguments are evident for repurposing LNG import terminals. Greenfield ammonia terminals with a capacity of 5 million tons per year (Mt/year) are estimated to cost between ₹20,401 crore (US$234.2 million) and ₹21,209 crore (US$243.4 million). In contrast, repurposing LNG terminals — either after or before commissioning — would cost approximately ₹14,766 crore (US$169.5 million) and ₹12,581 crore (US$144.4 million), respectively, assuming a 30-year operational lifespan for the LNG terminals. While repurposing these terminals could complement the development of new greenfield ammonia terminals, it may not always be feasible, particularly when existing consumers of LNG continue to rely on these facilities.

Optimised investment in new infrastructure, such as portside storage, will be essential in scaling up the green hydrogen ecosystem.

While existing infrastructure can be repurposed on a case-by-case basis, new infrastructure will also be required to cater to expected growth in the green hydrogen/ammonia industry. In new build-outs, storage is critical to meeting domestic production, consumption including refuelling, and export targets.

Because ammonia is primarily traded as fertiliser input,[ii] several ports already have nearby ammonia storage facilities. Cochin, Deendayal, and JNPA have a strategic advantage in supporting green hydrogen production, as they are electricity distribution licensees with established ammonia storage and handling facilities. However, additional portside ammonia storage is necessary if direct pipelines from production plants to port berths are unavailable or if plants are located farther from the port.

Although lifetime storage costs generally increase with scale, leveraging existing storage can reduce costs by avoiding additional capital expenditures. Given the high cost of new build, determining the optimal storage capacity is key to cost management. The levelised cost of storage declines significantly as capacity increases to a range of 1–1.5 Mt/y after which cost reductions from economies of scale become more gradual. Although economies of scale reduce capital expenditures initially, beyond 1.0–1.5 Mt/y costs continue to decrease only marginally. Additionally, electricity and other operational and variable costs rise proportionally with storage size, offsetting some capital expenditure savings. However, a constant tank utilisation rate can provide extra revenue from the tank itself, which will result in a net lower levelised cost.

Ports must secure both domestic and global bunkering export demand to capitalise their substantial investments.

Given the expected investment in production, transportation, and storage infrastructure, it is important for producers and port operators to assess and capitalise on competitiveness of green hydrogen/ammonia from India. East Asia, particularly Japan, Singapore, and South Korea, represents a prime market for green ammonia production due to its proximity to India's eastern coast. Anticipated production volumes from ports like VOC and Paradip are well aligned to supply significant volumes of green fuel to these nations. Moreover, producing at India's East Coast ports is competitive with production at other hubs, such as Egypt and Australia, primarily due to government incentives, India's renewable resources, and shorter transportation times. However, it is worth noting that overall production costs in Australia could be lower, due to the country's Hydrogen Production Tax Incentive, introduced in May 2024.

For the western ports of Deendayal, JNPA, Mumbai, and Cochin, the European Union (EU) is a promising market. The EU aims to import 10 million tons of green hydrogen by 2030, and India is well positioned to fulfil a significant portion of this demand.

ii. Ammonia is an input for the majority of fertilisers produced in India, especially in urea, diammonium phosphate, etc.

India can export green ammonia to Rotterdam at competitive costs compared to other green hydrogen-exporting nations like Namibia and Egypt, making imports from India particularly appealing for the EU. Although transportation costs are also an important factor, they can be offset by India's competitive renewable energy prices.

Recommendations

Accelerating ports' readiness as green hydrogen hubs requires sustained and collaborative efforts to facilitate land availability, stimulate demand, develop infrastructure, foster international partnerships, and encourage active investments.

To fully realise the potential of ports as green hydrogen hubs, it is crucial to prioritise strategic CUI improvements and cultivate global collaboration. Five key areas of recommendation for enhancing port infrastructure to support the development of green hydrogen hubs are summarised in **Exhibit ES1** with details in section 5.

Exhibit ES1 Recommendations for preparing port infrastructure for a green hydrogen hub

Key Focus Areas	Recommendations
Facilitate Land Availability	Ensure that sufficient land parcels in and around ports are available and accessible for green hydrogen projects and related industrial and infrastructure development. • Establish long-term leasing programmes by introducing state-backed long-term leasing initiatives, similar to Gujarat's model of offering 40-year leases at competitive rates. • Designate land for end-use industries by setting aside allocated parcels for green hydrogen offtakers to develop an integrated green hydrogen system. • Create a tiered land allocation strategy that prioritises green hydrogen production facilities, end-user industries, and related facilitators.
Map and Facilitate Demand Creation	Map and facilitate demand for green hydrogen and its derivatives domestically (within and around the port) and internationally to drive the initial offtake and market creation. • Conduct demand mapping analysis to estimate green hydrogen volumes and identify offtake sectors, informing infrastructure sizing and requirements. • Facilitate global demand generation opportunities and target international markets to initiate demand creation measures and strengthen production capacity. • Facilitate local demand creation by working with industrial stakeholders to co-locate projects with green hydrogen production facilities.
Invest in Backbone Infrastructure	Establish dedicated CUI such as intra-port pipelines, storage units, electricity transmission and distribution, water and CO_2 pipelines, etc. to ensure that the infrastructure at port is ready to support exports and domestic hub development. • Establish a hub-based CUI model based on projected demand and production. • Support bunkering and export facilities including appropriately sized storage infrastructure to align with forecasted demand. • Install intra-port transport pipelines for green hydrogen and carbon dioxide to streamline the transportation process for green molecules and support carbon management initiatives. • Ensure water supply and develop desalination facilities, which could be scaled for community use in water-scarce areas. • Aggregate energy demand for green power by partnering with distribution companies (DISCOMs) and independent power producers to pool demand from existing port industries.

Exhibit ES1 Recommendations for preparing port infrastructure for a green hydrogen hub (continued)

Key Focus Areas	Recommendations
Transition in Role of Ports	Move beyond being enablers by becoming active investors, starting with joint pilots to demonstrate the viability of green hydrogen and derivatives projects. • Identify and prioritise high-potential partnership for joint venture opportunities to co-invest in infrastructure and thereby maximise technical expertise and resource allocation. • Initiate joint pilot projects with industry partners to test the viability of green hydrogen and hydrogen derivatives production, storage, and export at the port. • Implement hydrogen bunkering and refuelling pilots following the example of ports like Singapore. • Establish green hydrogen industrial parks within port premises, where infrastructure, land, and utilities are jointly managed.
Foster International Collaboration	Promote international partnerships and collaborations with global ports or industries to integrate ports into the global green hydrogen and derivatives supply chain. • Establish green corridors, like the Port of Singapore creating a green corridor between Singapore and China in 2024. • Create and integrate supply chains, taking inspiration from the collaborative agreements between the Port of Rotterdam and Spanish giant Cespa. • Promote technology transfer with technological partners to create global standardisation as seen with the Ulsan Port involving major South Korean stakeholders on the creation of an ammonia bunkering industry.

RMI graphic.

Introduction

India has set an ambitious target to achieve net-zero carbon emissions by 2070, aligning with global efforts to combat climate change.[2] The nation's strategy focuses on transitioning to clean energy, enhancing energy efficiency, and reducing reliance on fossil fuels. Hydrogen, particularly green hydrogen produced using renewable energy, is poised to play a pivotal role in this transition.[3] It serves as a versatile and sustainable energy carrier while enabling decarbonisation across hard-to-abate sectors. By leveraging its vast renewable energy resources, India aims to become a global hub for hydrogen production and export, fostering energy security and economic growth while also advancing its net-zero objectives.

Ports have evolved beyond serving merely as transit points for goods to providing dynamic ecosystems at the forefront of the global energy transition.[4] In addition to driving economic growth, facilitating international trade, and fostering regional development, ports are increasingly transforming into clean energy hubs.[5] With a legacy of handling energy molecules as importers or exporters worldwide, ports possess a strong foundation in terms of infrastructure and capabilities needed to support both domestic and global energy supply chains.[6] This also positions them as pivotal hubs for the production, distribution, storage, and consumption of new energy and feedstock molecules like green hydrogen and its derivatives.[vi, 7]

The evolving synergy between ports and green hydrogen presents an opportunity for India to accelerate its clean energy transition. Ports and green hydrogen share interdependencies that can drive the growth of both industries. While green hydrogen production need not be exclusively concentrated near ports, the infrastructural capabilities of ports and the co-location of industries in their vicinity offer a competitive advantage for establishing domestic hubs and enabling trade. In return, green hydrogen positions ports at the forefront of decarbonisation efforts, unlocking additional revenue opportunities such as bunkering and refuelling by facilitating the handling and distribution of green hydrogen and its derivatives.

> **"Ports are transforming from transit points into dynamic clean energy hubs, leveraging their infrastructure and expertise to drive the global green hydrogen economy."**

vi. Feedstock here refers to natural gas

Ports are strategically positioned to become hubs for green hydrogen production and trade, leveraging their existing infrastructure, such as ammonia storage tanks, pipelines, and liquefied natural gas (LNG) import terminals. These facilities can be partially repurposed to support hydrogen and its derivatives. However, the potential for repurposing is limited, creating both need and opportunity for ports to develop new, dedicated infrastructure to enable a large-scale hydrogen value chain. By fostering infrastructure development while capitalising on the potential of existing assets, ports can serve as catalysts for a faster and more cost-effective transition to green hydrogen.

Globally, ports are making significant strides in integrating green hydrogen infrastructure. Export hubs like Walvis Bay in Namibia and Salalah in Oman are investing in water desalination facilities and hydrogen pipelines, essential for large-scale hydrogen exports. Oman has established “InfraCo” to oversee development and completion of shared hydrogen infrastructure by 2029, while Namibia is conducting market soundings to explore shared infrastructure.[8] Meanwhile, importing nations like those in the EU are also advancing, with the Port of Rotterdam expanding its ammonia import terminal and building dedicated hydrogen pipelines to support transport and distribution.[9]

India is also positioning its ports at the mainstream of the green hydrogen transition. In May 2023, the Ministry of Ports, Shipping, and Waterways (MoPSW) launched the Harit Sagar Green Port Guidelines, aimed at decarbonising the maritime sector and contributing to India’s goal of achieving net-zero emissions by 2070.[10] These guidelines set ambitious targets, such as establishing green ammonia bunkering and refuelling facilities at all major ports by 2035.[11]

To support this initiative, leading ports like Deendayal, Paradip, and V.O. Chidambaranar (VOC) are being developed to become key export hubs for green hydrogen, ammonia, and methanol by 2030.[12] These ports have already allocated approximately 4,500 acres to more than 19 developers expressing interest in developing green hydrogen complexes.[13] These projects are expected to bring in investments of up to ₹1.5 lakh crore (US$172 billion), and more are in the pipeline, making ports a conduit for green hydrogen-based investment, aimed at harnessing export opportunities.[14]

In addition to their export potential, ports can support production facilities capable of meeting demand through hybrid consumption models, combining domestic industrial use with international trade. For instance, European ports like the Port of Rotterdam have established agreements to facilitate the import of green molecules from exporters such as Australia and Mauritania, thereby aggregating demand while encouraging local production for regional consumption.[15] Ports and their surrounding areas often host clusters of energy-intensive industries, including steel, cement, and chemicals, making them ideal for fostering aggregated demand for green hydrogen and its derivatives. This presents a dual opportunity: ports and their vicinities can serve as both supply centres for green hydrogen exports and consumption hubs for domestic industries transitioning to cleaner energy sources.

Despite the immense potential of Indian ports to become green hydrogen hubs, several challenges and knowledge gaps remain unresolved. There is a need for a comprehensive assessment of the infrastructure and investment required to support green hydrogen production, storage, and distribution.

This includes analysing the technical and economic feasibility of integrating green hydrogen into port operations and handling of different green fuels, such as green hydrogen itself, methanol, and ammonia. Furthermore, the role of ports as hydrogen producers, distributors, or consumers needs to be clearly defined, and potential operational and financial hurdles must be addressed for effortless creation of green hydrogen ecosystems.

Understanding market demand, developing offtake agreements, and establishing logistical frameworks for hydrogen distribution will be crucial for ports to capitalise on the growing green hydrogen market. By addressing these challenges via preparatory actions, ports can unlock their full potential as green hydrogen hubs, contributing to both domestic energy needs and international trade.

Enablers and challenges for ports to lead development of green hydrogen hub

Ports are more than just facilitators in the green hydrogen value chain; they are dynamic ecosystems capable of anchoring production, facilitating demand aggregation, and enabling seamless connectivity between domestic consumption and global export markets. By leveraging their locational advantages, presence of industrial clusters and infrastructure in the vicinity, ports can accelerate the green hydrogen transition. Several key opportunities are summarised below.

Proximity to industrial clusters

Industries such as steel production, refining, and chemical processing are often strategically clustered around major ports.[16] These industrial hubs, with access to both land and maritime transportation networks, position ports as ideal centres for developing green hydrogen value chains.[17]

Existing infrastructure

Ports already possess robust logistics, supply chains, storage, and distribution systems that can be adapted to support the green hydrogen value chain.[18] With upgrades, these facilities can handle some of the early small-scale projects to establish the business case for ports.

Ability to manage land

Ports often operate as landlords offering land parcels to industries.[19] This allows ports to also allocate land parcels for emerging green hydrogen projects as they have done in Deendayal, Paradip, and VOC.[20] Additionally, ports are often accompanied by Special Economic Zones that allow industries to establish their operations near port infrastructure.

Experience in trading and managing energy commodities

Many ports already handle significant volumes of energy commodities like crude oil, LNG, and ammonia.[21] This experience provides the foundation for handling hydrogen, including the necessary safety protocols, regulatory frameworks, and operational know-how. Ports such as Mumbai and Cochin are already major marine fuel bunkering hubs in the Indian subcontinent and have the potential to be transformed into hubs for green fuel bunkering.[22]

Offering captive demand and emission reduction potential

In addition to supporting industrial hydrogen applications, ports have the opportunity to decarbonise their own operations and logistics. By adopting hydrogen fuel cell electric vehicles for heavy-duty transport, such as trucks, boats, and other port machinery, ports can offer an additional captive market for green hydrogen.[23] According to India's submission to the United Nations Framework Convention on Climate Change (UNFCCC), the maritime sector, including international fleet bunkering, emitted over 3 million tonnes of CO_2e, equivalent to 1 million metric tonnes of oil.[24] Adopting green hydrogen and derived zero-emission fuels like green ammonia and green methanol can decarbonise port operations, including intra-truck and global shipping movements, accelerating ports towards net-zero emissions.[25] This transition not only helps mitigate fuel-related emissions but also opens up new revenue streams through bunkering of zero-emission fuels, supporting both domestic consumption and exports.

Key challenges include infrastructural limitations, complex regulatory landscapes, and the need for substantial project investments. Furthermore, integrating hydrogen into existing operations demands the establishment of new safety protocols, advanced transmission and storage solutions, and robust stakeholder coordination. Addressing these challenges is crucial for ports to harness the benefits of the green hydrogen economy and contribute to a broader energy transition. Some barriers are detailed below:

Traditional role of ports

Scaling up green hydrogen infrastructure and access to competitive financing is essential for developing costly projects like renewable energy production and hydrogen production and transport systems. Ports would need to shift away from their traditional role of focusing on infrastructure provision. This will signal the need for growth in technical capacity and changes in their business model to enable the creation of large-scale green hydrogen hubs.

High capital costs of infrastructure

Although storage units for hydrogen/ammonia already exist in some ports, their current handling capacity is minimal compared with the projected future demand.[26] Transitioning to green hydrogen will require significant investment in new infrastructure, such as storage facilities and specialised transportation networks. These needs, coupled with the high up-front capital costs, present major challenges as funding such large-scale projects requires both public and private investment. The high costs also increase the financial risk, making it difficult to secure investment without strong government support and policy incentives.[27]

Limited and uncertain market demand for green hydrogen

Although the green hydrogen ecosystem is emerging, the actual market demand and timeline for adoption remain uncertain. Although there have been several high-level announcements and pilot projects, long-term offtake agreements are rare.[28] This uncertainty makes it difficult to plan and scale port infrastructure, as demand projections directly influence the size and scope of the required facilities. High-level production capacities and unclear utilisation targets for the industries blur the market dynamics of the industry.[29] Without clear market signals, there is a risk of creating stranded assets or underutilising infrastructure, which could lead to financial losses and decreased investor interest.

Complex land acquisition and permitting

The land acquisition process is often time-consuming due to complex legal frameworks, ownership disputes, and bureaucratic delays. Furthermore, obtaining the necessary permits for construction and operation can be a lengthy process. These regulatory hurdles can slow down the pace of green hydrogen infrastructure development, leading to missed opportunities in a rapidly evolving global market.

Risk translating to high cost of financing capital

The above-mentioned risks translate into a higher weighted average cost of capital (WACC) for the projects, increasing the overall cost of the project.[30] Elevated WACC signifies that investors require higher returns to offset the perceived risks, making it more expensive for developers to secure financing.[31] Without clear guarantees on returns or proven business cases, many investors will remain cautious. This hesitancy exacerbates the funding gap, further increasing the overall cost of projects and slowing their implementation.

Scope of the study

While acknowledging the challenges highlighted, this report aims to bridge the gaps in knowledge and action items by providing valuable insights to key stakeholders — including port authorities, policymakers, investors, developers, and consumers. Using extensive analyses and global case studies, the report offers valuable insights and lessons that Indian ports can leverage as they embark on their journey toward green hydrogen infrastructure readiness. **Exhibit 1** on the next page provides an overview of the scope of the study.

The study examines the new infrastructure and investment requirements to meet the volume-handling goals ports are anticipating in future. Additionally, it compares costs and benefits of repurposing existing port infrastructure, such as gas pipelines for hydrogen blending and converting LNG import terminals into ammonia export hubs with the investment needed for new infrastructure. The report also delves into the production cost economics and the infrastructure and investment requirements.

Finally, the report provides strategic recommendations for transforming Indian ports into key players in the global green hydrogen transition, ensuring that they can meet both domestic and international demand, and fully realise their role as catalysts in the clean energy economy.

The report seeks to complement the Harit Sagar Guidelines and the Amrit Kaal 2047 vision by positioning ports as hubs for green hydrogen-related activities. With VOC, Paradip, and Deendayal ports already designated as green hydrogen hubs, and more expected to follow, the report lays a foundation by evaluating infrastructure and investment requirements and analysing the cost competitiveness of green hydrogen production at these ports.[32]

