Australia's National
Science Agency

Northern Territory Low Emissions Carbon Capture Storage and Utilisation Hub

Transnational CO_2 Shipping

Logistics and Technoeconomic Model – Task 8 Report

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CSIRO Energy

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Foreword

Transitioning the global energy system while rapidly reducing emissions to net zero by 2050 is a vast and complex global challenge.

Modelling of a range of emissions pathways and decarbonisation scenarios from the Intergovernmental Panel on Climate Change (IPCC, 2023a), International Energy Agency (IEA, 2024) and Net Zero Australia (NZA, 2024) shows that to meet net zero 2050 greenhouse gas emissions targets, a wide range of emissions reduction technologies will be required to decarbonise existing and future industries globally (IPCC, 2023b).

These organisations identify that emissions elimination from hard-to-abate and high-emissions industries will require using carbon capture and storage (CCS) alongside other abatement strategies, such as electrification, underpinned by power generation from renewable energy sources such as photovoltaics and wind.

Globally, there is considerable effort to identify industrial hubs and clusters where common user infrastructure can enable rapid decarbonisation of existing industries and future low-emissions industrial development.

Australia has an opportunity to create new low-carbon growth industries and jobs in these areas, but lacks the infrastructure, skills base and business models to realise this. The transition to net zero will have greater impact on regional communities, particularly those reliant on industries in transition, but it may also create economic opportunities through a wide range of new industries and jobs suited to regional areas.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) is working to identify decarbonisation and transition pathways for existing and potential future industries that may be established in the Northern Territory by developing a Low Emissions Hub concept in the Darwin region.

CSIRO has established a portfolio of projects to explore and evaluate a range of emissions reduction and emerging transition technologies and approaches. This includes research into Northern Territory renewable energy potential, hydrogen demand generation and storage, and carbon capture utilisation and storage (CCUS). CSIRO is working collaboratively with industry and government to understand their needs, drivers and strategic directions so that our research is informed and relevant. This includes establishing appropriate pathways and partnerships to understand and incorporate the perspectives of First Nations peoples.

A key activity is the research into a business case project (CSIRO, 2024) that aims to enhance understanding of the viability of a CCUS hub centred on the Middle Arm of Darwin Harbour.

The work has three elements comprising 15 tasks:

1. analysing macroeconomic drivers, Northern Territory and regional emissions, low-emissions product markets (Ross et al., 2023), identifying key learnings from other low-emissions hubs being developed globally, and cross-sector coupling opportunities (Tasks 0–5)

2. completing CCUS hub technical definition and technical risk reduction studies, including detailed studies on the infrastructure requirements for a CCUS hub, renewable power requirements for existing and potential future industries, and road-mapping for CO_2 utilisation industries that could be established to produce low or net zero products (e.g. zero-emission chemical feedstocks) (CSIRO, 2023) (Tasks 6–9)
3. creating a business case to appreciate the scale of investment required to develop a Low Emissions Hub and the economic returns from doing so; this will lead to suggested business models and routes of execution (Tasks 10–14).

The CCUS business case project will involve research that is based on possible industrial development scenarios, models of future potential emissions, market demand, technologies and costs. The project is intended to provide an understanding of possible future outcomes. Industry development will be determined by individual industry proponent investment decisions, government policies and regulations, and the development trajectories of technologies essential to the energy and emissions transition.

On completion of this research, outcomes of the CCUS business case project will be made publicly available.

The work summarised in this report comprises Task 8 of the Northern Territory CCUS business case project. It assesses the technical and logistical considerations around CO_2 shipping and estimation of costs. Understanding CO_2 shipping is an important consideration in the development of CCUS hubs globally as it can provide additional volumes of CO_2 for storage, which could both help enable CO_2 emissions reductions from regions without suitable CO_2 storage geology and provide sufficient volume to lower the unit cost of CO_2 storage.

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Acknowledgements

CSIRO acknowledges the Traditional Owners of the land, sea and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture, and we pay our respects to their Elders past and present.