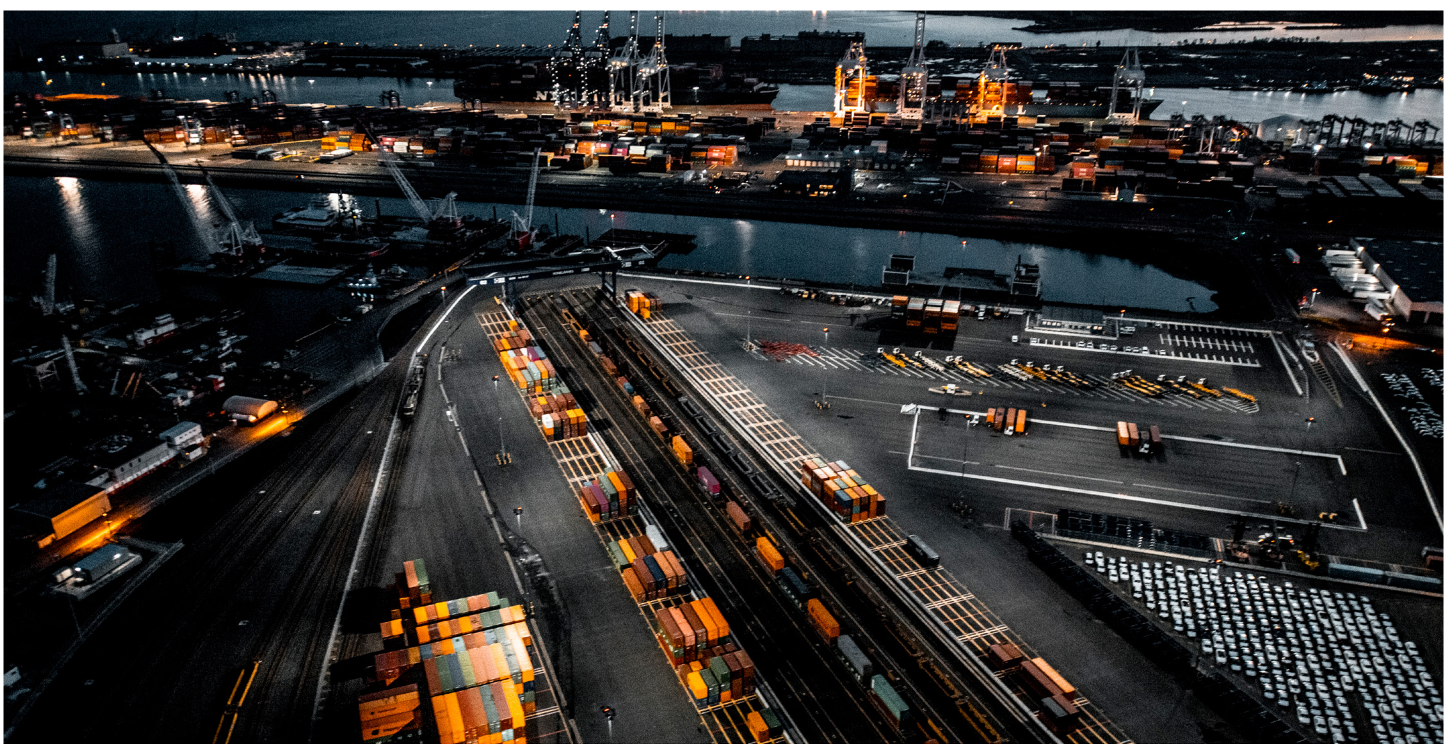
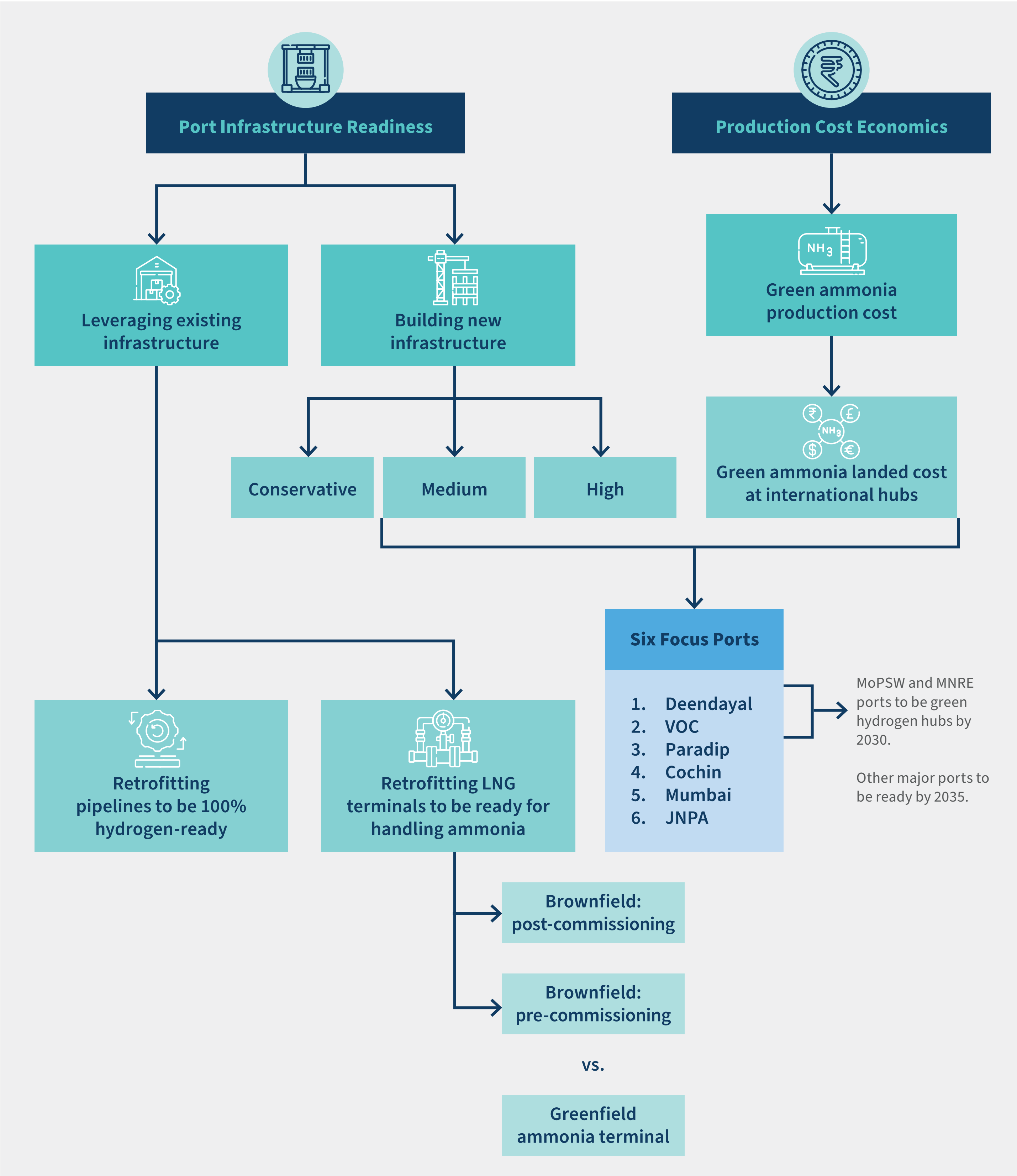


Exhibit 1 Scope of the study



RMI graphic.

Framing the narratives

"Port infrastructure readiness" is a nuanced and variable concept shaped by different conditions and is not easy to define. To address this complexity, a scenario-based approach provides a practical framework for analysis. While this study does not aim to define port readiness conclusively, it highlights the key factors necessary for ports to play a central role in the green hydrogen transition.

The study on infrastructure readiness is divided into two parts:

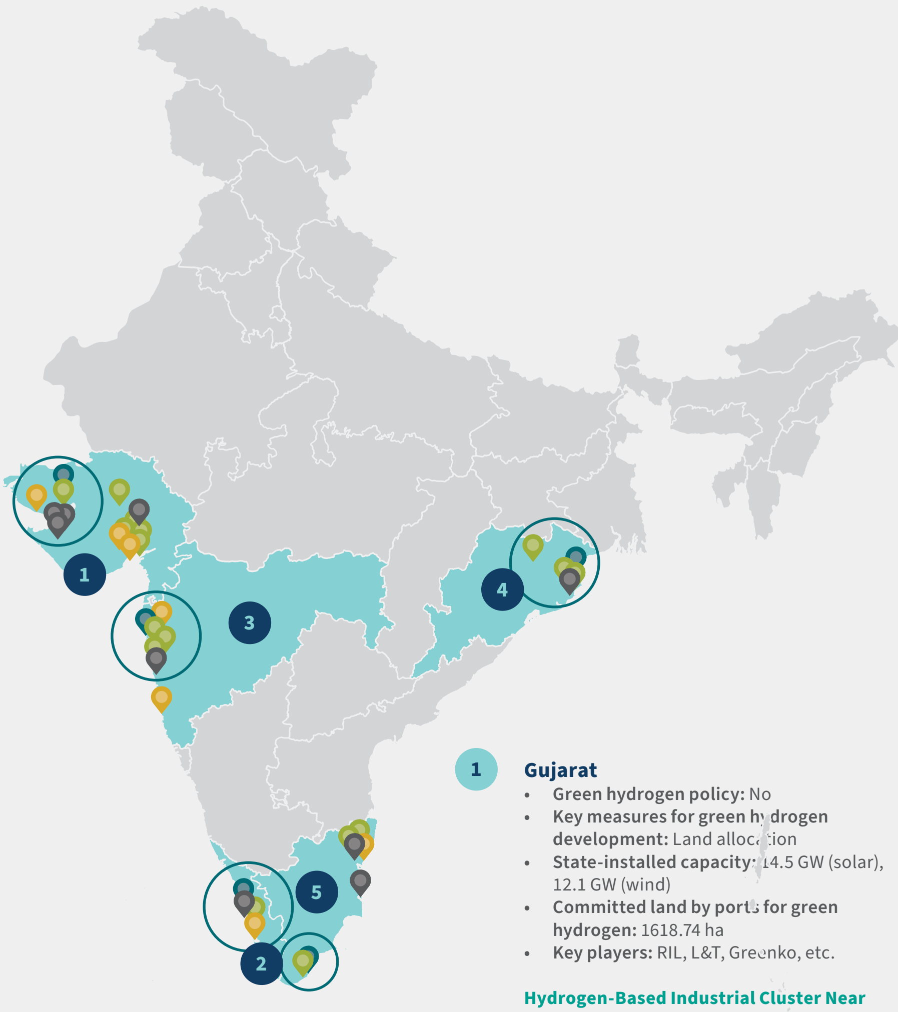
A. **Leveraging existing infrastructure:** This includes assessing current electricity supply systems and the ability to integrate renewables, existing ammonia storage facilities and pipelines, as well as LNG handling terminals that can be scaled or repurposed for handling green hydrogen and its derivatives in the future.

B. **Building new infrastructure:** The scale of the green hydrogen transition requires more than just repurposing of existing facilities. The study evaluates the requirements for new ammonia storage units at ports to avoid infrastructure bottlenecks.

Collectively, the existing and new assets described here are classified as common user infrastructure (CUI) for the ports. CUI represents the shared facilities, networks, and systems that support the entire green hydrogen value chain from production to end use. These are not proprietary assets for individual companies or projects but are designed to serve multiple producers, consumers, and sectors.

The focus is on six key ports identified as critical to India's green hydrogen ambitions: Deendayal in Gujarat, VOC in Tamil Nadu, Paradip in Odisha, Cochin in Kerala, and Mumbai and JNPA in Maharashtra.

Exhibit 2 Characteristics of ports and states evaluated in this study



3 Maharashtra
- **Green hydrogen policy:** Approved
- **Key measures for green hydrogen development:** Electricity-based incentives
- **State-installed capacity:** 7.1 GW (solar), 5.2 GW (wind)
- **Committed land by ports for green hydrogen:** None announced
- **Key players:** ReNew, NTPC Green Energy, AVAADA, etc.

Hydrogen-Based Industrial Cluster Near Mumbai/JNPA Port
- **Refineries:** HPCL (9.5 Mt/y), BPCL (12 Mt/y)
- **LNG terminal:** None
- **Fertiliser units:** RCF Thal (urea:1.7 Mt/y), RCF Trombay (0.33 Mt/y, Deepak Fertilizers (0.6 Mt/y)

4 Odisha
- **Green hydrogen policy:** Yes
- **Key measures for green hydrogen development:** Electricity-based incentives
- **State-installed capacity:** 0.5 GW (solar), 0.1 GW (wind)
- **Committed land by ports for green hydrogen:** None announced, but land allocation initiated
- **Key players:** ReNew, Welspun New Energies, ACME, etc.

Hydrogen-Based Industrial Cluster Near Paradip Port
- **Refineries:** IOCL (15 Mt/y)
- **LNG terminal:** None
- **Fertiliser units:** Paradeep Phosphates (DAP:1.2 Mt/y), IFFCO (DAP: 1.5 Mt/y)

1 Gujarat
- **Green hydrogen policy:** No
- **Key measures for green hydrogen development:** Land allocation
- **State-installed capacity:** 14.5 GW (solar), 12.1 GW (wind)
- **Committed land by ports for green hydrogen:** 1618.74 ha
- **Key players:** RIL, L&T, Greenko, etc.

Hydrogen-Based Industrial Cluster Near Deendayal Port
- **Refineries:** None
- **LNG terminal:** Mundra (5 Mt/y)
- **Fertiliser units:** IFFCO (DAP: 1.2 Mt/y)

5 Tamil Nadu
- **Green hydrogen policy:** In progress
- **Key measures for green hydrogen development:** Land allocation
- **State-installed capacity:** 8.8 GW (solar), 10.8 GW (wind)
- **Committed land by ports for green hydrogen:** 202.34 ha
- **Key players:** ACME, NGEL, etc.

Hydrogen-Based Industrial Cluster Near VOC Port
- **Refineries:** None
- **LNG terminal:** None
- **Fertiliser units:** SPIC (0.62 Mt/y)

2 Kerala
- **Green hydrogen policy:** In progress
- **Key measures for green hydrogen development:** Hub-based model initiated
- **State-installed capacity:** 1.1 GW (solar), 0.06 GW (wind)
- **Committed land by ports for green hydrogen:** None announced
- **Key players:** ReNew

Hydrogen-based Industrial Cluster Near Cochin Port
- **Refineries:** BPCL (15.5 Mt/y)
- **LNG terminal:** Kochi (5 Mt/y)
- **Fertiliser units:** Fertilizers and chemicals Travancore Limited (0.9 Mt/y)

Port | LNG Terminal | Fertiliser Plant | Refinery

RMI graphic.

The report also provides an overview of global competitiveness of the green hydrogen produced at these facilities. We benchmark the green ammonia landed costs against those from competitor exporters in the Indo-Pacific region such as Australia, the Middle East, and North Africa, which also have the potential for producing green ammonia at competitive prices due to their abundant renewable energy resources, favourable regulatory environments, and established trade routes.

The study scenarios within each section evaluate the economic viability, infrastructure needs, and investment requirements across different timelines and scales of development. These scenarios provide a comprehensive understanding of the potential for Indian ports to evolve into global green hydrogen hubs catering to both domestic consumption and international trade demands.

Box 1 Comparing green ammonia and methanol

A boundary condition for this study is the focus on green ammonia over methanol. Ammonia and methanol both are emerging as promising green fuels in the transition to a sustainable energy future. But more attention has been placed on green ammonia at the moment due to its ease of production compared to methanol. In terms of production, green ammonia needs a limited array of feedstock, which can be easily procured, while production of methanol requires biogenic carbon dioxide to make it truly green, making it more difficult and expensive to produce. Methanol, however, is easier to handle than ammonia due to ammonia's toxicity.

Exhibit 3 **Comparison between green ammonia and methanol on technical and handling parameters**

	Green Ammonia	Green Methanol
Production Scenario	Produced using nitrogen and green hydrogen via renewable-powered Haber-Bosch process	Synthesised from green hydrogen and captured CO_2 or biomass, requiring a catalytic conversion process
Costs	Costs vary based on the renewable energy used in hydrogen production	Costs vary based on CO_2 source (captured or biogenic) and the renewable energy used in hydrogen production
Advantages	Carbon-free combustion; high energy density; scalable for shipping and grid-scale energy storage	Carbon-neutral when using captured CO_2; liquid at room temperature; compatible with existing fuel infrastructure
Handling	Toxic and corrosive, and requires stringent storage protocols due to its gaseous form and high vapor pressure	Easier to handle as a liquid, with lower toxicity and flammability compared to ammonia
Constraints	Safety risks due to toxicity and potential for leaks; requires significant infrastructure upgrades for adoption	Dependency on sustainable CO_2 sources
Scalability	Large-scale production and global shipping networks already exist, though adaptation for fuel use is needed	Emerging production networks are adaptable to local CO_2 sources and renewable energy availability

RMI graphic. RMI compilation.

This report focuses on green ammonia because none of the six ports being considered plan to handle green methanol as of today based on primary data collection from port authorities and limited to no publicly known green methanol project announcements within close proximity of the focus ports (see section titled *Assessing scale of investment,* page 40 for more details). If ports are able to access green methanol, it can be strategic to incorporate this fuel into their future bunkering fuel mix.

Furthermore, the scope of the study goes beyond zero-emission fuel and extends to the prospect of shared molecule and infrastructure to support the fledgling green hydrogen economy.[iii] This is also where green ammonia has an edge, given its synergy with the fertiliser sector and the emergence of international trade in green hydrogen in the form of green ammonia.

iii. Zero-emission fuels for the maritime sector are energy sources that do not produce greenhouse gas (GHG) emissions during their production, storage, transportation, or use in ship propulsion. Examples include green hydrogen and derivatives such as green ammonia, green methanol, and biofuels.

Harnessing Existing Infrastructure for the Green Hydrogen Economy

Leveraging existing infrastructure at ports offers a unique opportunity to accelerate the growth of the hydrogen economy. By repurposing assets such as renewable energy distribution systems, existing ammonia storage facilities and gas infrastructure like pipelines and LNG import terminals, ports can support initial green hydrogen projects for the domestic supply and export of green ammonia and other derivatives.

Repurposing gas infrastructure

Gas infrastructure is often strategically located near ports and industrial hubs, making it ideal for adaptation to hydrogen distribution.[33] Repurposing existing pipelines, storage facilities, and distribution networks for hydrogen can reduce the need for entirely new infrastructure, lowering costs and speeding up hydrogen supply chain development.

However, this transition is more challenging than it may seem. Hydrogen's unique properties — such as lower density and the risk of embrittlement[iv] — require significant upgrades to materials, equipment, and safety systems.[34] Hydrogen's higher susceptibility to leaks means that each component of the existing

iv. Hydrogen embrittlement is a phenomenon where hydrogen atoms diffuse into materials, particularly metals, and compromise their mechanical properties, leading to cracking or failure under stress. This poses a significant challenge to the widespread adoption of hydrogen technologies, especially in storage and transportation.

infrastructure must be thoroughly analysed for technical limitations, including pipeline compatibility, leakage risks, and the need for enhanced monitoring systems.

In the early stages, hydrogen can be blended with gas in existing pipelines, allowing for gradual decarbonisation while scaling up infrastructure.[35] However, this is dependent on the end use of the blend due to variations with respect to different end-user industries and the need of a deblending system.[36] This phased approach offers a practical path toward a hydrogen-based energy system.

Repurposing India's gas infrastructure — especially pipelines and LNG terminals — offers a cost-effective way to connect hydrogen production hubs with demand centres. This approach mirrors efforts like the European Hydrogen Backbone (EHB), where 33 operators are converting a portion of Europe's 2,00,000 km gas pipeline network for hydrogen.[37] By 2040, 59% of the EHB's projected 57,662 km hydrogen network will come from repurposed pipelines with an estimated total cost of the backbone reaching US$87.3–US$156 billion.[38]

In this context, we explore the potential of repurposing India's gas infrastructure with a specific focus on converting LNG terminals into ammonia export hubs to facilitate the green hydrogen transition.

Pipeline adaptation for green hydrogen uptake

India consumed more than 68,700 million metric standard cubic metres (MMSCM) of natural gas in 2023, with the fertiliser and gas distribution systems being the largest consumers.[39] Of this, 46% was primarily imported from Qatar, the United Arab Emirates, and the United States — at a cost of about ₹1.37 lakh crore (US$15 million).[40] To meet its growing energy demands and pursue the "One Nation, One Gas Grid" vision, India is expanding its gas pipeline infrastructure.[41] Currently, over 24,723 km of gas pipelines are operational, with a capacity of 542 MMSCM per day, and an additional 10,860 km are under construction.[42] The target is to extend this network to 34,500 km by 2025.[43]

Hydrogen can be transported through pipelines in two ways: either blended with natural gas or as pure hydrogen. Blended hydrogen is suitable for industries like steel and city gas distribution, while sectors such as fertilisers, refineries, and chemicals require pure hydrogen or ammonia.

While blending of green hydrogen with natural gas (see **Box 2,** page 27) can be a stop gap option, prioritising hydrogen-ready natural gas and dedicated hydrogen pipelines can support infrastructure to be in place for hydrogen distribution while serving for natural gas ecosystem transition.

New pipelines are nearly four times more expensive than repurposed ones, primarily due to material capital expenditures (capex) (steel), labour, and other construction-related charges, which account for 70%–80% of transmission pipeline and compressor costs (see **Exhibit 4,** next page).[44] Additionally, securing the right of way for new pipelines can be challenging, especially for smaller networks, making repurposing pipelines an attractive option.[45]

Several factors, including pipeline diameter, pressure, and proximity to urban areas, must be considered when planning pipeline routes.[46] There is no one-size-fits-all solution for adapting existing natural gas pipelines, and decisions must account for end-use requirements, construction, operation, and cost considerations.[47] This will determine whether blending, repurposing for 100% hydrogen, or constructing new pipelines is the most appropriate solution.

Repurposing is preferred where pipelines are underutilised in terms of transporting capacity or parallel pipelines exist where established rights of way and pre-approved permits can be leveraged, reducing costs and speeding up timelines.[48] However, if repurposing is technically unfeasible or natural gas demand persists, constructing new hydrogen pipelines alongside existing gas infrastructure can be beneficial. For example, the EHB, which includes 46% large, 42% medium, and 12% small pipelines,[49] expects to repurpose 59% of its network, resulting in a levelised cost of ₹10.26–₹19.59 (US$0.12–US$0.22) per kg/1,000 km, allowing hydrogen to be transported cost-efficiently over long distances across Europe.[50] While the creation of the backbone similar to the EHB could be pivotal in connecting producers to end-users across India, the strategy should be followed with its own caveats and extensive analysis must be conducted on the current system before taking a call on repurposing or building new pipelines for such a backbone.

Exhibit 4 Cost comparison for new and repurposed pipelines

		Capex (INR crores/km)	Pipeline capacity (GW H_2, LHV)	Compression capacity (MW/1000 km)	Compression Capex (INR crores/km)	Pipeline and Compression Costs (INR crores/km)
20” pipelines	New	16.8	1.2	26	0.9	17.7
	Repurposed	5.0				5.9
36” pipelines	New	29.9	4.7	93	3.7	33.6
	Repurposed	5.9				9.6
48” pipelines	New	41.1	16.9	434	15.8	56.9
	Repurposed	8.2				24.0

Note: Pipeline capacities are taken at 100% design capacity; 20" and 36” pipelines are assumed to operate at 50 bar while 48” pipelines operate at 80 bar (common natural gas pipeline configurations in Europe).
RMI graphic. RMI compilation based on International Energy Agency (IEA)[51] **Source:** International Energy Agency (IEA), **https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-e8e626a11c4/GlobalHydrogenReview2022.pdf**

Box 2 Blending hydrogen into the natural gas pipelines

Blending hydrogen into natural gas pipelines is being considered by various stakeholders in India including the state and national government agencies.[52] There are various challenges — uncertainties around hydrogen's impact on pipeline materials due to the small size of the hydrogen molecule and natural gas — hydrogen composition balance complicates the process.[53] Ongoing research is crucial to establishing standards for the safe blending of hydrogen in pipelines. Along with standards, a section-by-section analysis of pipeline infrastructure needs to be undertaken before suggesting/implementing blending of hydrogen.

Retrofitting components of existing pipelines based on hydrogen blending percentages, as shown in **Exhibit 5,** next page, is essential for the utilisation of natural gas infrastructure for blending. While the costs of retrofitting are relatively minor when compared to repurposing them for 100% hydrogen, certain capital expenditure increments are notable; for instance, retrofitting gas turbines increases capital expenses by almost 10% while retrofitting compressors would cause a capital expense increase by 6.5%–11%.[54] Additionally, blending hydrogen beyond 20% — with an upper limit of 23.5% — may create operational challenges considering the variation in gas composition.[55]

Blending hydrogen also creates downstream issues for end-users. For sectors like fertilisers, refineries, and mobility, deblending facilities would be required, adding to blending costs of around US$1.5/kg.[56] In the case of urea production, using a 10% hydrogen blend with natural gas could raise production costs from ₹268/kg to ₹300/kg.[57] Despite these technical hurdles, repurposing existing infrastructure remains a faster and more cost-effective option than constructing new, dedicated hydrogen networks. It also reduces the risk of stranded assets.

Exhibit 5 Replacement checklist of various parts of existing pipelines according to the potential hydrogen blending percentages

Element	Blending Percentages			
	0%–2%	2%–5%	5%–10%	10%–20%
Compressor	No replacement needed	No replacement needed	Replacement needed	Replacement needed
Valve	No replacement needed	No replacement needed	No replacement needed	Replacement needed
Gas filter	No replacement needed	No replacement needed	No replacement needed	Replacement needed
Fuel filter	No replacement needed	No replacement needed	No replacement needed	Replacement needed
Odouriser	No replacement needed	No replacement needed	No replacement needed	Replacement needed
Insulation joint	No replacement needed	No replacement needed	No replacement needed	No replacement needed
Volumetric metres	No replacement needed	No replacement needed	No replacement needed	Replacement needed
Process gas chromatograph	Replacement needed	Replacement needed	Replacement needed	Replacement needed
Gas metres	No replacement needed	No replacement needed	No replacement needed	Replacement needed
Gas turbine	No replacement needed	Replacement needed	Replacement needed	Replacement needed
Feedstock reformer	No replacement needed	Replacement needed	Replacement needed	Replacement needed
Burner	No replacement needed	No replacement needed	No replacement needed	No replacement needed

No replacement needed   Replacement needed

RMI graphic. **Source:** RMI compilation based on Petroleum and Natural Gas Regulatory Board (PNGRB)'s study, https://www.pngrb.gov.in/pdf/press-note/ICF_15032024.pdf

Repurposing LNG import terminals to ammonia export terminals

India currently operates eight LNG receiving terminals in addition to its gas grid, with six located on the West Coast. These include Petronet's 17.5 Mt/y terminal in Dahej; 5 Mt/y terminal in Cochin; Shell's 5.2 Mt/y terminal in Hazira; the 5 Mt/y Dabhol terminal operated by Ratnagiri Gas and Power (a subsidiary of NTPC); a 5 Mt/y terminal in Mundra; and the recently commissioned 5 Mt/y terminal at Chhara. On the East Coast, India has two operational terminals: a 5 Mt/y facility operated by Indian Oil Corp. and a newly launched 5 Mt/y terminal at Dhamra, which is a joint venture between Adani and Total Energies.[58] Additional terminals in Karaikal, Jaigarh, and Jaffrabad are expected to become operational in the near future.

Although these LNG terminals will continue to cater to natural gas demand, there is an opportunity to repurpose for green hydrogen derivatives like ammonia if needed. Globally, there is growing interest in converting LNG import terminals for ammonia, especially in Europe, with early stage plans underway in locations like Fos Tonkin in France and Stade and Wilhelmshaven in Germany.[59] Although it is a reasonable proposition, these changes face technical and regulatory challenges, requiring infrastructure upgrades and approvals.

Globally, over 100 new hydrogen and ammonia terminals and port infrastructure projects are expected to be operational by the end of the decade, with more than half focused on ammonia exports.[60] At least 10 terminals are planned in Australia, with additional projects in Brazil, Egypt, Mauritania, Namibia, and the United Arab Emirates.[61] Retrofitting LNG export terminals into ammonia export hubs is attractive for countries aiming to shift to green ammonia exports.[62]

India's plan for transition is unique with all LNG terminals being import-focused. Retrofitting these facilities would support the country's goals of developing the infrastructure for green hydrogen and its derivatives.

Scenario design

The potential of repurposing natural gas infrastructure to support the green hydrogen transition has been widely explored, with pipelines and LNG terminals serving as critical components of this infrastructure.[63] The Petroleum and Natural Gas Regulatory Board (PNGRB) has conducted comprehensive studies on the readiness of natural gas pipelines for hydrogen integration, providing valuable insights referenced in this report.[64] However, there remains a significant knowledge gap regarding the techno-economics of retrofitting LNG terminals to align with and complement the development of new green hydrogen infrastructure.

To estimate the repurposing costs for converting an LNG import terminal into an ammonia export terminal, we examine two scenarios related to repurposing brownfield assets. Each scenario includes a case study to highlight potential cost savings and strategies to mitigate the risk of stranded assets through strategic energy transition planning in India's economy.

A. Brownfield: Post-Commissioning: Conversion of an Operational LNG Import Terminal to an Ammonia Export Terminal

This scenario examines the repurposing of a commissioned LNG import terminal into an ammonia export terminal, where modifications are made after the initial investment in the LNG facility. In this scenario, the LNG facility is already operational and has not been planned originally to transition for ammonia handling.

B. Brownfield: Pre-Commissioning: Conversion of an LNG Import Terminal Under Construction to an Ammonia Export Terminal

This scenario envisions an LNG terminal that is yet to be commissioned, with its engineering and design strategically incorporating provisions for future repurposing to handle ammonia. While the terminal will primarily serve LNG consumers, it is designed with a transition plan in mind, enabling the potential handling of ammonia in the future. Key components required for this transition are considered during the initial investment phase.

Assessing the cost of conversion of LNG terminals to ammonia terminals

Beyond theory, converting an LNG terminal into an ammonia export terminal involves substantial engineering work. This includes reinforcing storage tanks; repurposing pipelines, pumps, and auxiliary systems; and implementing stricter safety protocols. Although some existing infrastructure, such as jetties and berthing facilities, can be reused, specialised equipment — such as compressors and heat exchangers — will require modifications or replacement. The handling of hydrogen-based fuels is complex, and ammonia's high toxicity adds more layers of uncertainty. Stringent safety measures must be put in place, ensuring the terminal's safety distances and operational outlays.

Box 3 Comparative characteristics and chemical differentiation between LNG and ammonia

LNG and liquid ammonia are both stored and transported at low temperatures. However, they have different characteristics which affect the storage, safety, and infrastructure requirements, making the repurposing of LNG terminals for ammonia a complex transition.

Converting an LNG terminal into an ammonia terminal requires a detailed evaluation of the existing infrastructure to address the distinct characteristics and risks associated with ammonia. For instance, while LNG is flammable and has explosion risks, ammonia is toxic and corrosive. Therefore, different safety and environmental mitigation measures are needed.

Storage tanks for LNG may be overdesigned for ammonia's higher temperature but would need retrofitting with ammonia-compatible materials to prevent stress corrosion cracking. Pipelines and low-pressure systems, typically designed for LNG's lower pressures and non-corrosive properties, must be recalibrated and adapted to work at ammonia's higher density and corrosive behaviour.

Critical systems, such as boil-off gas (BOG) management and leak detection, require modifications or complete replacement. Similarly, spill containment, safety systems, and civil works must be upgraded to account for ammonia's environmental hazards and higher load-bearing requirements. Moreover, operational and maintenance efforts increase with ammonia as it demands frequent inspections to mitigate corrosion risks.

While many components of an LNG terminal, such as storage tanks and pipelines, can be retrofitted, the fundamental differences between LNG and ammonia require important modifications to ensure safe and efficient operations. Proper evaluation, analysis, and planning are crucial to control retrofitting costs for operation and safety requirements of liquid ammonia handling.

Additional details are provided in **Appendix A.**

Globally, the cost of typical LNG import terminals ranges between US$185/ton and US$350/ton, while costs in India are significantly lower, ranging from US$95/ton to US$105/ton.[65] In contrast, LNG export terminals are far more cost intensive. These facilities require large-scale liquefaction plants to convert natural gas into its liquid state by cooling it to –162°C, as well as cryogenic storage tanks capable of holding large volumes of LNG at extremely low temperatures for extended periods.[66] Additionally, export terminals are typically designed to handle large-scale LNG production for global trade, requiring substantial up-front investment and years of development. As a result, export terminal costs are two to three times higher than those of import terminals, ranging from US$525/ton to US$625/ton (see **Exhibit 6,** next page); details are provided in **Appendix A**.

A greenfield ammonia export terminal in India would cost around US$470/ton to US$490/ton, 10% to 20% cheaper than a global LNG export terminal, but nearly three times more expensive than the Indian LNG import terminals. Since there is a change in process between liquefaction and vapourisation, the core components for this process such as the condensers and compressors will need to be new, requiring capital investment, as old components cannot be repurposed.

Repurposing an import LNG terminal into an export ammonia terminal is significantly less capital-intensive than building a greenfield ammonia terminal. However, repurposing an import terminal is only feasible if its utilisation rate is significantly low, indicating the absence of a substantial pool of gas consumers.

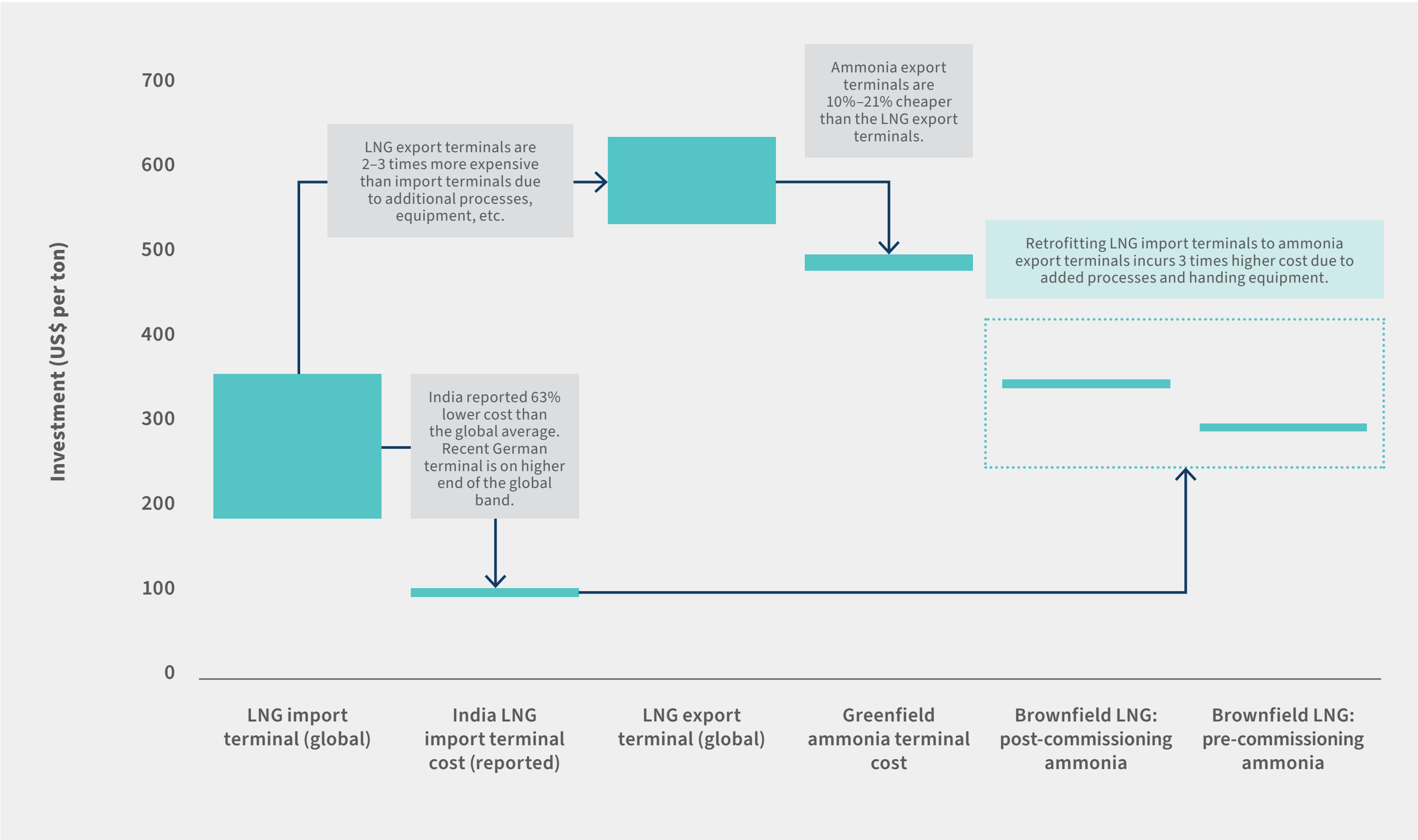
This cost efficiency is due to the reutilisation of existing infrastructure, as much of the investment in LNG storage tanks and related facilities is already accounted for. LNG storage tanks, for example, can be adapted for ammonia storage at a fraction of the original capital cost, estimated at around 3% to 5% of the tanks' initial expense; details are provided in **Appendix A**.[67]

However, additional equipment specific to ammonia export, such as liquefaction compressors, condensers, and specialised jetties, would need to be installed, requiring new capital investments. Furthermore, due to the distinct properties of LNG and ammonia, key systems like the BOG handling components must be entirely replaced. Despite these necessary adjustments, components like storage tanks, low-pressure pumps, and pipelines can be reused to provide significant cost savings.

As illustrated in **Exhibit 6** on the next page, the cost of repurposing before the commissioning of the terminal (Brownfield: pre-commissioning) is lower than post-commissioning repurposing or building a greenfield terminal. Designing LNG terminals to be "ammonia-ready" from the outset further reduces costs, as future modifications can be accounted for during the initial design and engineering phases, eliminating additional civil works; engineering, procurement, and construction (EPC); and related expenses. This proactive approach optimises long-term cost efficiency and operational flexibility.

Greenfield ammonia terminals of 5 Mt/y capacity costs in the range of ₹20,401–₹21,209 crores (US$2.4–US$2.5 billion) while Brownfield: post-commissioning and pre-commissioning LNG terminals, on repurposing, would cost ~₹14,766 crores (US$1.76 billion) and ~₹12,581 crores (US$1.5 billion), respectively, considering that the LNG terminals remain active for 30 years.

Exhibit 6 Investment per ton for the construction of ammonia and LNG terminals under different scenarios



RMI graphic. **Source:** RMI analysis

This cost assessment assumes repurposing the LNG import terminals to ammonia export terminals by 2050, giving enough time for the green ammonia industry to mature while utilising LNG as an effective energy carrier. It is more cost-effective to repurpose LNG terminals closer to the end of their operational life to maximise the value derived from their initial investment. Repurposing at this stage aligns with the system's natural life cycle and extends its utility through extensive modifications to key components and equipment. In the Indian context, the relatively young age of LNG terminals makes immediate repurposing less favourable. For instance, the oldest LNG terminal in India, the Dahej terminal, was commissioned in 2004 and continues to be critical amid the near-term rise in LNG demand.[68]

The analysis shows that repurposing LNG terminals not only facilitates a cost-effective transition to green hydrogen but also helps avoid stranding of natural gas assets when the decarbonisation of the economy accelerates. While repurposing an LNG terminal, several factors such as estimated production, demand for green ammonia in the terminal vicinity, and demand for other derivatives such as methanol, must also be considered to make an informed decision.

As India pursues its energy ambitions, including the One Nation, One Gas Grid initiative, and setting a target to increase the share of natural gas in the energy mix from 6.7% to 15% by 2030, LNG terminals will play a critical role in meeting the country's growing natural gas demands.[69] As the consumption of natural gas is set to rise, LNG terminals along with greenfield ammonia terminals can be converted to "multi-molecule" hubs,[v] capable of handling both ammonia and other substances like CO_2 captured from industrial processes for synthetic fuel production or storage. This model is already gaining traction in Europe, as seen in April 2024, when Enagás initiated plans to convert the Musel LNG terminal into a multi-molecule facility.[70] The Fos Tonkin terminal in France, with a capacity of 1.2 Mt/y, is also following a similar model with re-developing a part of the LNG terminals into a 0.2 Mt/y ammonia import terminal by 2029.[71] The simultaneous development of green ammonia export terminals, alongside retrofitting LNG facilities, will be essential for future-proofing India's energy landscape and ensuring a smooth transition to green hydrogen.

Key Insights

1. **A greenfield ammonia export terminal in India would cost around US$470/ton to US$490/ton, 10% to 20% cheaper than a global LNG export terminal, but nearly three times more expensive than the Indian LNG import terminals.**

2. **Greenfield ammonia terminals of 5 Mt/y capacity costs in the range of US$2.4–US$2.5 billion.**

3. **Repurposing brownfield LNG terminals, either at the post- or pre-commissioning stage would cost around US$1.76 billion and US$1.50 billion, respectively. This considers the LNG terminals to remain active for 30 years.**

4. **Repurposing LNG terminals closer to the end of their operational lifespan is a cost-effective strategy. It minimizes capital expenditures while maximising the infrastructure's utility by supporting the uptake of natural gas as a transitional fuel in the country's energy mix and facilitating a gradual shift towards decarbonisation by enabling a future conversion to green ammonia.**

v. Multi-molecule hubs refer to an integrated industrial and logistics centre where the production, storage, distribution, and utilisation of multiple energy carriers and decarbonised products occur in a synergistic manner. These hubs could be designed to optimise the supply chain and reduce emissions across various sectors by leveraging shared infrastructure, technologies, and resources.

Utilising existing ammonia storage and handling capabilities

Port users typically transfer ammonia shipments directly through dedicated pipelines to their respective storage facilities, either located at production plants or in port-based tanks. From these facilities, ammonia can be further distributed using barges or road tankers, ensuring efficient transportation to end-users.[72]

The selected ports are well equipped to handle ammonia operations, except for Mumbai. **Exhibit 7** illustrates the ammonia handling specifications and storage capabilities of the ports analysed, highlighting their readiness to facilitate some early projects with limited volumes.[73]

Indian ports have begun handling green ammonia, with VOC Port successfully importing 37.4 tons of green ammonia from Damietta Port in Egypt in September 2023 for Tuticorin Alkali Chemicals.[74]

Exhibit 7 Existing ammonia handling parameters at the six focus ports

Category	Variable	Units	Deendayal	Paradip	VOC	Mumbai	JNPA	Cochin
Boundary	**State**		**Gujarat**	**Odisha**	**Tamil Nadu**	**Maharashtra**		**Kerala**
Port Parameters	**Cargo handled volume (2023)**	MMT	132.3	145.38	38.04	67.26	85.82	36.32
	Primary managed commodities		Petroleum, chemicals, iron, steel, fertilisers, and iron machinery; handles salt, textiles, and grain	Iron ore, limestone, manganese ore, coal, large-scale fertiliser, and crude oil	Industrial coal, copper concentrate, fertiliser, timber logs, iron ore	Machinery, crude and petroleum oil, liquid chemicals, motor vehicles, iron and steel, edible oil	Petroleum, oil and lubricants (POL), vegetable oil, coal, iron ore, cement, fertilisers	Petroleum products, rubber products, vegetable oil, cement, metallic ores, machinery
Ammonia Handling	**Ammonia storage facility**	Kilotons	3	-	20	-	15	10
	Permissible vessel draft for ammonia berth	Metres	10.7	14.5	13	-	15	9.1
	Length overall (LOA) for ammonia berth	Metres	223	230	226	-	330	170
Green Hydrogen Project Development	**Land committed by ports for green hydrogen**	Hectares	1618.74	None announced	202.34	None announced	None announced	None announced

RMI graphic.

Box 4 Ammonia trade in India

Global ammonia demand surpassed 190 Mt in 2023, marking an approximate 4% increase compared to 2022. This growth was primarily fuelled by increased fertiliser production, supported by stabilizing global natural gas prices.

China leads global ammonia production, contributing to 30% of total output and 45% of related CO_2 emissions. Other significant producers include the United States, the EU, India, Russia, and the Middle East, each accounting for 8%–10% of global production. Approximately 10% of global ammonia production is traded internationally, while while urea — a derivative — sees even broader trade, with nearly 30% of its production exported. Major exporters in 2023 include Saudi Arabia, Canada, Indonesia, and the United States with their exports totalling 5.43 Mt.

The availability of feedstock and energy is critical in determining where ammonia is produced. Regions with access to low-cost natural gas, such as the United States, the Middle East, and Russia, dominate production through gas-based methods. Conversely, China relies on its abundant coal reserves, which fuel around 85% of its ammonia production.

It is estimated that India consumes 17–19 Mt/y of ammonia primarily for the fertiliser industry.[75] Ammonia is already a widely traded and consumed commodity in India, with imports totalling approximately 2.43 Mt/y primarily from the Middle East.[76] India also exports ammonia to various Asian countries such as Sri Lanka and Nepal, with exports totalling 1.41 Mt in 2022.[77] The import bill for ammonia amounted to about US$2.16 billion in 2022.

India can offset this by increasing local production using green ammonia and can even become a net exporter. In the near term, ammonia demand in India is expected to remain tied to fertiliser production. Transitioning to green ammonia could significantly alleviate the Indian government's substantial fertiliser subsidy burden. Currently, subsidies are driven by the reliance on imported LNG, a key input for traditional ammonia production. By adopting green ammonia, produced using renewable energy, India could reduce its dependency on costly LNG imports. This shift would also enhance the nation's energy and food security, aligning with its broader goals of achieving a low-carbon economy and supporting sustainable agricultural practices. However, in the long term, the demand trajectory will likely shift toward other sustainable applications, including its use as a marine fuel and as an energy carrier as the world transitions to a low-carbon future.