The authors of this report acknowledge the support and funding provided by CSIRO to undertake this work. We thank the internal CSIRO independent peer reviewers for their review of the report and valuable comments and suggestions.

While this report is an output from a CSIRO-funded initiative, we thank our industry and government collaborators for their insights, contributions and suggestions, which have improved the report outcomes. In addition, we thank NT-DIPL, Woodside Energy, Total Energies and Santos for their insights and advice on CO_2 shipping. In addition, CSIRO has had valuable discussions with SINTEF and Equinor (Northern Lights), which have enabled validation of model input assumptions and costs.

Although CSIRO has sought feedback from government and industry on the technical content of the report, CSIRO has sole discretion on including such feedback.

Northern Territory Low Emissions Carbon Capture Utilisation and Storage Hub business case project

The Northern Territory Low Emissions Carbon Capture Utilisation and Storage Hub business case project is a result of a collaborative approach between CSIRO, government and industry to develop a business case to assess the viability of a large-scale low-emissions carbon capture utilisation and storage hub outside Darwin.

The project includes inputs from the wider Northern Territory Low Emissions Hub (NT LEH) collaboration group, whose current members include the Northern Territory Government, Xodus, INPEX, Santos, Woodside Energy, Eni, TotalEnergies, Tamboran Resources and SK E&S.

Abbreviations

A$	Australian dollar
ACCUs	Australian Carbon Credit Units
Barg	Bar gauge pressures
CapEx	Capital expenditure
CCTS	Carbon capture transport and storage
CCS	Carbon capture and storage
CCUS	Carbon capture utilisation and storage
CEF	Connecting Europe Facility
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CPI	Consumer price index
CRF	Capital recovery factor
DWT	Deadweight tonnage
€	Euro
EOR	Enhanced oil recovery
FEED	Front-end engineering design
FID	Final investment decision
IEAGHG	International Energy Agency Greenhouse Gas R&D Programme
kn	Knots
kWh	Kilowatt hour
LCO_2	Liquefied carbon dioxide
LCOT	Levelised cost of transportation
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
m^3	Cubic metre
MASDP	Middle Arm Sustainable Development Precinct
MCR	Maximum continuous rating (main engine total power)
MMBTU	One million British thermal units
Mtpa	Millions of tonnes per annum
MWh	Megawatt hour
N_2	Nitrogen gas
NO_x	Nitrogen oxides
NT-DIPL	Northern Territory Department of Infrastructure, Planning, and Logistics
OpEx	Operational expenditure
PCI	Project of Common Interest

£	British pound
PPA	Power purchase agreement
SFC	Specific fuel consumption
SINTEF	Stiftelsen for industriell og teknisk forskning (The Foundation for Industrial and Technical Research)
SO_x	Sulphur oxides
t	Tonne
US$	United States dollar
¥	Japanese yen

Summary

Globally there is significant interest in CO_2 shipping as an enabling mechanism for jurisdictions that have limited geological storage so that they can transport captured CO_2 to areas where CO_2 geological storage capacity is available and thus reduce their greenhouse gas emissions.

The carbon capture, transport and storage (CCTS) value chain is often described in terms of three key components: (1) point source carbon capture, after which the CO_2 is either compressed or liquefied before being transported; (2) transport, including by pipelines, road/rail or ships; and (3) utilisation, for example in the production of various chemicals, or storage permanently within deep geological formations.

Previous research has highlighted that for long distances, shipping often becomes the lower-cost alternative compared with pipelines, which require large upfront capital expenditure (Jakobsen et al., 2013; Smith et al., 2021). Given the significant potential geological CO_2 storage capacity of the basins offshore of the Northern Territory (Johnstone and Stalker, 2022), there is the possibility for CO_2 captured overseas or within other parts of Australia to be stored there, along with CO_2 that has been captured from existing liquefied natural gas (LNG) plants and future Middle Arm Sustainable Development Precinct[1] (MASDP) facilities operating in Darwin.

This report:

1. provides an overview of the CCTS value chain, describing in detail the key assets required to transport CO_2 from its capture source to the final storage site
2. describes previous models that have been developed, as well as recent contributions to issues relevant to the value chain
3. presents results of the development of logistics and technoeconomic models to estimate the levelised cost of importing CO_2 from the Port of Kawasaki, Japan, to the Port of Darwin.

The results form inputs into the overall economic assessment of a CCUS hub associated with the CCUS business case project. CSIRO has consulted widely with industry and the Northern Territory Government for guidance on the inputs into the models used. It is important to note, however, that the results presented herein do not consider detailed proponent design factors, their individual needs or commercial arrangements, but rather seek to understand system-levelised costs only and therefore should only be used for this purpose. The report does not include a detailed review of the technical elements of CO_2 shipping; however, where required appropriate literature is cited.

The modelling suggests that CO_2 shipping from Japan to Darwin could be realised at costs ranging from A$122/t to $224/t, with the variation driven in part by the annual volumes of CO_2 transported, as well as ship capacity.

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[1] https://middlearmprecinct.nt.gov.au/

The system boundaries used in the models presented are shown in Figure 1 and comprise liquefaction of CO_2 assuming that it is transported in a low-pressure state (7 barg and –46°C [Roussanaly et al., 2021]).

Once the CO_2 has been liquefied, it is transferred to a buffer storage facility. This facility contains a series of insulated storage tanks for the liquid CO_2 prior to loading onto a ship. A set of loading arms linked to the buffer storage facility attaches to the ship to transfer the CO_2. The CO_2 is then transported to the receiving port where the vessel docks and the CO_2 is unloaded to another buffer storage facility. This facility keeps the CO_2 in its liquid state until it can be sent to a permanent storage location via an export pipeline. Buffer storage allows for operational flexibility, since there may be interruptions with ship movements or storage flow rates. In addition, due to differences in pressure/temperature requirements it is not possible to directly inject CO_2 into a storage site from a ship.