Box 5 Ports supporting access to renewable energy

The Harit Sagar guidelines lay out the goal of increasing the share of renewable energy at India's ports to over 60% by 2030 and 90% by 2047.[78] Renewable energy capacity at ports has been steadily expanding, with 140 megawatts (MW) of generation capacity present currently across the major ports, primarily for their own consumption.[79]

VOC, Deendayal, and JNPA are already fully operational on green power, with Deendayal Port generating surplus renewable energy that can be offered for early small-scale projects. Other ports are investing in assets to increase their renewable energy consumption as well. For instance, Cochin Port Trust has plans to install a solar power plant with a capacity of 4,000–5,000 kilowatts peak (kWp). This initiative supports the port's goal of transitioning to 60% solar power by 2030.[80] Individual terminals are also switching to renewable electricity. For instance, APM Terminal in Mumbai has switched to 80% renewable consumption with a 10.65 MW captive solar photovoltaic plant under a power purchase agreement (PPA) with O2 Power.[81]

Cochin, Deendayal, and JNPA's status as electricity distribution licensees provides a significant autonomy and advantage in supporting access to renewable energy for green hydrogen production.[82] This licensing allows these ports to co-develop and operate electrical distribution systems, enabling them to develop critical infrastructure such as substations and feeders that can handle the large power demands of electrolysis.[83]

The ability to directly manage energy distribution ensures a reliable and efficient supply of electricity and can potentially avoid grid bottlenecks. Moreover, being distribution licensees enables these ports to engage in large-scale renewable energy PPAs which could result in competitive rates, ultimately lowering the cost of green hydrogen production.[84]

Scaling Up: Investments in New Infrastructure Development

Repurposing LNG terminals and pipelines offers a cost-effective foundation for initiating early hydrogen projects. However, given the anticipated scale and rapid growth of the green hydrogen market, repurposed infrastructure can only serve as a complementary solution. Although leveraging existing infrastructure helps mitigate the risk of stranded assets, not all LNG terminals can be retrofitted. Moreover, the anticipated scale of green hydrogen production, nearly 5 Mt/year for exports by 2030, will require significant new investments, such as the construction of dedicated ammonia export terminals, to establish the necessary infrastructure.[85]

When developing new infrastructure, storage plays a pivotal role in supporting domestic production, consumption, and export objectives. Ammonia, widely traded as a fertiliser feedstock, accounted for significant import volumes exceeding 2 million tons in 2022. Many ports already house ammonia storage facilities within their premises; however, these existing capacities are limited and fall short of the anticipated handling volumes projected by port authorities.

Portside storage plays a crucial role in the investment costs associated with ports transitioning into green hydrogen hubs, as economies of scale can help reduce the levelised cost of ammonia storage. However larger storage capacities beyond the optimal volume and usage cycles typically lead to higher lifetime costs. Though the reduction is marginal, utilising existing ammonia storage can offset some of the expenses by minimising the need for additional capital investments.

Given that four of the six focus ports have existing ammonia storage, utilising these facilities effectively could help reduce costs. However, if additional capacity exists but is already in use, it underscores the need for expanding storage to meet future demands.

> **“Optimising existing and new ammonia storage requirements at ports can help reduce costs and minimise additional capital investments, making the transition to green hydrogen hubs more efficient.”**

Scenario Design

The scale of green hydrogen production and development at different ports may vary depending on the commitments made by developers and the efforts of state governments. To account for the uncertainty in these varying visions, this study explores three key scenarios — conservative, moderate, and high ambitions (see **Exhibit 8,** next page) — to assess the potential outcomes in a changing ecosystem.

The target volumes for ammonia handling directly affect the levelised costs of green hydrogen and its derivatives, as larger volumes typically lead to economies of scale, which reduce costs per unit over the infrastructure's lifetime. These handling goals also influence the total lifetime costs of infrastructure and play a key role in determining the port's long-term strategy for exporting green fuels and decarbonising its bunkering fuel supply.

1. **Conservative ambitions**

   Ports with conservative ambitions might aim for lower volumes of ammonia handling, which allows for a gradual entry into the green fuel market. With smaller initial investments in infrastructure, these ports can focus on building foundational capabilities, such as small-scale ammonia storage and transport facilities. By doing so, they mitigate financial risk while gaining valuable operational experience. Additionally, such ports can benefit from international knowledge-sharing partnerships, learning from more advanced green fuel hubs without committing to large, up-front investments. This approach allows the port to stay flexible and scale up later based on demand growth and technology advancements.

2. **Moderate ambitions**

   Ports with moderate ambitions would aim for medium-scale infrastructure investments, positioning themselves as important players in India's green hydrogen economy. These ports can balance risk and opportunity by scaling infrastructure just enough to support meaningful exports while fostering international cooperation through technology transfer agreements. By doing so, they can contribute to building India's reputation as a critical green hydrogen producer, exporting green ammonia and other fuels to regions like Europe and other parts of Asia. Moderate-scale ports can also provide an essential supply of green fuels for domestic industries while laying the groundwork for future expansion as global demand for hydrogen increases.

3. **High ambitions**

   Ports with high ambitions would pursue large-scale investments, aiming to become leaders in the global hydrogen economy. This would involve constructing extensive ammonia storage, transport, and export facilities, allowing the port to handle substantial volumes of green hydrogen and its derivatives. In this scenario, the port can benefit from significant economies of scale, driving down costs per unit and making green hydrogen more competitive in the global market. Additionally, these ports can adopt demand-generation strategies, such as establishing green corridors with major international markets in Europe and East Asia. By creating these trade routes, they can secure consistent demand for green fuels, thus maximising the utilisation of their infrastructure.

Furthermore, such ports can explore synergies between bunkering and exporting green fuels, allowing them to diversify revenue streams and strengthen their position as critical nodes in the global hydrogen supply chain.

To develop scenarios aligned with the outlined storylines, primary data was gathered from respective port authorities. This data encompassed existing bunkering volumes, anticipated bunkering demand, and projected export volumes of hydrogen, ammonia, and methanol. The reported figures from the ports are treated as representing high-ambition scenarios. For medium and conservative scenarios, the target volumes were scaled down to 50% and 20% of the projected volumes, respectively. Given the inherent uncertainty surrounding the expected handling capacities of ports, this scenario-building approach mitigates uncertainty by evaluating all three distinct ambition levels, providing a structured framework for each port authority's planning and decision-making processes.

Exhibit 8 **Projected ammonia handling for the six focus ports across three ambition scenarios based on announced green ammonia projects within the ports' state**

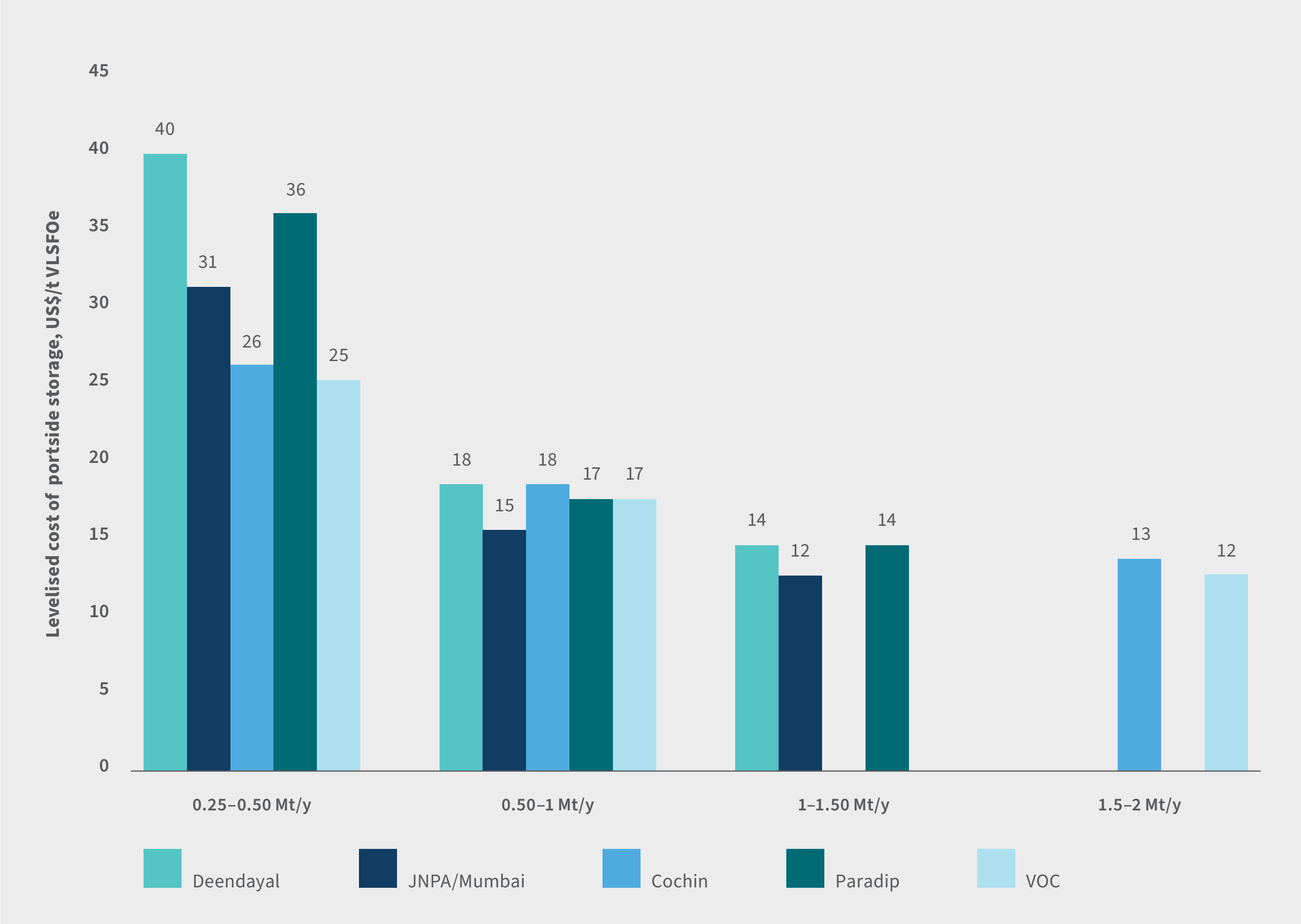
Volume in million tons per year (Mt/y) of ammonia			
Port/scenarios	**Conservative Ambition**	**Medium Ambition**	**High Ambition**
Deendayal	0.2	0.6	1.2
VOC	0.4	1.0	2.0
Paradip	0.3	0.7	1.4
Cochin	0.4	1.0	2.0
Mumbai and JNPA	0.3	0.8	1.6

Note: High, medium, and conservative ambitions assume 100%, 50%, and 20% of the state's green ammonia capacity is handled by the port, respectively. RMI graphic.

Assessing scale of investment

Determining the ideal size for portside storage is essential for managing costs effectively. **Exhibit 9** on the next page illustrates the significant decrease in levelised cost of storage as capacity increases up to the 1.0–1.5 Mt/y range, after which the cost reduction becomes more gradual as the impact of economies of scale becomes marginal beyond optimal buildout threshold. The cost decline is more rapid when moving from ranges close to 250–500 kilotons/year (kt/y) as seen with Deendayal and Paradip ports.

Exhibit 9 Levelised cost of portside storage by volume at the six focus ports



Note: VLSFOe = Very low sulphur fuel oil equivalent. RMI graphic. **Source:** RMI analysis

Although variable operating expenditures, such as electricity, increase proportionally with size, the economies of scale and extra revenue from utilising the tank result in a net lower levelised cost, assuming a constant tank utilisation rate. Therefore, carefully sizing the storage facilities based on projected local production levels to maximise tank utilisation and revenue while ensuring sufficient storage capacity becomes critical for ports. This approach not only supports cost-effectiveness but also enhances the overall efficiency of the port's role in the hydrogen and ammonia supply chain.[vii]

vii. Tank utilisation reflects the quantity of ammonia stored compared to the facility's total capacity. This is important for planning, as underutilisation could indicate inefficiency, while overutilisation might lead to risks like capacity constraints.

Although some consistent trends can be observed across ports such as optimised storage sizing ranging around 1–5 Mt/year and levelised costs declining with initial scaling until the threshold is reached, distinct variations exist that reflect each port's unique circumstances. These differences primarily stem from the specific capital expenditure requirements and levelised costs associated with the volume goals set by each port (see **Exhibit 8,** page 40), which are influenced by anticipated project announcements and resulting demand for ammonia in domestic and global markets, as reported by the port authorities during primary data collection.

The existing storage at ports can enhance the effectiveness of their future expansion plans. By leveraging the current infrastructure, these ports can optimise their storage capabilities without incurring the full costs associated with constructing new facilities. This strategic advantage allows them to respond more flexibly to market demands and integrate their operations with ongoing green hydrogen and ammonia initiatives.

To better analyse the cost economics and storage requirements across different ports, we categorised them into two groups:

1. Ports focusing primarily on greenfield investments, and
2. Ports with some existing storage complementing new investments.

• Ports focusing primarily on greenfield investments

This category includes ports that lack or have minimal existing ammonia storage capacity and hence require substantial up-front capital to develop new storage facilities and associated infrastructure. Although these investments can lead to state-of-the-art facilities designed specifically for green hydrogen and ammonia, they also come with higher initial costs and longer timelines for completion.

Deendayal and Paradip ports are considered in this category.

Ensuring adequate volume handling is critical for greenfield investments, particularly until reaching the demand threshold of 1.0–1.5 Mt/year of ammonia, as illustrated in **Exhibit 9** on the previous page. While many ports may develop their infrastructure incrementally, greenfield projects typically involve higher up-front costs.

To optimise costs, ports undertaking greenfield investments must carefully size their equipment to accommodate potential scale-up operations and maintain higher utilisation rates. Achieving an initial build-out close to the 1.0–1.5 Mt/y threshold is vital for leveraging economies of scale, enabling revenue generation that offsets the high initial capital expenditure. This can be observed in **Exhibit 10** on page 44, highlighting that the increasing storage capacity significantly reduces the levelised cost of storage. For example, doubling storage volumes — from 229 to 573 kt/y at Deendayal Port or 270 to 675 kt/y at Paradip port — halves the levelised cost. This reduction occurs because capital expenditure remains constant for similarly sized ammonia tanks, while increased utilisation rates drive down costs.

With a nearly 150% increase in handling volumes at both Deendayal and Paradip ports, the required lifetime costs (capital expenditures + operating expenditures) rise by 12% and 22%, respectively, reflecting differences in the absolute volumes handled by the ports. However, the reduction in the levelised cost of storage — exceeding 50% at both ports — far outweighs the increase in capital investment. Notably, this trend reverses if the volume expansion exceeds the threshold.

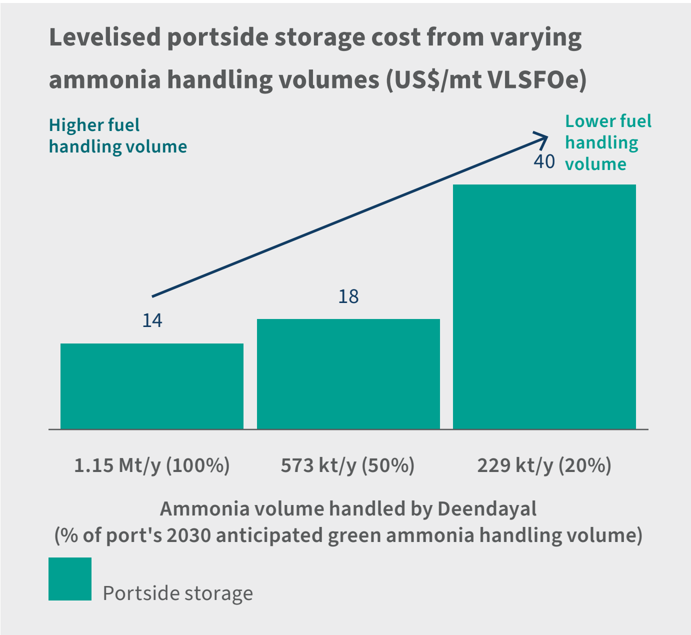
The analysis further demonstrated that for volumes below 1 Mt/year, capital expenditure for ammonia tanks remains fixed at approximately US$32 million, whereas operational expenditure rises incrementally with size, amounting to 45% and 71% increase in Deendayal and Paradip, respectively. However, the increased operational costs are offset by higher revenues from greater utilisation, resulting in a significant decrease in levelised costs. This underscores the importance of maintaining high utilisation rates for storage facilities to achieve cost efficiency.

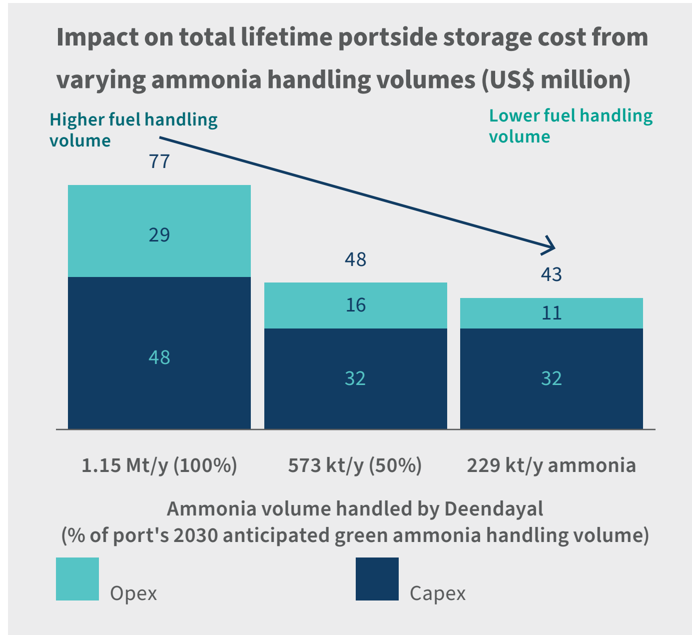
Ports with limited existing infrastructure face higher up-front capital costs and greater investment risks. To mitigate these risks, it is essential to align the infrastructure build-out with parallel demand generation efforts. By fostering sufficient demand, ports can reduce risks and levelised costs through economies of scale and optimised utilisation. Initiatives such as green corridors can serve as a catalyst for demand creation, driving early adoption of green fuel-related port infrastructure.

Finally, as ammonia volumes increase, both operational and capital expenditures will rise, emphasising the need for robust infrastructure planning. Strategic demand aggregation and infrastructure scalability are critical to ensuring that ports can meet growing demand while maintaining financial and operational efficiency.

Exhibit 10 Storage requirements, levelised storage, and investment requirements for Deendayal and Paradip ports

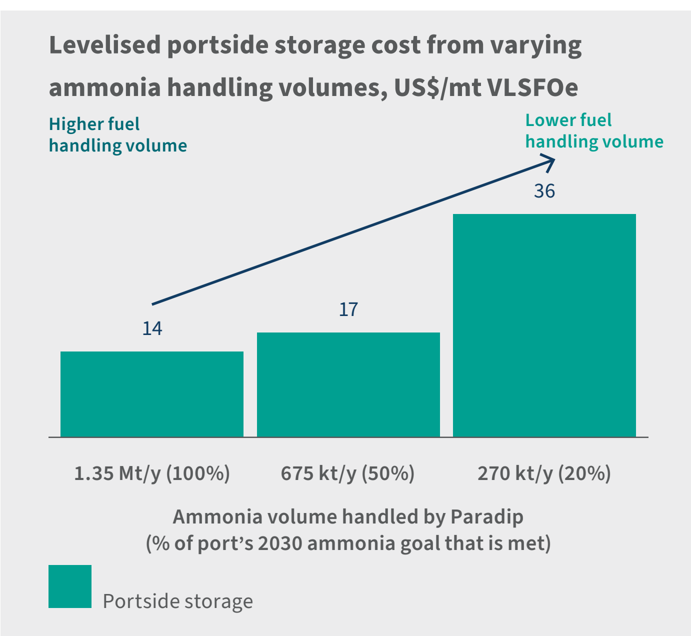
A. Deendayal

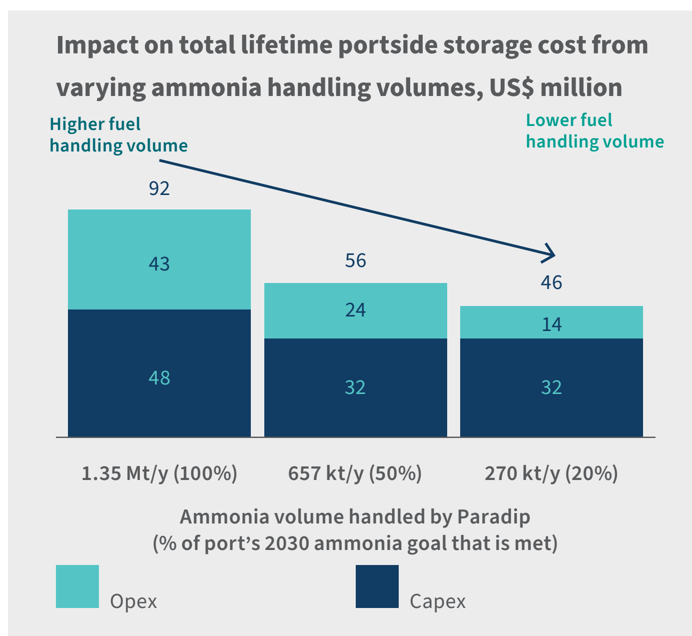




Note: The 1.15 Mt/y demand scenario will require two 10,000-ton ammonia tanks, and the other two smaller demand scenarios of 573 and 229 kt/y ammonia will require two 5,000-ton ammonia tanks. This assumes a tank lifetime of 30 years.