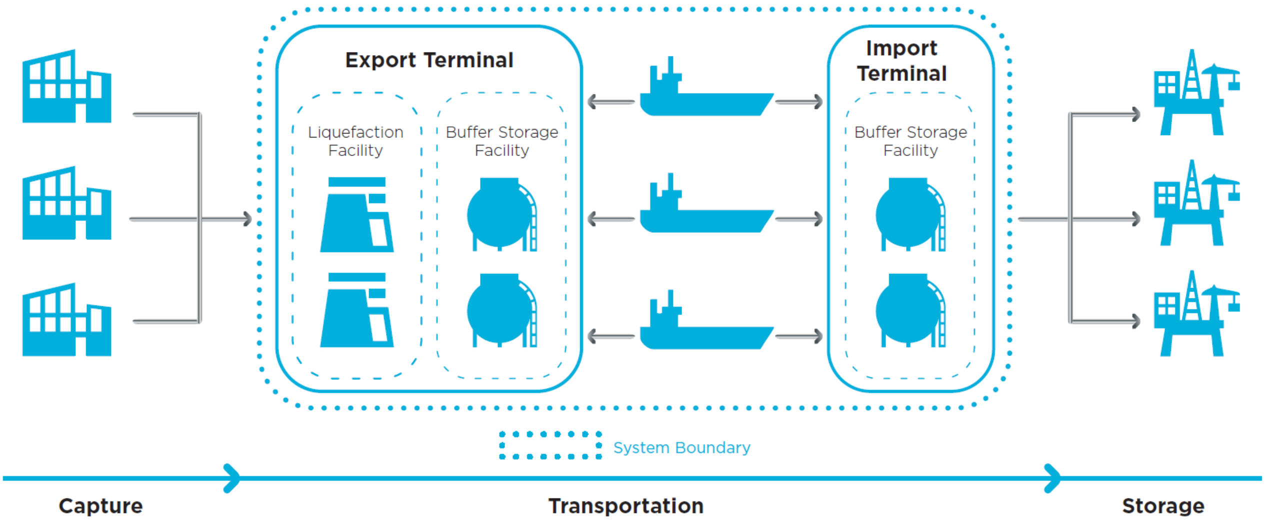

Figure 1: Overview of the CCTS value chain

Prior to developing the logistics and technoeconomic model presented in this report, a review of past models was conducted. Based on the models reviewed, the approach has been to use the tool developed by Daiyan et al. (2021) as a template for this study. The model combines a logistics and technoeconomic model to estimate the levelised cost of shipping CO_2 from the Port of Kawasaki to the Port of Darwin. The modelling involves two steps: (1) calculating the number of ships required to transport a desired volume of CO_2 each year; and (2) calculating the levelised cost of transportation (LCOT).

The modelling included a range of transported volumes from 1 Mtpa to 6 Mtpa and three LCO_2 ship capacities were investigated (40,000 m^3, 60,000 m^3 and 80,000 m^3). Regardless of which estimation method is used, there is significant uncertainty in estimating costs for ships that have yet to be constructed at the capacities proposed.

The required number of ships is based on capacity and on the desired amount of CO_2 to be transported per annum. Across the range of ship sizes (40,000–80,000m^3) and required transport capacities (1–6 Mtpa), a maximum of 11 ships would be required using the smallest ship size considered, or six ships for the largest size.

As expected, the annual number of port arrivals falls at a constant rate with larger capacity vessels. A change in total round-trip duration across different capacities is due to the longer load/unload times. However, if loading and unloading speeds were increased from 3000 m^3/per hour to 6000 m^3/per hour, the round-trip duration would reduce from 23 days to 22 days for the largest capacity ship, reducing berth utilisation by 50%.

At all capacities there is spare capacity within the fleet to transport greater volumes of CO_2. Focusing on the most extreme example, two 60,000 m^3 ships could complete 15 round trips transporting approximately 1.76 Mtpa, but they are constrained in the model to transport only 1 Mtpa. To account for this underutilisation in the cost model, the actual number of trips made is reduced to the minimum required, lowering the associated fuel costs. The reduced trips lead to each ship being filled close to capacity whilst still leaving capacity for additional volumes to be transported. Progressively scaling up the infrastructure would enable greater volumes to be transported, increasing the number of trips required. Having flexibility in the onshore infrastructure to accommodate fully loaded ships (i.e. optimise the model for vessel utilisation) could lead to reduced costs associated with CO_2 transport.

The variation in costs across different ship capacities is most pronounced at lower annual volumes. This is due to the capital expenditure associated with export storage rising as ship capacity increases. This variation decreases as economies of scale are realised, with the range in costs falling from between $184/t and $224/t with 1 Mtpa transported to between $122/t and $128/t with 6 Mtpa transported (Figure 2).