B. Paradip





Note: The 1.35 Mt/y demand scenario will require two 10,000-ton ammonia tanks, and the other two smaller demand scenarios of 675 and 270 kt/y ammonia will require two 5,000-ton ammonia tanks. This assumes a tank lifetime of 30 years.
RMI graphic. **Source:** RMI analysis

- ### Ports with some existing storage complementing new investments

This group encompasses ports like Cochin, VOC, and JNPA, which already have operational storage units that can be upgraded or repurposed to support new projects. Due to the challenge of attributing projects individually to each port and distinguishing volumes between JNPA and Mumbai — given their proximity and location within the same state — these ports are analysed collectively. However, this assumption serves merely as a preliminary approach to conducting the analysis. A more detailed mapping and in-depth analysis of these individual ports are necessary to provide comprehensive insights.

Ports with existing storages benefit from lower capital expenditures because they can utilise existing infrastructure, thereby accelerating the timeline for meeting storage capacity needs and reducing overall investment risks. However, this comes with the caveat that the existing storage must be available for transition, either entirely or in the form of blended green ammonia volumes. If existing storage is unavailable for use, the ports will need to pursue new build-outs to meet the expected demand.

Ports considering utilising existing infrastructure will minimally benefit from economies of scale and utilisation maximisation. Therefore, ports with existing infrastructure may have more ability to gradually enter the green fuel market. By doing so, they can minimise financial risk while still building operational experience and ramping up green fuel demand generation.

As seen in **Exhibit 11** on the next page when existing infrastructure is present, scaling up storage results in almost the same levelised costs between all sizing scenarios for both ports. Therefore, ports should size the scale of their infrastructure according to their expected scale of operations and maintain adequate utilisation rates to take advantage of the economies of scale.

Utilising existing ammonia storage capacity could help reduce the excess investment requirement, primarily the capital expenditures required to cater to the volume. Operational expenses remain constant over utilising existing storage and building only new storage infrastructure for any specific storage scenario, while the capital expenses reduce due to the fact that existing infrastructure can be used to add capacity. Operational expenses are also more significant at lower storage capacities relative to capital expenses (US$4 million in capital expenses versus approximately US$13 and US$16 million in operational expenses for VOC and Cochin, respectively) due to the presence of existing storage reducing capital expense costs for additional build-outs.

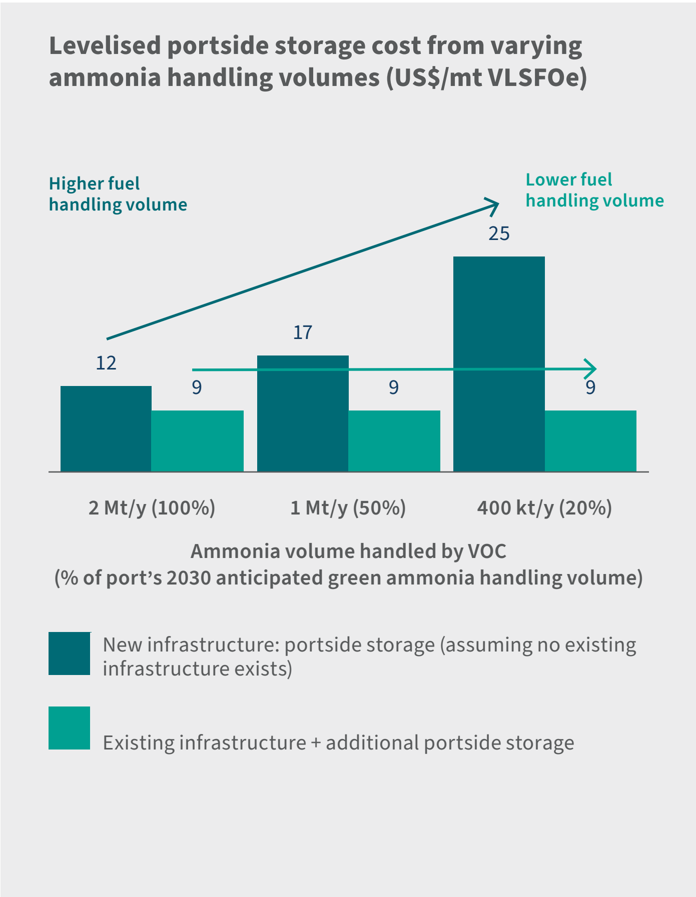
When utilising existing infrastructure and complementing it with additional infrastructure to meet demand volumes, lifetime costs for portside storage are approximately 47% lower than that of new investment cases across all storage scenarios in the three ports considered. Fall in capital expenses is more drastic during lower storage capacities as existing infrastructure usually accounts for most of the storage and less investment is needed for additional infrastructure. In the case of JNPA/Mumbai, due to the presence of an existing 15 kt storage facility, there would be no additional infrastructure needed for the 314 kt/y scenario.

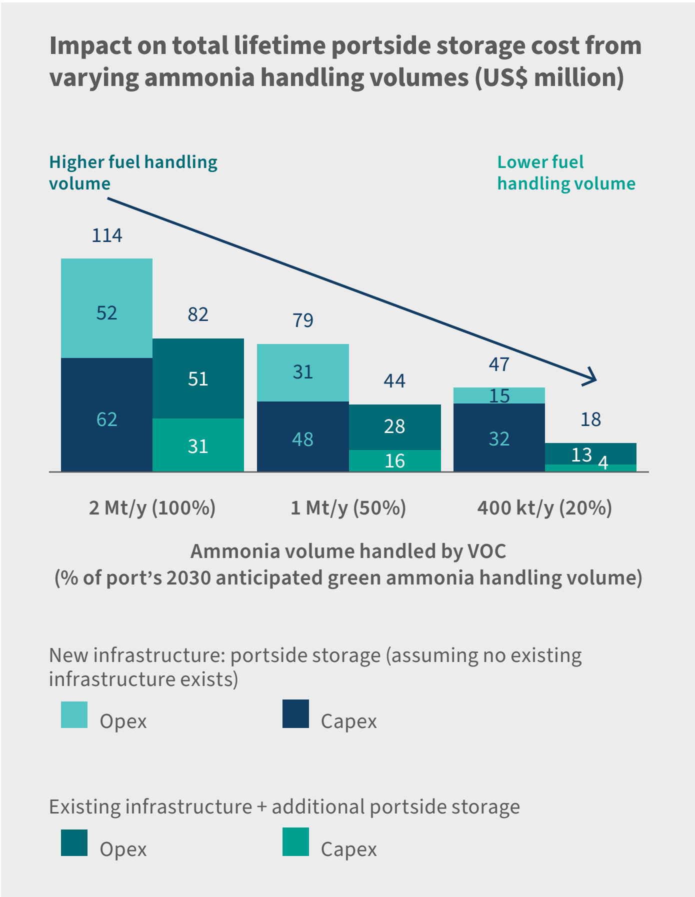
Capital expenses while utilising existing storage is almost halved for VOC and Cochin in case of higher volumes of storage. In the case of JNPA/Mumbai, the drop in capital expenses is almost three times, as JNPA has a higher existing storage volume of 15 kt and has a potentially lesser storage sizing of 1.57 Mt/y.

If a port wants to maximise molecule transfer and establish itself in the global fuel market, it can scale operations accordingly. Initial capital expenditure is high for larger storage scenarios such as 2 Mt/y, when compared to lower storage scenarios as the importance of existing storage decreases. These high capital expenditures will be offset over time assuming the infrastructure is utilised appropriately and, therefore, revenue is generated over the infrastructure lifetime.

Exhibit 11 Storage requirement, levelised storage, and investment requirements for VOC, Cochin, JNPA, and Mumbai ports

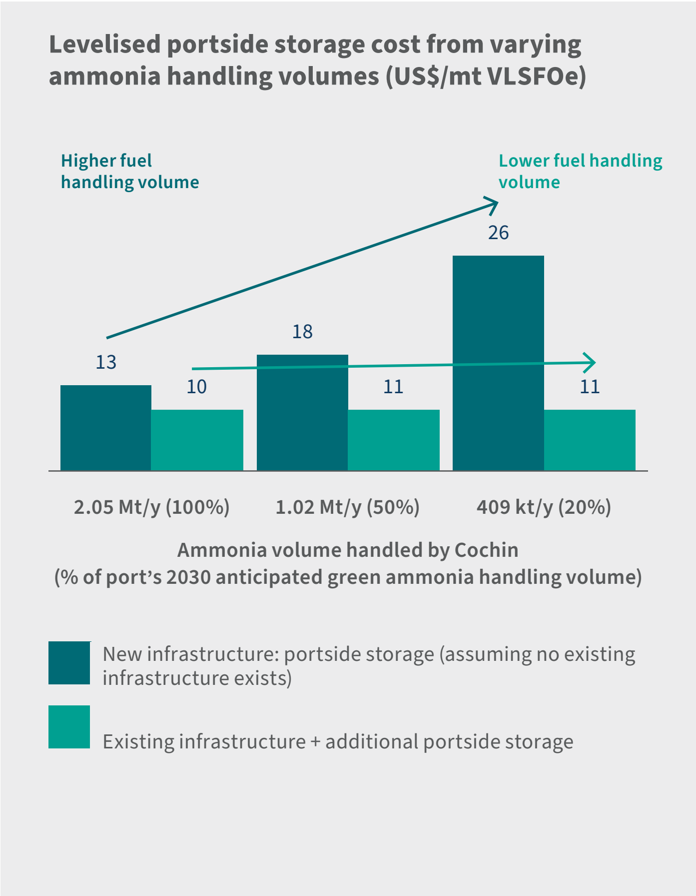
A. VOC

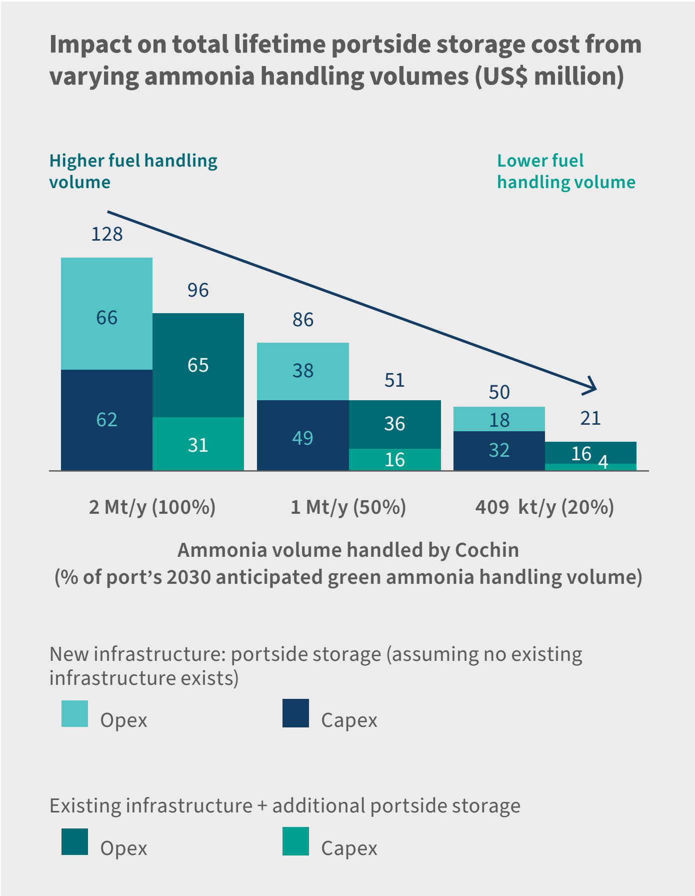




Note: The 2 Mt/y scenario requires two 15,000-ton ammonia tanks, whereas the 1 Mt/y and 400 kt/y scenarios require two 10,000-ton and two 5,000-ton tanks, respectively. Existing infrastructure includes a 10,000-ton ammonia tank. With existing infrastructure, only one additional 15,000-ton tank is needed for the 2 Mt/y scenario and one additional 5,000-ton tank for the 1 Mt/y scenario. No additional tank is needed for the 400 kt/y scenario. This assumes a tank lifetime of 30 years.

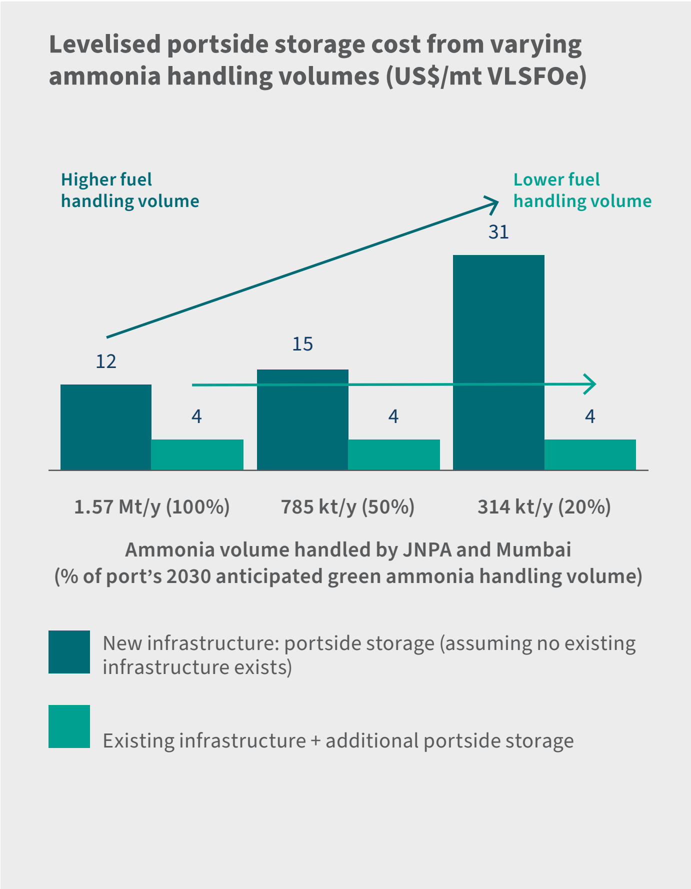
B. Cochin

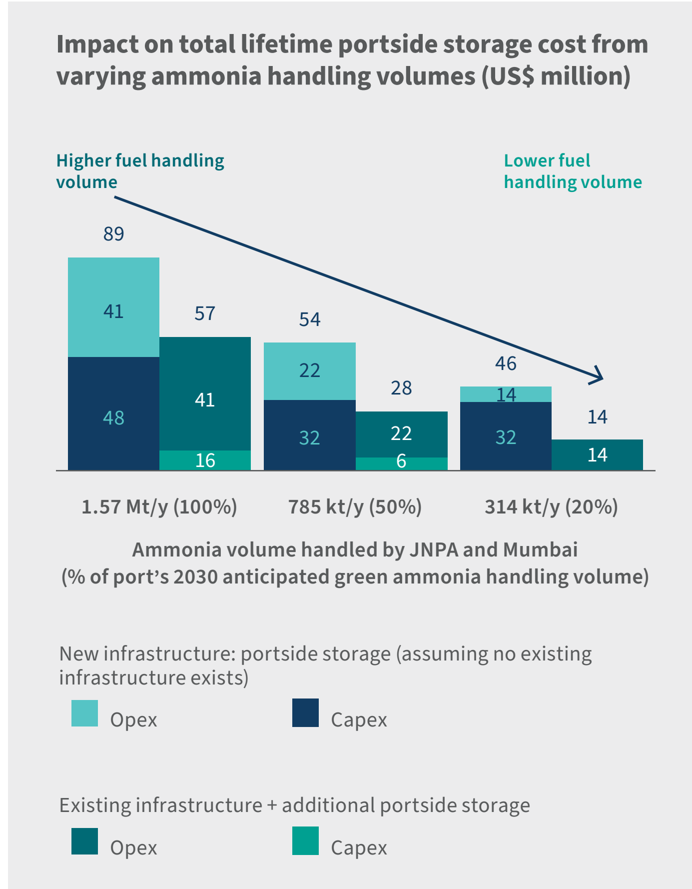




Note: The 2.05 Mt/y scenario requires two 15,000-ton ammonia tanks, whereas the 1.02 Mt/y and 409 kt/y scenarios require two 10,000-ton and two 5,000-ton tanks, respectively. Existing infrastructure includes a 10,000-ton ammonia tank. With existing infrastructure, only one additional 15,000-ton tank is needed for the 2.05 Mt/y scenario and one additional 5,000-ton tank is needed for the 1.02 Mt/y scenario. No additional tank is needed for the 409 kt/y scenario. This assumes a tank lifetime of 30 years.

C. JNPA and Mumbai





Note: The 1.57 Mt/y demand scenario will require two 10,000-ton ammonia tanks, and the other two smaller demand scenarios of 785 kt/y and 314 kt/y ammonia will require two 5,000-ton ammonia tanks. Existing infrastructure includes a 15,000-ton ammonia tank. With existing infrastructure, only one additional 5,000-ton tank is needed for the 1.57 Mt/y. No additional tank is needed for the 785 kt/y scenario and 314 kt/y scenario. This assumes a tank lifetime of 30 years.

Key Insights

1. The levelised cost of storage decreases significantly as capacity increases up to 1.0–1.5 Mt/year due to economies of scale. Beyond this, the cost reduction becomes more gradual. Ports like Deendayal and Paradip demonstrate a rapid decline in costs within the 250–500 kt/y range, highlighting the critical importance of initial scaling.

2. Effective port infrastructure planning should align storage capacity with projected production levels to maximise utilisation and revenue. Ports undertaking greenfield investments must carefully size their facilities to achieve economies of scale, with an optimal build-out near the 1.0–1.5 Mt/y threshold being essential for cost efficiency.

3. For ammonia tanks, the capital expenditure remains constant at approximately US$32 million for capacities below 1 Mt/y. As volumes increase, operational expenditures rise incrementally, ranging from 45% to 70%, but the higher utilisation offsets this increase, resulting in a marked decrease in levelised costs.

4. Ports with existing storage infrastructure, such as Cochin, JNPA/Mumbai, and VOC, benefit from reduced capital expenditure and faster scalability. Leveraging existing infrastructure can help reduce lifetime costs by 47%. By upgrading existing facilities, these ports can minimise investment risks, enter the green fuel market gradually, and optimise costs without needing extensive new construction.

5. Adjacent ports like JNPA and Mumbai can aggregate demand and capital by sharing port infrastructure, thus reducing overall risk.

Opportunity Sizing: Competitiveness at International Bunkering Hubs

The infrastructure and investments required to capitalise on the green hydrogen opportunity extend far beyond physical assets. Achieving a strong return on investment depends not only on the capacity to produce green hydrogen and its derivatives, such as ammonia, but also on ensuring their competitiveness in global markets. For ports to play a successful role in the global green fuel trade, the production costs of green ammonia, the primary traded derivative of green hydrogen, must be carefully managed. Equally important is the ammonia's landed cost — the total cost incurred to transport and deliver the product to international bunkering hubs — where it competes with ammonia from other export-driven nations.

> **India's ports have the potential to be key players in the global green ammonia trade, leveraging low-cost renewable energy and strategic location to supply major bunkering hubs in Asia and Europe competitively.**

To ensure that the green ammonia produced at Indian ports is both domestically and internationally competitive, this study evaluates its landed cost at key global bunkering hubs. Competitiveness at hubs in Japan, Singapore, and South Korea — important bunkering centres in East Asia — is essential for eastern Indian ports, as these hubs serve as major refuelling and trade points for shipping routes in the Pacific. Similarly, for western Indian ports, ensuring a competitive landed cost at hubs in Belgium, Germany, and the Netherlands is key, as these ports are critical to the European hydrogen economy and form part of the major North Sea hydrogen trade route.

As the global maritime industry pivots toward sustainable energy solutions, green ammonia is emerging as one of the crucial fuels in this transition, especially within international bunkering hubs.

This section explores opportunity sizing for Indian ports aiming to capitalise on green ammonia production, assessing their competitiveness in supplying this vital fuel to bunkering hubs in Europe and Asia, particularly in comparison to key exporters like Australia, Egypt, and Namibia. By examining two essential factors — ammonia production costs and landed costs of the produced ammonia at international demand centres, as well as the ability to meet volume demand — this section seeks to provide a comprehensive analysis of how Indian ports can leverage their distinctive advantages to tap into the growing market for zero-emission fuels, including green ammonia, in the shipping sector. In doing so, it aims to highlight pathways for positioning Indian ports as leading players in the international energy landscape.

Green ammonia production costs at ports

The five case studies in this section utilise a combination of modelling and insights provided by the ports. Although extensive efforts were made to ensure the accuracy of the modelling, including validation from industry experts, the levelised fuel costs presented should not be interpreted as definitive forecasts or projections. Moreover, these figures are not endorsed by the case study ports. The costs are based on various assumptions, particularly regarding real-world demand for green ammonia, which remains highly uncertain.