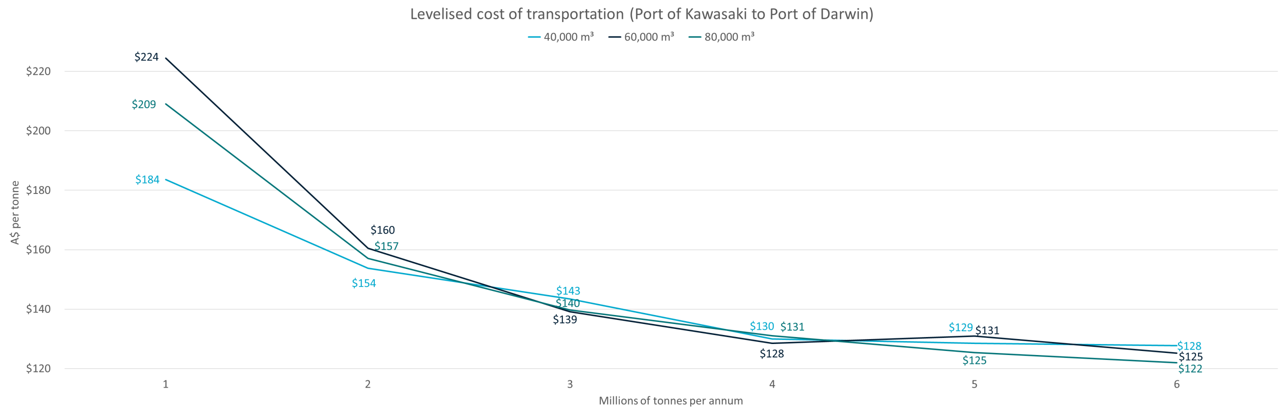

Figure 2: Levelised cost of transportation

This result is unsurprising given the assumptions of either constant or increasing economies of scale. These results do not imply that 80,000 m^3 is the capacity for which the levelised cost of transportation (LCOT) is minimised (larger ship sizes have not been modelled). Larger sizes might result in lower costs; however, economies of scale may be exhausted beyond a certain capacity. Constraints regarding vessel size could limit port access, and other unmodelled constraints might also prevent lower levelised costs.

The sensitivity analysis has shown that faster vessel speeds can lead to reduced fleet sizes, reducing the levelised cost despite higher rates of fuel consumption. One of the most significant factors in the technoeconomic model is the cost associated with the import terminal's buffer storage facility. Significant cost savings could be realised if the number of onsite storage vessels were reduced, leading to lower capital expenditure (CapEx).

Currently, it is assumed that the liquefied carbon dioxide (LCO_2) is unloaded off the site to a buffer storage facility and then progressively converted to a dense state before being transferred to an export tie-in pipeline. Greater conversion capacities and associated downstream capacities could reduce the amount of buffer storage required. Alternative methods of storage – for example, a second ship or ships spending longer at the wharf – could also reduce costs, but this would need to be balanced against ship utilisation rates.

There are several limitations and assumptions in the reported costs for each key asset required in this study. The CapEx equations often assume constant or increasing returns to scale, but this assumption may not hold true since facilities and ships at the proposed scales have not yet been constructed. While storage and liquefaction technologies are relatively mature, reducing the risk of failing to achieve cost efficiencies, the design and construction of larger LCO_2 ships are more uncertain. Few shipyards currently specialise in building liquefied gas container ships, and existing orders for other vessels could delay the expansion of the required fleets. Therefore, purchasing adequately sized vessels is identified as a key risk for minimising the costs of developing an LCO_2 value chain.

Achieving the lower end of this modelled cost range depends on using the largest ships modelled and leveraging economies of scale by spreading the fixed infrastructure costs over larger CO_2 volumes. The model uses formulas and parameters from existing literature, but the costs reflect a single set of assumptions about the value chain. It is not a cost-minimisation optimisation model, and other parameters or uncertainties could lead to more accurate cost estimates. However, the model does highlight areas where costs could be reduced through optimisation, such as by reducing the required buffer storage size or by using faster ships to minimise the fleet size and lower capital requirements. These cost reductions would then need to be weighed against additional risks, for example reduced buffer storage introducing operation risk.

1 Introduction

Globally, there is significant interest in CO_2 shipping as an enabling mechanism for jurisdictions that have limited geological storage so that they can transport captured CO_2 to areas where that CO_2 geological storage capacity exists and thus reduce their greenhouse gas emissions. This is of particular interest for hard-to-abate industries in these jurisdictions where long-term CO_2 abatement is required (e.g. iron and steel making). As shown in the *Task 2 report* of this study (Rogers et al., 2024), there is large potential CO_2 storage demand from these industries within the region.

While CO_2 shipping costs are high (see below), CO_2 shipping is also seen as a way of increasing the capacity for CO_2 storage projects, since greater volumes of CO_2 can reduce the unit cost of CO_2 storage. For CCUS hubs, having CO_2 import-export terminals provides some contingency for periods when CO_2 local storage may not be possible (e.g. periodic maintenance), allowing the export of CO_2 to alternative CO_2 storage projects. This approach is part of the business model being considered by many of the CCUS projects around the North Sea (see the *Task 4 report* (Stalker et al., 2024)).

The CCTS value chain is often described in terms of three key components. The first component involves point source carbon capture – for example, emissions associated with power generation, resource extraction or industrial processes. Second, the captured CO_2 is either compressed or liquefied before being transported. The transport methods evaluated often include pipelines, road/rail or ships. Finally, once the CO_2 has been transported, it is either utilised – for example, in the production of various chemicals (for further information see the *Task 9 report*; Banfield et al. (2023)) – or stored permanently within deep geological formations.

Previous research has highlighted that for long distances, shipping often becomes the lower-cost alternative compared with pipelines, which require large upfront capital expenditure (Jakobsen et al., 2013; Smith et al., 2021). Given the significant potential geological CO_2 storage capacity of the basins offshore of the Northern Territory (Johnstone and Stalker, 2022) there is the possibility for CO_2 emitted overseas or within other parts of Australia to be stored there, along with CO_2 that has been captured from existing LNG and future MASDP facilities operating in Darwin.

Due to the long distances between Darwin and countries requiring CCUS – for example, Singapore, South Korea and Japan – the method of transporting CO_2 is assumed to be via ship (see the *Task 3 report*; Joodi et al. (2024a)). As Darwin is also remote from other major CO_2 emissions sources within Australia, it is similarly assumed that transport of domestic emissions would also be by ship, especially if importation infrastructure was already established.

While CO_2 has been transported by ship (typically for food and beverage or fertiliser manufacturing) in the high hundreds to low thousands of tonnes (Al Baroudi et al., 2021; Brownsort, 2015), currently the CO_2 shipping value chain for CCS is in its infancy, with the Northern Lights Longship project the most mature example. This project is expected to commence in 2024-25 and to permanently store 1.5 million tonnes of CO_2 each year (Northern Lights Project, 2024). See the case study below.

This report focuses on evaluating ship transportation as part of the CCTS value chain. It aims to:

1. provide an overview of the CCTS value chain, describing in detail the key assets required to transport CO_2 from its capture source to the final storage site
2. describe previous models that have been developed, as well as recent contributions to issues relevant to the value chain
3. present the results of the development of a logistics and technoeconomic model to estimate the levelised cost of importing CO_2 from Japan to the Port of Darwin.

The results obtained through this task of the CCUS business case project form inputs into the overall economic assessment of a CCUS hub for the Darwin region. As with all tasks within the CCUS business case, the CSIRO team has consulted widely with industry and the Northern Territory Government for guidance on the inputs into the models used. It is important to note, however, that the results presented herein do not consider detailed proponent design factors, their individual needs or commercial arrangements, but rather seek to understand system-levelised costs only and therefore should only be used for this purpose. The report does not include a detailed review of the technical elements of CO_2 shipping; however, where required appropriate literature is cited.

Case study: Northern Lights

The early experiences of the Sleipner CCS project (Furre et al., 2017), and subsequent development of CCS for the Snøhvit Field in northern Norway, were stimulated by the introduction of a form of carbon price in the mid-1990s. These discrete source-to-sink projects are precursors to the more complex and large-scale hub or cluster models that are in development. The earliest of these has been the initiation of Northern Lights and associated Project Longship (Figure 2) (Equinor, 2019).

The value chain associated with the project comprises two parts: (1) the development of CO_2 capture facilities at a cement production facility at Brevik, Oslo, Norway (0.4 Mtpa) and a waste-to-energy plant at Hafslund Oslo Celsio, Norway (0.4 Mtpa), and (2) additional development of associated liquefaction and shipping terminal infrastructure. This part of the value chain is known as Project Longship (Gassnova, 2024a; Heidelberg Materials, 2020).

The Northern Lights scope comprises the construction and operation of two 7,500 m^3 LCO_2 ships that will carry CO_2 at –46°C and 7 barg from the CO_2 capture sites to a receiving terminal at Øygarden, Norway, near to Bergen. CO_2 will be unloaded from the receiving terminal into storage tanks, after which it will be conditioned prior to being transported 100 km by subsea pipeline to the geological CO_2 storage location in the Norwegian North Sea (Equinor, 2019). While the aims of this project are modest 1.5 Mtpa demonstration of the technologies and infrastructure for CO_2 shipping, the project has been designed to allow for up to 5 Mtpa to be transported through the subsea pipeline before duplication is required. This phase of the project could capture and store up to 4.2% of Norway's 2022 CO_2 emissions (IEA, 2024) and demonstrates capture and storage from hard-to-abate industries.