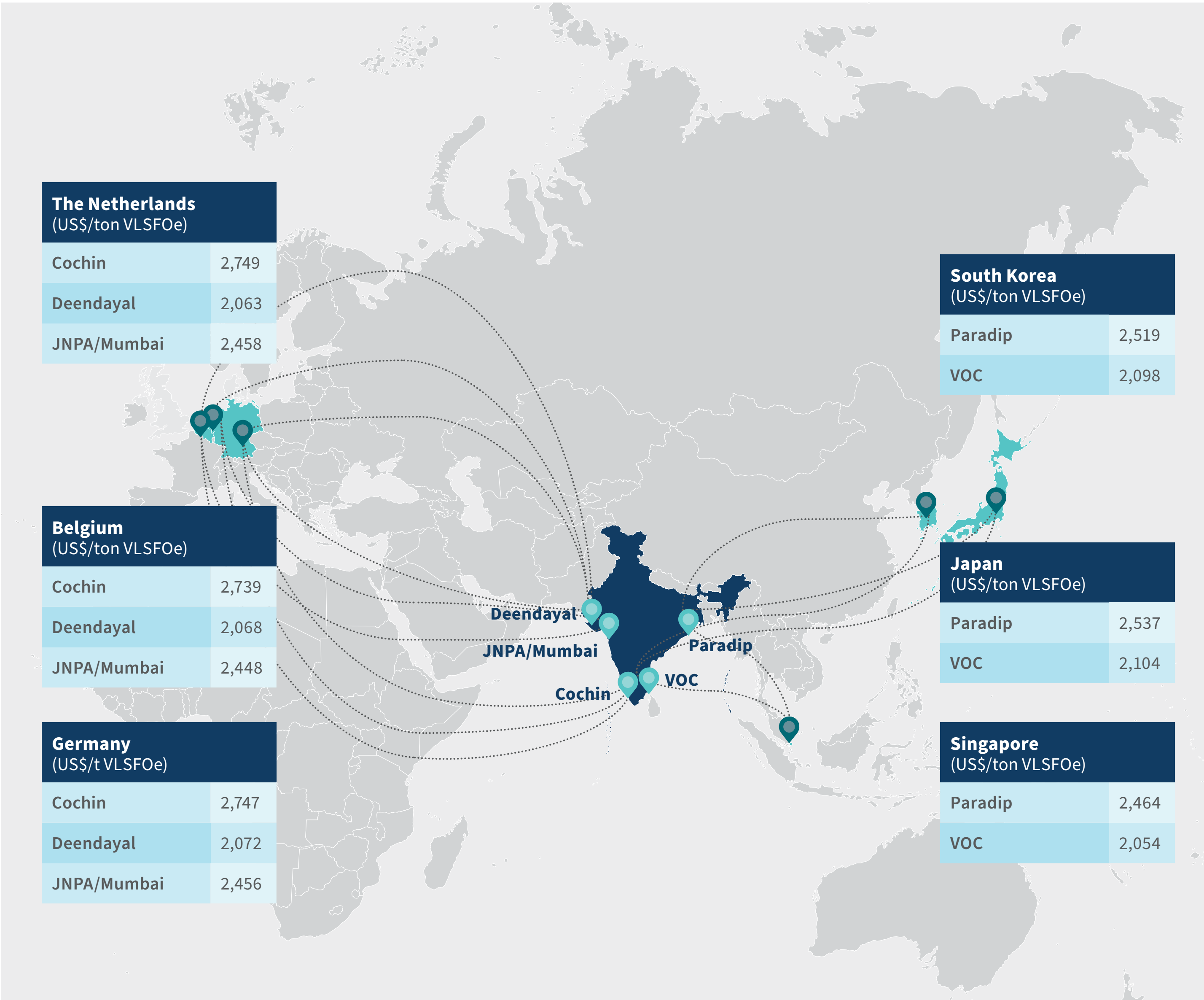
India holds a strategic maritime position for green hydrogen hubs and has an attractive low-cost renewable potential — comparable to some of the globally recognised green hydrogen hot spots such as Australia and Namibia. For the five case studies in comparison, the levelised cost of ammonia (LCOA) ranges from US$1,048/ton to US$2,048/ton without any state-issued subsidies. In states such as Maharashtra and Odisha, where tax exemptions, capital expense subsidies, and waiving of certain electricity charges have been announced for green hydrogen projects, the LCOA is US$764/ton–US$1,255/ton. The volumes of production considered in this analysis were the projected 2030 volumes as there is no current production.

The impact of capital subsidy and electricity cost waivers are significant. Although not all states have announced subsidies, those announced in states like Odisha and Uttar Pradesh, help accelerate deployment of green hydrogen projects. The impact of these subsidies is even clearer when compared with the projected production costs in 2030. According to RMI analysis, LCOA for production without subsidies in Maharashtra, Tamil Nadu, and Odisha in 2030 will be, on average, US$1,022/ton, US$911/ton, and US$1,100/ton, respectively. As expected in 2030, the decreased costs of production are attributable to economies of scale, lower renewable production costs, and lower cost of equipment such as electrolysers. After this decrease, the LCOA is comparable to the current subsidised costs of US$1,013/ton, US$1,099/ton, and US$876/ton for Maharashtra, Tamil Nadu, and Odisha, respectively.

Landed costs of ammonia at European and Asian bunkering hubs

With the global demand for green ammonia projected to rise due to its increased adoption across various sectors, major demand centres such as East Asia, the EU, and Singapore will require imports to meet their needs. India’s abundant renewable energy resources and expanding green hydrogen capacity position it to produce green ammonia at competitive costs. As these regions pursue sustainable solutions to achieve their decarbonisation goals, India’s strategic advantages and commitment to clean energy make it a promising partner in the global green ammonia supply chain.

Exhibit 12 Landed costs of ammonia at various international bunkering hubs (US$/ton VLSFOe)



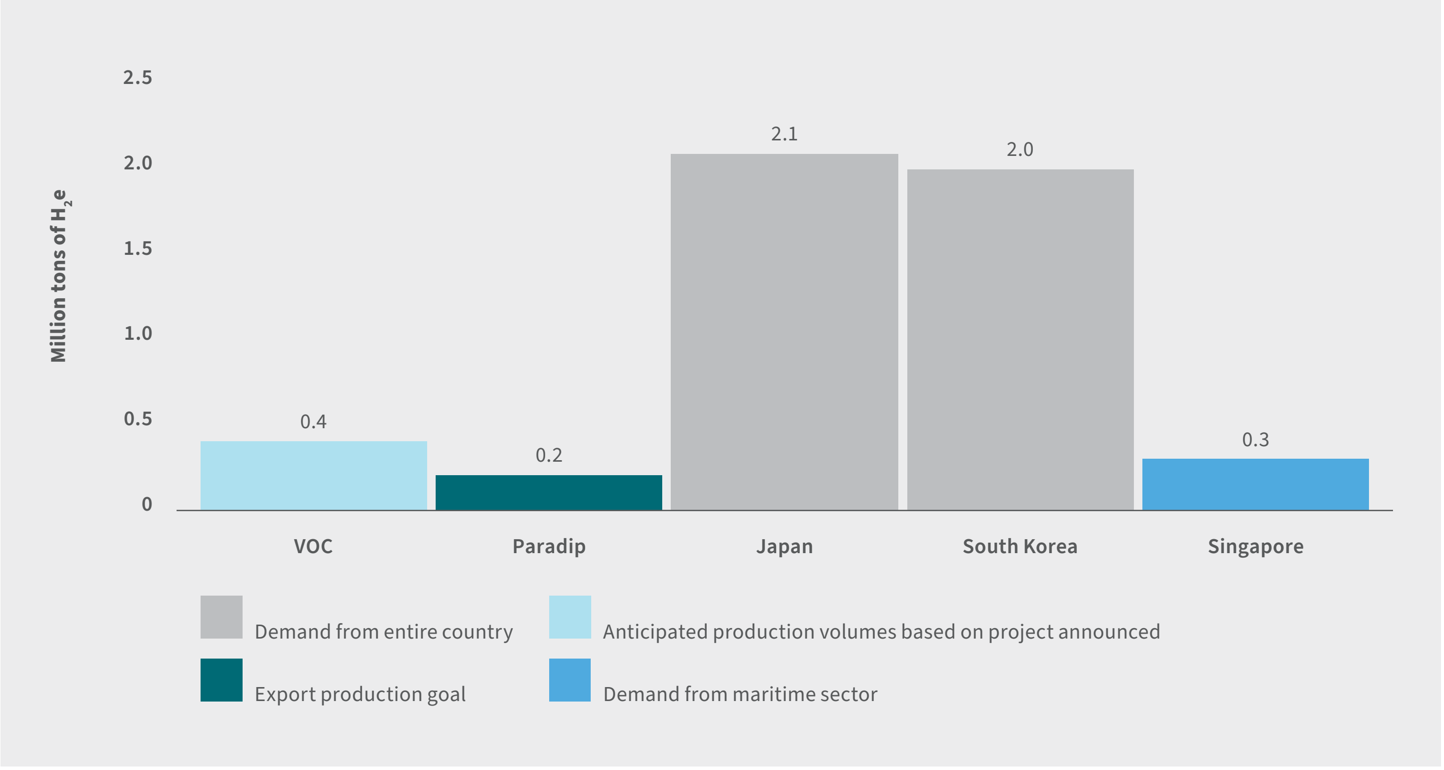
RMI graphic. **Source:** RMI analysis

The analysis focuses on six Indian ports — two on the East Coast and four on the West Coast, as illustrated in **Exhibit 12**. Due to their proximity, landed costs for Asian markets are lower. Ports like Deendayal and VOC benefit from low-cost renewable energy capacity, enabling them to meet demand from both eastern and western markets. However, production costs may fluctuate based on the implementation and extent of subsidies, providing states with the opportunity to further reduce landed costs.

- ## Eastern ports catering to the East Asian market

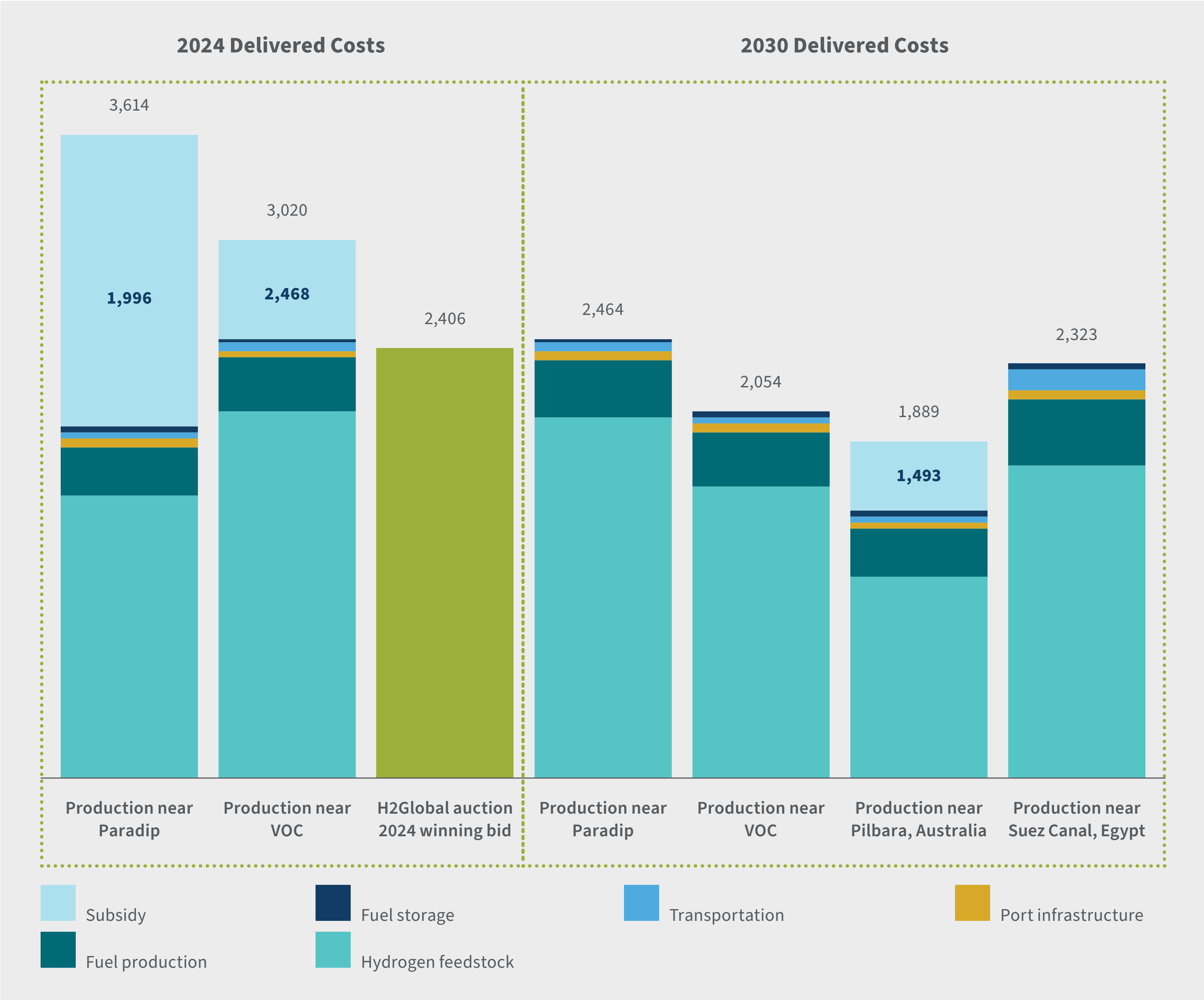
  East Asia, particularly Japan, Singapore, and South Korea, presents a natural target market for green ammonia production on India's East Coast due to its proximity. Japan and South Korea have set ambitious import targets for green ammonia as part of their decarbonisation strategies and are also positioned to develop green ammonia bunkering given their significant marine traffic. Japan and South Korea have integrated ammonia into their power generation plans, while Singapore aims to establish itself as a green ammonia bunkering hub, leveraging its status as the world's busiest transshipment hub and largest bunkering port.[86] The anticipated production volumes from ports like VOC and Paradip are well suited to meet the demands of these nations, as illustrated in **Exhibit 13.**

Exhibit 13 Anticipated production volumes at VOC and Paradip ports compared with expected 2030 demand in three Asian markets



Note: Japan's total import H2 volume is based on its 3 million tons/year 2030 demand goal multiplied by an assumed 70% for the import amount. South Korea's total import H2 volume is from a 2021 S&P Global article based on information from Japan's Ministry of Trade, Industry and Energy. No information was found on Singapore's total H2 demand or imported H2 volume by 2030. The value shown on the graph is from an RMI analysis estimating Singapore's demand for green ammonia for the maritime sector. RMI graphic. **Source:** RMI analysis

Exhibit 14 Total delivered cost of green ammonia imported to Singapore (US$/ton VLSFOe)



Note: Numbers in bold indicate post-subsidised production costs based on the announced subsidies. H2Global auction 2024 winning bid is added for comparison. This fuel will be going to Europe and not Singapore.

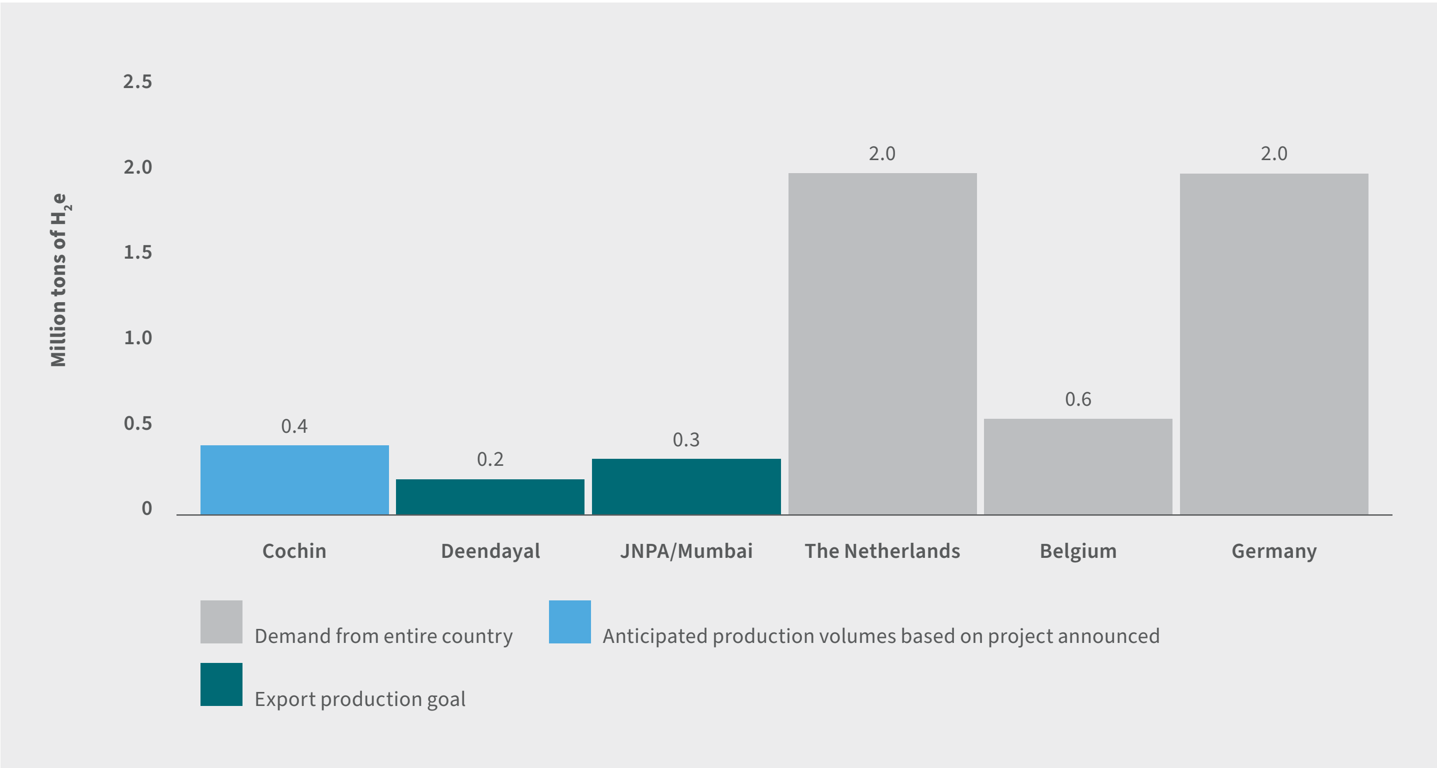
RMI graphic. **Source:** RMI analysis

The Port of Singapore is the focus of this analysis. In 2024, Singapore successfully conducted its first bunkering trial using ammonia as a maritime fuel and is expected to commence commercial bunkering by 2026.[87] As shown in **Exhibit 12**, production at India's East Coast ports is competitive for delivery to Singapore in comparison to other production hubs, such as Egypt and Australia. Production in the vicinity of VOC and Paradip are cheaper, when subsidised, than the winning bid in the H2Global auction in 2024.[88] While overall production costs in 2030 at Pilbara, Australia, is the lowest due to the Hydrogen Production Tax Incentive introduced in May 2024, Indian-produced ammonia can be economically comparable if subsidised.[89]

- ## Western ports catering to the European market

For the western ports of Deendayal, JNPA/Mumbai, and Cochin, a promising market to explore is the EU, which has a goal of importing 10 Mt of green hydrogen by 2030.[90] India is well positioned to meet a portion of this demand. EU member states are making significant strides in developing infrastructure for green ammonia imports. The Brunsbüttel Terminal in Germany opened in October 2024, targeting an import capacity of approximately 3 Mt/y of green ammonia by 2030. Additionally, an import terminal is planned in Hamburg, Germany. Other EU member states are also advancing initiatives, with terminals for green ammonia planned at the ports of Rotterdam and Vlissingen in the Netherlands, as well as at the Port of Antwerp-Bruges in Belgium.

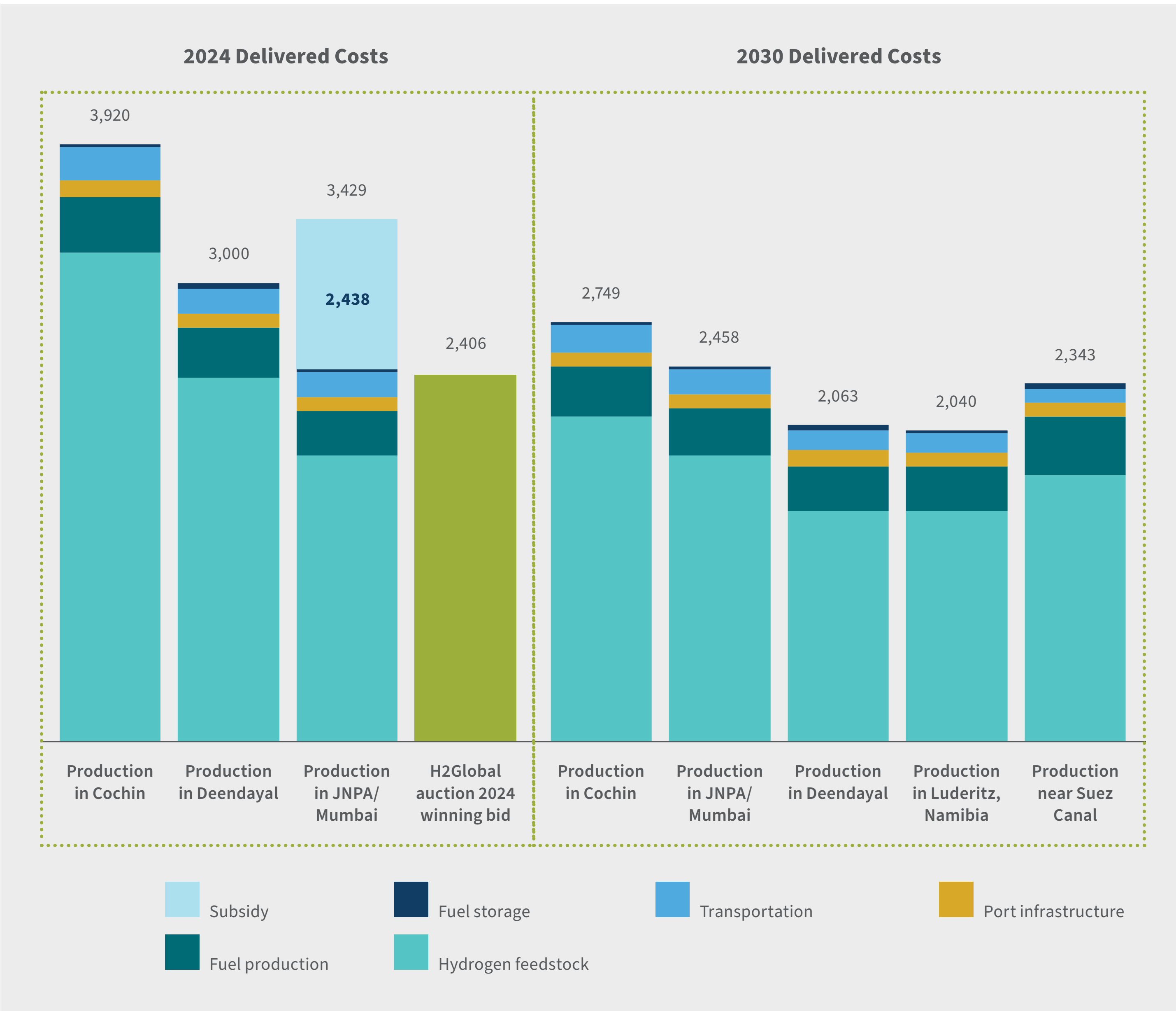
Exhibit 15 **Anticipated production volumes at Cochin, Deendayal, and JNPA/Mumbai compared with expected demand by centres in the EU — the Netherlands, Belgium, and Germany**



Note: The Netherland's imported H_2e. volume is based on a projected ammonia 2030 import volume from the Institute for Sustainable Process Technology's 2024 report. Germany's imported H2 volume is based on the average of the H2 import volume range according to Clean Energy Wire's 2023 factsheet on Germany's National Hydrogen Strategy. Belgium's imported H2 volume is from Belgium's Vision and Strategy Hydrogen 2022 report. RMI graphic. **Source:** RMI analysis

This analysis focuses on the Port of Rotterdam due to its status as Europe's largest port. India is strategically positioned to export green ammonia to Rotterdam, benefiting from lower production costs than other green hydrogen-exporting nations such as Egypt and Namibia. While abundant and low-cost renewable resources are key, lower production costs are also achievable due to better financial parameters such as weighted average cost of capital (WACC) creating a lower financial risk in comparison to the other green hydrogen-producing nations in the analysis. Additionally, the impact of subsidies is evident, as the production costs at JNPA and Mumbai in 2024 align with the expected costs for 2030, as illustrated in **Exhibit 16**.

Exhibit 16 **Total delivered cost of green ammonia imported to Rotterdam (US$/ton VLSFOe)**



Note: Numbers in bold indicate post-subsidised production costs based on the announced subsidies.
RMI graphic. **Source:** RMI analysis

When subsidised, production near JNPA/Mumbai is comparable to the winning bid in the H2Global auction announced in 2024.[91] This shows the impact of capital and operational expense subsidies in making costs globally competitive. Although the 2030 analysis shows that costs are competitive with major production hubs, they can be further reduced if policy support persists. Countries must also prioritise finding the best scenario for procuring low-cost renewable energy to lower production costs of green hydrogen. Additional initiatives, such as concessional funding, loan guarantees, and incentive programs like grants, can also contribute to lowering costs. Although exporting green ammonia to projected demand centres is promising, it is essential to also prioritise domestic use cases to capitalise on the benefits of reduced transportation costs.

Key Insights

1. **Without subsidies, the LCOA for Indian ports in Maharashtra, Tamil Nadu, and Odisha ranges from around US$911/ton to US$1,100/ton in 2030. Currently, subsidies, including capital support and electricity charges waivers, reduce the LCOA to as low as US$764/ton–US$1,255/ton. This demonstrates up to a 37% reduction in costs in states with favourable policies.**

2. **East Coast ports, particularly VOC and Paradip, are strategically located to serve major demand centres like Japan, Singapore, and South Korea, which are expected to require significant green ammonia imports, 4.4 million tons of hydrogen equivalent, as part of their decarbonisation goals by 2030.**

3. **West Coast ports like JNPA/Mumbai are ideally positioned to supply Europe, which aims to import 10 Mt of green hydrogen by 2030. Key EU terminals, such as Rotterdam and Brunsbüttel, plan to handle 3 Mt/y of green ammonia imports by 2030.**

4. **With subsidy supports, production costs among the Indian ports in 2024 are globally competitive. Assessed costs are similar to the H2Global auction's winning bid.**

5. **In 2030, Indian-produced green ammonia is comparable to other key exporters such as Australia, Namibia, and Egypt, but can be the most cost-effective if subsidy support remains.**

Recommendations for Accelerating Development of Ports into Green Hydrogen Hubs

> **Ports, as catalysts for the green hydrogen transition, must prioritise strategic infrastructure upgrades and forge global partnerships. Empowered with enhanced capabilities and investment allure, they are poised to shape vibrant green hydrogen ecosystems, driving innovation and economic growth opportunities.**

To unlock the potential of ports as green hydrogen hubs, it is essential to focus on strategic infrastructure enhancements and fostering global partnerships. As outlined in the preceding analysis, ports are uniquely positioned to drive the green hydrogen transition due to their capacity to integrate multiple roles — from production and storage to distribution and demand facilitation. However, to realise this vision, ports must be equipped with the necessary infrastructure upgrades, while simultaneously engaging in international collaboration to leverage advanced technologies, create stable demand, and attract investments. Ports can play a pivotal role in developing green hydrogen ecosystems by implementing essential steps to establish themselves as key hubs in this emerging energy landscape.

Based on the insights from the techno-economics of green hydrogen/ammonia projects at ports including the infrastructure and investment sizing for new and existing infrastructure, the following five key recommendations can enable the transition of ports to green hydrogen and derivatives hubs.

Facilitate land availabiliy

Ensure that sufficient land parcels in and around ports are available and accessible for green hydrogen projects and related industrial and infrastructure development.

To successfully establish ports as hubs for green hydrogen, ensuring the availability of land for producers, consumers, and infrastructure providers is crucial. In India, state governments are leasing government-owned land to industries at affordable rates. For instance, Gujarat is offering 40-year leases at ₹15,000/hectare with incremental increases.[92]

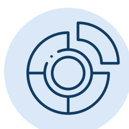
Ports, primarily Deendayal, Paradip, and VOC, have committed more than 4,500 acres (1,821 hectares) to more than 19 developers expressing interest in developing green hydrogen complexes.[93] With initial steps already underway, focus could be shifted onto the following:

Establish long-term leasing programmes

Implement state-supported long-term leasing programmes like Gujarat's model of 40-year leases at competitive rates,[94] to attract green hydrogen developers and create stable investment conditions for infrastructure.

Designate land for end-use industries

Set aside dedicated land parcels for industrial units that consume or facilitate green hydrogen, such as fertiliser plants, steel mills, refineries, and transport hubs. This supports the development of an integrated green hydrogen ecosystem, which is essential for long-term market stability.



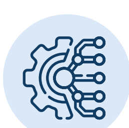
Create a tiered land allocation strategy

Develop a tiered strategy for land allocation that prioritises green hydrogen production facilities, end-user industries, and related facilitators.[viii] This ensures that critical areas of the green hydrogen ecosystem receive sufficient space and infrastructure support.

Map and facilitate demand creation

Map and facilitate demand for green hydrogen and its derivatives domestically (within and around the port) and internationally to drive the initial offtake and market creation.

Effective demand aggregation is essential for planning green hydrogen infrastructure as it provides the data necessary to size equipment accurately and gauge the need for various components. Conducting a detailed assessment of potential demand volumes and identifying where the product will be utilised are critical first steps. This process also aids in developing a timeline for infrastructure advancements and enables strategic decisions on repurposing existing infrastructure for integration into the green hydrogen supply chain.



Conduct a demand mapping analysis

Perform a comprehensive demand mapping exercise to estimate green hydrogen volumes and identify usage sectors to inform infrastructure sizing and requirements.

viii. A tiered land allocation strategy is a structured framework for allocating port land based on priority tiers to optimise utilisation, address diverse needs, and align with strategic goals. This approach helps ports balance operational demands, infrastructure development, and long-term planning.

Create global demand generation opportunities

Following demand mapping analysis, initiate demand mapping measures to strengthen production capacity. Target partnerships with international import ports, such as those in Europe and the Far East, for hydrogen trade agreements or green corridor initiatives. International collaboration with other ports can also help with connecting producers and potential demand centres. In 2022, the government of Queensland entered into a partnership with the Port of Rotterdam to establish an ammonia supply chain, facilitating the movement of clean energy from Australia to the EU.[95]

Facilitate local demand creation

In addition to export-oriented projects, foster local demand for green hydrogen by supporting a green hydrogen ecosystem near the port. Work with industrial stakeholders to co-locate projects with green hydrogen production facilities, offering land-based and infrastructural support.

Invest in backbone infrastructure development

Establish dedicated CUI, such intra-port pipelines, storage units, electricity transmission and distribution, and water and CO_2 pipelines, to ensure that the port infrastructure is ready to support exports and domestic markets.

To develop effective CUI as part of their transition to green hydrogen hubs, ports should focus on the following key actions:

Establish a hub-based CUI model

Design CUI based on projected demand and production, creating a shared infrastructure hub that supports increased production volumes while catering to local offtake needs. This approach reduces the need for costly captive infrastructure and allows for future scaling. A sustainable business model should follow by identifying investment pathways that reduce risks, such as revenue-sharing arrangements, fee-based access for multiple users, and risk-mitigation partnerships with private and public sectors.

Support bunkering and export facilities

Invest in CUI that includes bunkering hubs for green hydrogen and ammonia, as well as berths dedicated to large-scale exports, particularly for ammonia. Additionally, install appropriately sized storage infrastructure to align with forecast demand, ensuring that storage capacity matches production and offtake requirements for green hydrogen and derivatives.

Install intra-port transport pipelines for green hydrogen and CO_2

Install intra-port transport pipelines to facilitate efficient movement of green hydrogen and CO_2 within the port. These pipelines will streamline the transportation process for green molecules and support carbon management initiatives, reducing reliance on road transport, lowering operational costs, and enhancing safety and efficiency.

Ensure water supply

Leverage port access to water resources by facilitating freshwater sourcing or developing desalination facilities, which could be scaled for community use in water-scarce areas. Desalination can be a low-cost component, accounting for 1%–2% of project costs.[96]

Aggregate energy demand for green power

Act as energy aggregators by partnering with DISCOMs and independent power producers to pool demand from existing port industries. Aggregated demand helps secure green power at competitive rates, reducing the high costs associated with green hydrogen production.

Transition to be an active investor

Move beyond being enablers by becoming active investors, starting with joint pilots to demonstrate the viability of green hydrogen projects.

Investing in green hydrogen projects enables ports to diversify revenue beyond traditional sources like port dues and land fees. These investments foster sustainable income streams, decreasing reliance on vessel and cargo traffic. New revenue opportunities arise from hydrogen production, storage, export, and partnerships with industries focused on decarbonisation. This strategic shift strengthens income stability, supports the energy transition, and enhances resilience in a dynamic global market.

Identify and prioritise high-potential partnerships for joint venture opportunities

Partner with established green hydrogen developers and industrial players through joint ventures to co-invest in critical infrastructure such as electrolysers, storage facilities, and hydrogen refuelling stations, maximising technical expertise and resource allocation by offering land contribution as equity.

Initiate joint pilot projects

Collaborate with industry partners to launch joint pilot projects at the port that test the viability of green hydrogen production, storage, and export. These pilots will provide critical insights into system complexities and help assess the technical and economic feasibility of green hydrogen operations. Draw on successful international examples, such as the ammonia bunkering safety study by the Global Centre for Maritime Decarbonisation and Singapore's hydrogen refuelling pilot, to inform the design and execution of local pilot projects.[97]

Implement hydrogen bunkering and refuelling pilots

Set up initial hydrogen bunkering and refuelling facilities, following the example of ports like Pasir Panjang in Singapore. Such facilities will test the feasibility of green hydrogen as an alternative fuel, paving the way for decarbonising port and maritime operations.[98]

Establish green hydrogen industrial parks

In collaboration with private partners, set up green hydrogen industrial parks within port premises, where infrastructure, land, and utilities are jointly managed. These parks can attract a mix of hydrogen producers, technology developers, and industrial consumers in a single, co-located ecosystem.

Foster international collaboration

Promote international partnerships and collaboration with global ports or industries to integrate ports into the global green hydrogen and derivatives supply chain.

Establishing international partnerships and promoting knowledge sharing generates opportunities and enhances the adoption of green hydrogen infrastructure by aligning with global standards. Successful global partnerships are highlighted in the following case studies:

Port of Singapore's green corridor establishment: In 2024, the Port of Singapore signed a memorandum of understanding (MoU) with the Shandong Provincial Transport Department to create a green corridor between Singapore and China.[99]

Port of Rotterdam's supply chain creation: In 2023, the Port of Rotterdam signed an MoU with Spanish multinational oil and gas company Cespa to create the green hydrogen supply chain from Spain to the Netherlands.[100]

Ulsan Port's technology transfer initiative: South Korea's Ulsan Port signed an MoU with Korean Register of Shipping, Lotte Fine Chemical, HD Hyundai Heavy Industries, and HMM on the creation of the ammonia bunkering industry.[101] Collaborating with these companies, including technology providers, is a way to bring global standardisation into the field.

Conclusion and Way Forward

This report highlights insights and strategic actions for advancing green hydrogen infrastructure at key Indian ports — Deendayal, VOC, Paradip, Cochin, Mumbai, and JNPA — positioning them as green hydrogen hubs to meet domestic and international demands.

The recommendations outlined in section 5: *Recommendations for Accelerating Development of Ports Into Green Hydrogen Hubs* are derived from rigorous analysis and stakeholder consultations involving experts within the ecosystem. These recommendations serve as foundational suggestions for ports to strategically plan their next steps. However, it is essential to recognise that each port possesses unique characteristics, from land availability to financial resources, and varying interests among developers and consumers of green hydrogen. These recommendations should serve as a framework for ports to initiate discussions on the feasibility of implementing these actions. Detailed assessments will be necessary to ensure efficient implementation on the ground.

Leveraging existing infrastructure, including ammonia storage facilities and LNG terminals, provides a foundation for initial hydrogen and ammonia operations.

Ports like Cochin, Deendayal, and JNPA, which have electricity distribution licenses, can develop the substations and power systems required for large-scale electrolysis, integrating renewable energy more effectively.

Pipeline retrofitting for hydrogen blending is viable up to 23.5%, though blending beyond 20% may increase capital expenditures, emphasising the importance of targeted infrastructure upgrades. Repurposing LNG terminals offers a cost-effective approach; with much of the infrastructure in place, minor adjustments could enable ammonia exports. For instance, converting the Mundra terminal could save ₹20,669 crore (US$2.37 billion), and the Chhara terminal ₹28,990 crore (US$3.33 billion), making repurposing a financially prudent alternative to new infrastructure.

In addition to existing infrastructure, new infrastructure, particularly expanded greenfield ammonia storage, will be essential to developing hubs and supporting growing demand. Economies of scale reduce storage costs significantly up to 1.0–1.5 Mt/y, with marginal returns beyond this size. Efficient use of storage facilities can offset rising electricity costs, supporting a sustainable scale-up as demand increases.

Indian ports like Deendayal and VOC benefit from proximity to low-cost renewable energy, supporting competitive export to Asian markets. Additionally, the ports of Deendayal, Cochin, Mumbai, and JNPA are well positioned for green ammonia exports to European markets, enhancing their international competitiveness. State-level subsidies could further reduce production costs, enabling targeted cost-effective incentives.

Securing land parcels near ports will support green hydrogen development and industrial growth. Aggregating domestic and international demand for green hydrogen derivatives will foster early market adoption and provide a consistent demand base for both local supply and exports.

Investing in shared infrastructure — such as intra-port pipelines, ammonia storage, and distribution systems — will help ports serve as robust export hubs and domestic centres for green hydrogen production.

Global partnerships with industry leaders and international ports will integrate Indian ports into the global green hydrogen supply chain, expanding market reach.

Transitioning from facilitators to active investors, Indian ports can lead pilot projects to demonstrate green hydrogen's viability, attracting further investment and supporting market adoption.

With these strategic actions, Indian ports can capitalise on their geographic positioning and infrastructure to drive India's decarbonisation goals, becoming key players in the global clean energy transition.

Appendices

Appendix A: Characteristics differentiation and possible repurposing of infrastructure from LNG to ammonia

Comparison between LNG and ammonia on key parameters

The global energy transition has brought renewed focus on low-carbon fuels like liquefied natural gas (LNG) and ammonia, both of which play critical roles in decarbonising energy systems and industries. While LNG is a well-established energy carrier primarily used for power generation and heating, ammonia is emerging as a versatile solution for energy storage, hydrogen transport, and as a direct fuel in industries and shipping. The distinct physical, chemical, and logistical characteristics of LNG and ammonia, highlighted in **Exhibit A1**, shape their roles, applications, and infrastructure requirements. This differentiation not only influences their adoption but also determines their compatibility with existing and future energy systems.

Exhibit A1 Comparison of key components between LNG and ammonia

Variable	Unit	LNG	Liquid NH_3
Density	t/m3	460	730
LHV	MJ/kg	50	18.6
Boiling point	°C	–162	–33
Storage	–	Requires highly insulated tanks to prevent Boil-off gas (BOG) losses.	Easier to handle than LNG from a refrigeration standpoint.
Safety and risks	–	Flammable, with explosion risks in confined spaces. Methane GHG leakages.	Toxic and corrosive. Combustion produces NOx, which requires mitigation technologies.
Storage tanks	The tank's structural integrity must be verified for compatibility with ammonia's different thermal and physical properties. The materials used in LNG tanks must be assessed and possibly coated or replaced with ammonia-resistant materials (e.g., stainless steel or specially treated steel). Moreover, LNG tanks are insulated for extremely low temperatures while ammonia is stored at –33°C, leading to possible overdesign and inefficiency.		

Exhibit A1 Comparison of key components between LNG and ammonia (continued)

Variable	Unit LNG Liquid NH_3
LP	LNG pipelines are designed for low pressures at cryogenic temperatures. Liquid ammonia, though stored at low temperatures, typically operates at higher pressures (depending on storage temperature). LNG pumps and compressors may not be suitable for ammonia's physical properties and may need to be replaced or retrofitted.
Boil-off gas (BOG)	LNG BOG systems are designed to manage methane vapour while ammonia vapour requires entirely different handling systems due to its toxicity and environmental impact. Thus, new systems must be installed to manage ammonia vapour.
Regasification unit	The unit would not be used in export terminal mode.
Pipelines	Existing pipelines may need to be replaced or lined with materials like stainless steel, ammonia-compatible alloys, or protective coatings. Therefore, a thorough review is critical to ensure the structural integrity of the pipelines. The pipelines must be recalibrated for the increased mass flow and pressure drops. Finally, ammonia spills need robust containment measures to protect personnel and the environment, which may not be present in LNG systems.
Loading arm and jetties	Loading arms used for LNG will need to be replaced or retrofitted with ammonia-compatible materials to prevent corrosion and leaks during ship loading/unloading.
Leak detection system	LNG terminals focus on flammability risks, while ammonia introduces significant toxicity hazards. A retrofitted ammonia terminal must install ammonia-specific gas detection and ventilation systems.
Civil works	Supporting structures must be assessed for increased load-bearing requirements (ammonia density is higher). Other works might include spill containment areas designed for cryogenic liquids, berms, dikes, and containment walls that must be lined with ammonia-compatible materials to prevent leaks into the soil or groundwater. Fire protection systems designed for LNG may need upgrading to address ammonia combustion characteristics.
O&M	Ammonia systems generally require more frequent inspections due to their corrosive nature and the risk of stress corrosion cracking (SCC).

RMI graphic.

Existing study and economic impact of converting LNG terminal components for ammonia usage

Exhibit A2 Feasibility of repurposing of terminal components

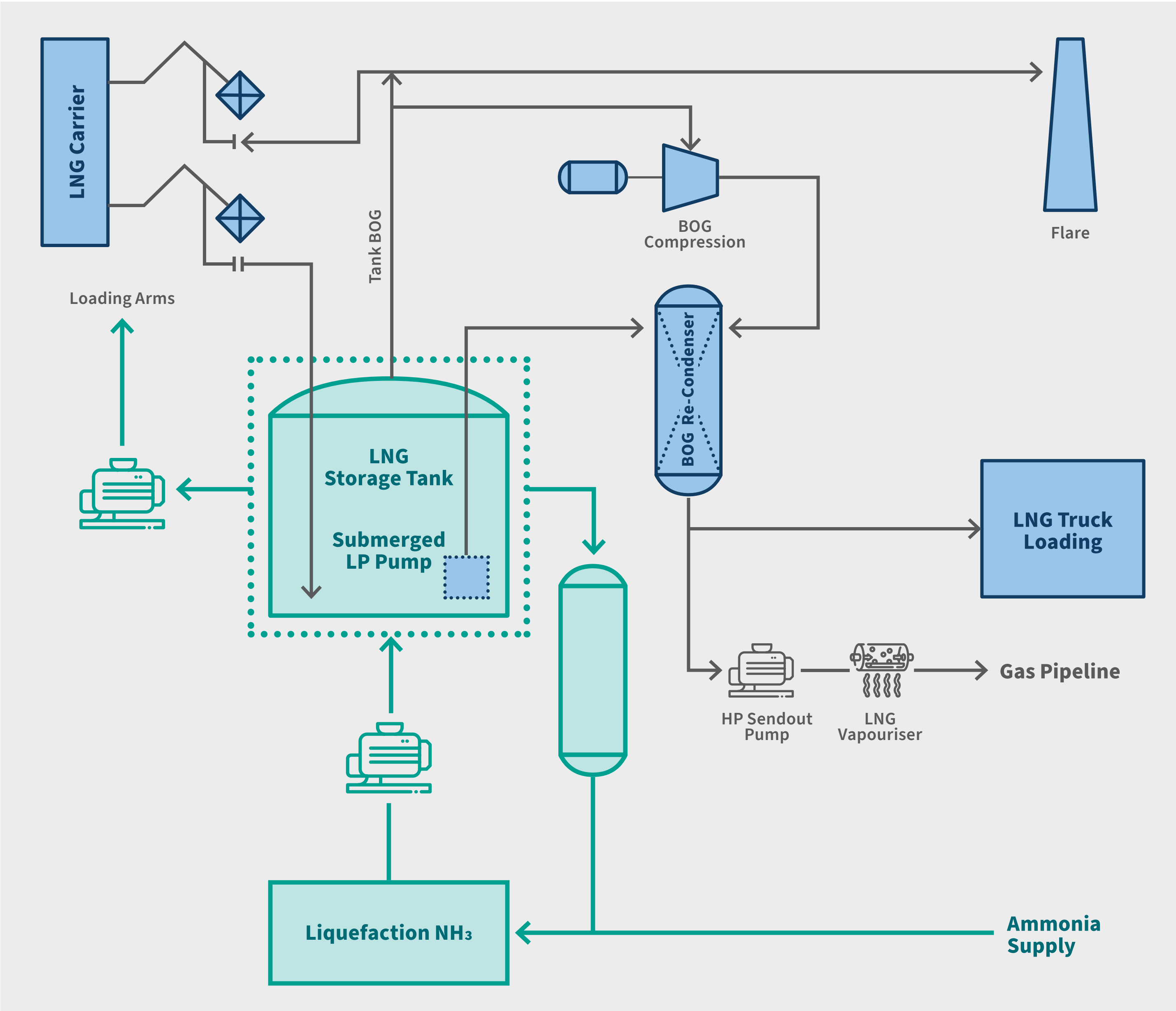
Terminal component	Economic feasibility of repurposing
Storage tanks	If reuse is viable, about 50% of the LNG capital expenditure can be recovered. The cost of modifications ranges from 1%–1.5%, though this comes with reduced capacity. Additionally, pre-investment expenses account for 22.5% of the LNG capital expenditure.
Pumps	Replacement cost of 3%–5% of LNG terminal CAPEX.
Piping	Modification cost of 2%–4% or pre-investment cost of 0.5%–1% of LNG terminal CAPEX.

RMI Graphic. **Source:** Fraunhofer Institute for Systems and Innovation Research ISI study titled LNG Terminals for Liquid Hydrogen or Ammonia: Analysis of Technical Feasibility under Economic Considerations, **https://publica.fraunhofer.de/entities/publication/493d48c5-6e8b-4e21-8e39-a7ebb35eef64**

Methodological framing and assumptions for converting LNG import terminal to ammonia export terminal

Ammonia terminals are like LNG terminals as both operate at low temperatures with cryogenic equipment or high pressures. One of the main differences is the corrosion and toxicity that is specific to ammonia. Due to this, certain components need to be repurposed to accommodate the use of ammonia. Storage tanks, LP pumps, and pipelines are repurposed, while systems like BOG need to be replaced. Components such as liquefaction units are also added as seen in **Exhibit A3** due to the process change that comes with the conversion of an import LNG to export ammonia terminals.

Exhibit A3 Flow diagram for the ammonia export terminal repurposed from an LNG import terminal



RMI graphic. **Source:** *Hybrid LNG & Ammonia Infrastructure: Key to a Green Economy,* Black & Veatch, https://www.bv.com/en-US/resources/hybrid-lng-and-ammonia-infrastructure-key-to-a-green-economy-ebook

When calculating the adequate equipment sizing to perform the cost analysis, two main parameters are key. Terminal capacities are determined by the logistical variables required for the transport of green ammonia. Optimising terminal capacity in turn feeds into the cost analysis where equipment is sized according to the required capacities and total costs are calculated. The definition of the capacity of the ammonia plant and cost estimation follows the steps shown in **Exhibit A4** on the next page.

Exhibit A4 Key metrics for the analysis focusing on converting LNG import terminals to ammonia export terminals

No.	Item	Influenced by
1.	**Capacity of the terminal**	a. Size of future vessels b. Loading duration and maximum time between ships c. Availability of the terminal
2.	**Cost of terminal**	a. Number and size of tanks (strategic and operational stock) b. Low-pressure pumps (height of tanks and loading arm, pipes distance, flow rate) c. Loading system d. Ammonia pipelines (gas and liquid) e. Liquefaction unit f. Civil works g. Project contingency

RMI graphic.

The LNG terminal considered for this analysis is 5 Mt/y (most Indian LNG import terminals are of 5 Mt/y), and is the assumed volume for transportation and characterisation of the ammonia export terminal. These are shown in **Exhibit A5**.

Exhibit A5 Capacity calculation metrics for the analysis focusing on converting LNG import terminals to ammonia export terminals

Capacity of terminal	Units	Value
Annual throughput	TWh	26.7
Annual throughput	Mt	5.2
Annual throughput	m^3	70,89,488
Terminal capacity	GW	4.10
Carrier LHV	MJ/kg	18.6
Number of carriers/year	No	81

Exhibit A5 Capacity calculation metrics for the analysis focusing on converting LNG import terminals to ammonia export terminals (continued)

Capacity of terminal	Units	Value
Loading duration	Hours	80
Interval between carriers	Hours	6
Loading system AF	–	0.8
Shipping duration India–Europe	Days	36
Dedicated India–Europe tankers needed	No	9
Size of large tanker		
Vessel/tanker capacity	m^3	87,000
Tanker capacity	Tons	63,510
Density	t/m^3	0.73
Pressure	Bar	1.2
Temperature	C	-33

RMI graphic.

A terminal with three storage tanks of 74,000 m^3 of ammonia to load large vessels of 87,000 m^3 at a flow rate close to 1,000 m^3/h would have a capacity or nearly 4.2–4.9 Mt/y or 21–25 terawatt-hours per year (TWh/y). Taking these metrics for capacity and the cost assumptions for components in **Exhibit A6** on the next page into consideration, the final cost of the terminals was calculated based on the scenarios and their conditions.

Exhibit A6 Assumptions for the calculation of converting LNG import terminals to ammonia export terminals in India

Variable	Units	Greenfield ammonia terminal	Brownfield: post-commissioning	Brownfield: prior-commissioning
LNG terminal CAPEX reference	€/ta	–	94.5–104.8	94.5–104.8
LNG terminal economic lifetime	Year	–	50	50
Remaining LNG economic lifetime	Year	–	20	20
Lifetime extension after repurposing	Year	–	10	10
WACC	%	3%	3%	3%
Fixed O&M	% capex	3%	3%	3%
Variable O&M	% capex	1%	1%	1%
Storage tank	€/t	652/947.70	3% of LNG tank capex	5% of LNG tank capex
LP pumps	€/kW	585.00	3% of the capex of pump used in the LNG terminal	585.00
Jetty	€/kW	1.93	1.93	1.93
Loading arm	€/unit	71,100.00	71,100.00	71,100.00
Liquid NH_3 pipeline	€/GW-m	1,118.47	40% of the capex of the pipeline used in the LNG terminal	10% of the capex of the pipeline used in the LNG terminal
Liquefaction compressor	€/kW	2,160.00	2,160.00	2,160.00
Liquefaction condenser	€/kg/h	740.47	740.47	740.47
BOG	€/kW	77.50	77.50	77.50

Exhibit A6 Assumptions for the calculation of converting LNG import terminals to ammonia export terminals in India (continued)

Variable	Units	Greenfield ammonia terminal	Brownfield: post-commissioning	Brownfield: prior-commissioning
Civil works	% equipment/ materials	80%	100%	100%
Engineering and project management	% equipment/ materials	30%	6%	3%
Owner cost	% equipment/ materials	20%	4%	2%
Contingency	% equipment/ materials	10%	2%	1%

RMI Graphic. **Source:** "LNG Plant Cost Estimation," Oxford Institute of Energy Studies, **https://www. oxfordenergy.org/wpcms/wp-content/uploads/2014/02/NG-83.pdf**; *LNG Terminals for Liquid Hydrogen or Ammonia: Analysis of Technical Feasibility under Economic Considerations*, Fraunhofer Institute for Systems and Innovation Research ISI, **https://publica.fraunhofer.de/entities/publication/493d48c5-6e8b-4e21-8e39-a7ebb35eef64**

The cost of the different components was obtained by consulting several sources. The cost characterisation does not replace a complete engineering and procurement analysis; instead, it provides reference values to estimate the cost of new or repurposed ammonia terminals.

LNG terminal capital expenditures were taken from the announced costs of the Chhara and Mundra terminals in India to give a range of capital expense costs. The same goes for ammonia storage tanks. Components such as storage tanks, LP pumps, and liquid NH_3 pipelines are repurposed with the assumptions mentioned in **Exhibit A6**. The numbers for costs such as civil works, engineering and project management, owner cost, and contingency were assumed in accordance with the prior- and post-commissioning scenarios where portions of these costs are already incurred up front in the LNG terminal.

Appendix B: Methodological framing and assumptions for cost analysis on portside ammonia storage at the six considered ports

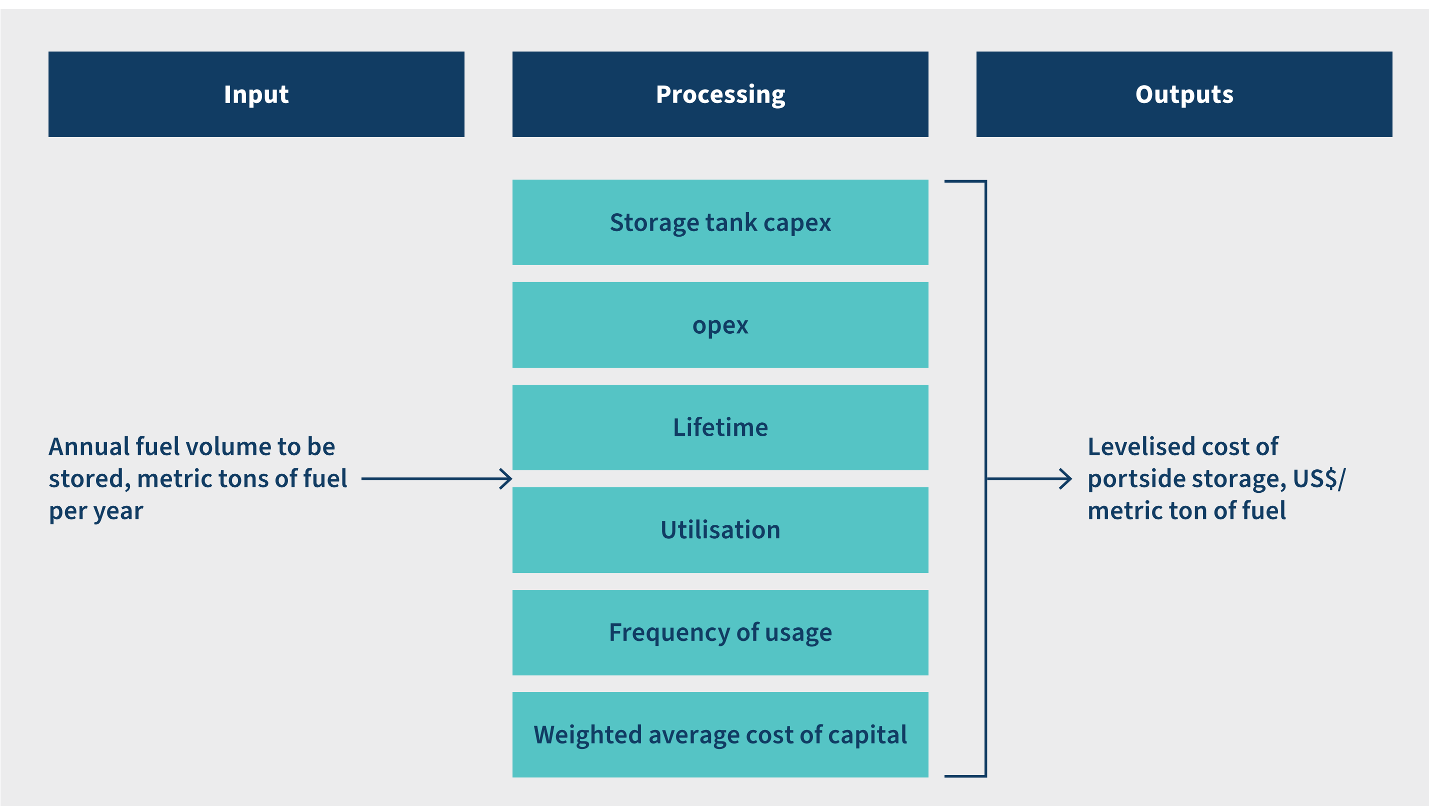
To assess how infrastructurally ready ports are for exporting and bunkering green fuels and how much additional investment is required, cost modelling was performed for the six major ports in India considered for this study.

For cost modelling, all green fuel that was bunkered or exported was assumed to be green ammonia. Cost modelling was performed to estimate:

1. The total delivered cost of bunkering or exporting ammonia, and
2. The total lifetime cost of ammonia portside storage tanks.

The total delivered cost of fuel includes the entire green fuel supply chain. This includes the cost of green hydrogen production and storage, ammonia production and storage at the production site, transport costs of ammonia from the production site to the port, and port infrastructure costs. If the fuel is exported and not just bunkered, the total delivered cost of fuel also includes ocean-going vessel transport costs and portside infrastructure at the importing port.

Exhibit A7 Modelling framework for portside storage assessment



RMI graphic.

The total lifetime cost of the portside ammonia storage tanks considers both capital and operational expenditures incurred over a 30-year lifetime. Lifetime costs and levelised costs for these ammonia portside storage tanks were tested for various ammonia handling volumes. This was done to test the sensitivity of the total investment, the levelised port infrastructure cost, and the infrastructure required for the volume of ammonia handled. If a port has existing ammonia storage, this infrastructure is accounted for in the total lifetime costs and levelised costs.

When a port authority develops its green fuel infrastructure strategy, it should consider its own ambitions and the green fuel production volumes of nearby projects. The analysis utilises each port's 2030 green ammonia handling goal, if it is known. If the port's volume goal is unknown, then the assumed ammonia handling value is based on the port's state total estimated 2030 green ammonia production volume. Realistically, these ports are not likely to handle the state's entire ammonia production volume because the fuel can be used domestically or exported from other ports. However, as mentioned above and in **Exhibit A7** on page 73, port infrastructure costs were modelled at various ammonia handling volumes, including at 100%, 50%, and 20% of the volumes.

Exhibit A8 Cost assumptions for portside ammonia (at production site) storage cost analysis

Category	Ammonia	Source(s)
CAPEX	US$843/metric ton–US$1,418/metric ton NH_3	RMI assumption based on HyDelta, Nayak-Luke et al., "Techno-Economic Aspects of Production" (2022)
OPEX	3% of capex	HyDelta; Lloyd's Register & UMAS "Fuel production cost estimates and assumptions" (2019)
Electricity requirement	37.8 kWh/metric ton NH_3	Lloyd's Register & UMAS, "Fuel production cost estimates and assumptions" (2019)
Tank utilisation	80%	Industry experts
Maximum usage frequency	20 times/year	Industry experts

RMI graphic.

Appendix C: Methodological framing and assumptions for cost analysis on portside green ammonia production and landed cost to global bunkering hubs in Europe and South Asia

The cost of green ammonia production is estimated as an average across five production scenarios analysed in this study. Two scenarios involved co-located facilities for solar power with batteries and green ammonia production, differing in their reliance on the grid. The other three scenarios considered non-co-located setups for renewable energy and green ammonia production. Among these, two scenarios considered production of renewable energy and green ammonia within the same state: one utilised solar power, batteries, and the grid, while the other combined solar and wind power with batteries and the grid. The third scenario involved generating renewable energy (solar and wind) in a different state, transmitting it via the grid, and incorporating battery storage.

Exhibit A9 Techno-economic assumptions for green ammonia production cost and landed cost at major bunkering hubs

Category	Variable	Unit	2024	2030
Electrolyser direct capex	Electrolyser uninstalled CAPEX (Stack + BOP)	US$/kW	741.50	248
	Stack overall	US$/kW	333.68	111.60
	Balance of plant overall	US$/kW	407.8	136.4
Electrolyser efficiency and durability	Total system energy requirement	KWh/kg	53.65	46.60
	Stack lifetime	Hours	71,666	100,000
Electrolyser indirect capex: EPC + land	Land cost	US$/acre	0	0
Electrolyser opex: Labour and overhead	Insurance	%	0.00	0.00
Hydrogen storage capex, O&M, operation	H_2 storage capex kg	US$/kg	466	345
	H_2 storage capex kWh	US$/kWh	14.13	10.45
H_2 storage indirect capex: EPC + land	Land cost	US$/acre	0	0

Exhibit A9 Techno-economic assumptions for green ammonia production cost and landed cost at major bunkering hubs (continued)

Category	Variable	Unit	2024	2030
Battery	Battery capex	US$/kWh	266.36	153.33
	Battery opex	US$/kWh-year	9.63	6.02
	Battery efficiency	%	90	92.5
	Battery lifetime	Years	15	15
Renewables capex	Solar single-axis tracking capex	US$/kW	650.60	469.88
	Onshore wind capex	US$/kW	802.41	751.81
	Solar degradation	%/ year	0.40	0.40
Renewables O&M	Solar O&M	US$/kW-year	4.22	2.65
	Onshore wind O&M	US$/kW-year	33.52	31.46

RMI graphic.

Exhibit A10 Levelised green ammonia cost model assumptions for 2030 production

Category	Assumption	Source
Overall CAPEX	US$611/metric ton ammonia	RMI assumption based on Fasihi et al., "Global potential of green ammonia..." (2021); Nayak-Luke et al., "Techno-Economic Aspects of Production..." (2021)
Electricity consumption	719 kWh/year	Cesaro et al., "Ammonia to power: Forecasting the levelised cost of electricity from green ammonia in large-scale power plants" (2020)
OPEX	4% of CAPEX	Lloyd's Register & UMAS "Fuel production cost estimates and assumptions" (2019)

RMI graphic.

Exhibit A11 Assumptions for portside storage

Category	Assumption	Source
CAPEX	US$1,156/metric ton–US$1,418/metric ton NH_3	RMI assumption based on HyDelta (2022) and Nayak-Luke et al. (2021)
OPEX	3% of capital expenditures	HyDelta (2022); Lloyd's Register & UMAS (2019)
Electricity requirement	37.8 kWh/metric ton NH_3	Lloyd's Register & UMAS (2019)

RMI graphic.

Exhibit A12 Assumptions for bunker vessel (based on a chemical carrier powered by VLSFO) for the ocean transport of green ammonia to major bunkering hubs globally

Category	Assumption	Source(s)
CAPEX	US$25 million/bunker vessel	Industry experts
Bunkering crew & operational costs	US$8,000/day	Industry experts
Size	12,000 metric tons NH_3/MeOH	Assumption
Bunker vessel utilisation	60%	Industry experts

RMI graphic.

Exhibit A13 Conversion factor for the energy equivalency of ammonia to VLSFO

Category	Assumption
Energy equivalency of ammonia to VLSFO	2.18 kg ammonia/kg VLSFO

RMI graphic.

Exhibit A14 Assumptions for ocean transport of green ammonia to major bunkering hubs globally

Category	Assumption	Source
Laden energy consumption	363 MWh/day	Industry experts
Ballast energy consumption	323 MWh/day	Industry experts
Ship speed	15 knots	RMI assumption
Loading + unloading time	4 days	RMI assumption
Charter cost	US$23,000/day; or US$80,000/day	RMI assumption based on Salmon et al., "Green ammonia as a spatial energy vector: a review" (2021); Argus Media (2023)
Insurance cost	12,600 US$/day	RMI assumption

RMI graphic.

Exhibit A15 Assumptions for other economies for landed cost competitiveness analysis

	India	Netherlands	Namibia	Egypt	Singapore	Australia
Cost of debt	9%	8%	12%	18%	8%	8%
Cost of equity	13%	12%	16%	22%	12%	12%
Debt	70%	70%	70%	70%	70%	70%
Equity	30%	30%	30%	30%	30%	30%
WACC	10.17%	9.20%	12.92%	18.76%	9.20%	9.20%
Inflation rate	2%	2%	2%	2%	2%	2%
Tax rate	30%	26%	32%	23%	17%	30%

RMI graphic.

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