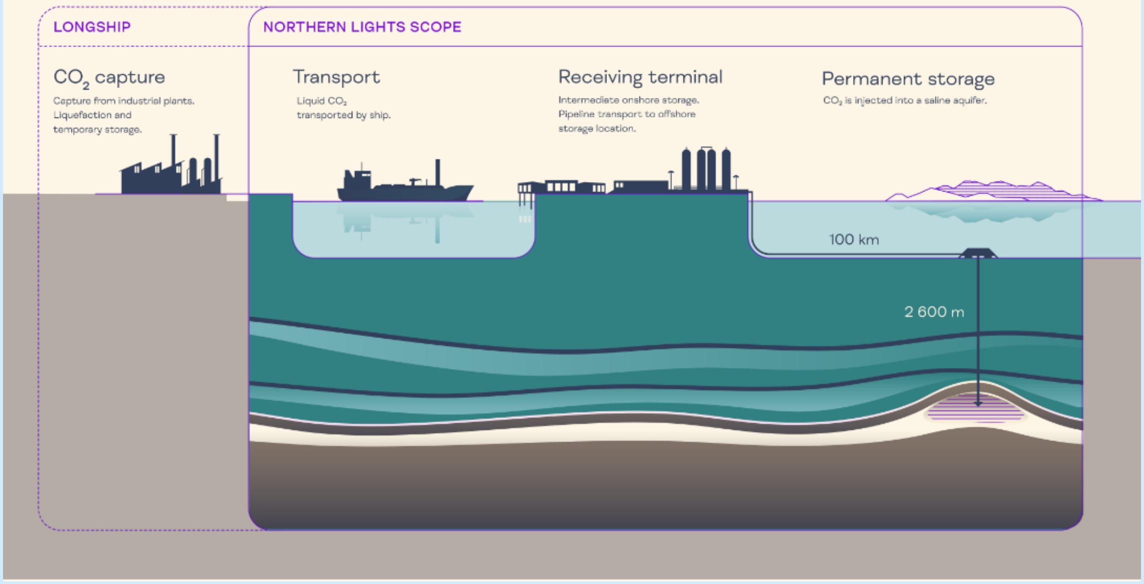

Figure 3: Schematic of the Longship CCS value chain

(Copyright © 2024 Northern Lights https://norlights.com/about-the-longship-project/).

As of August 2024, all of the elements of both Project Longship and Northern Lights were under construction (Gassnova, 2024b), and although there have been some delays to both projects due to COVID and inflationary pressures (Gassnova, 2023), much of the land-based infrastructure is nearing completion (Figure 4), as are the CO_2 ships (Figure 5), with anticipated startup in 2025.

Figure 4: Northern Lights CO_2 import terminal under construction in Øygarden, Norway

(Copyright © 2024 Northern Lights https://ccsnorway.com/current-status-of-the-longship-project/)

Figure 5: Northern Lights CO_2 carrier vessels under construction

(Copyright © 2023 Northern Lights https://norlights.com/news/northern-lights-enters-charter-agreement-to-expand-fleet-with-a-fourth-co2-ship/)

2 CCTS value chain and previous research

2.1 Overview of the CCTS value chain

The CCTS value chain describes a series of interconnected activities to collect, transport and permanently store CO_2 emissions associated with fuel combustion and other industrial processes. As discussed elsewhere in this CCUS business case project, it is one of the emissions reduction pathways to address the emissions associated with heavy industries such as power generation, chemical production and steel manufacturing. This report focuses on the export infrastructure, ship transport and importation infrastructure of the CCTS value chain. Figure 6 shows the key components that make up the system boundary discussed herein, with each component described below.

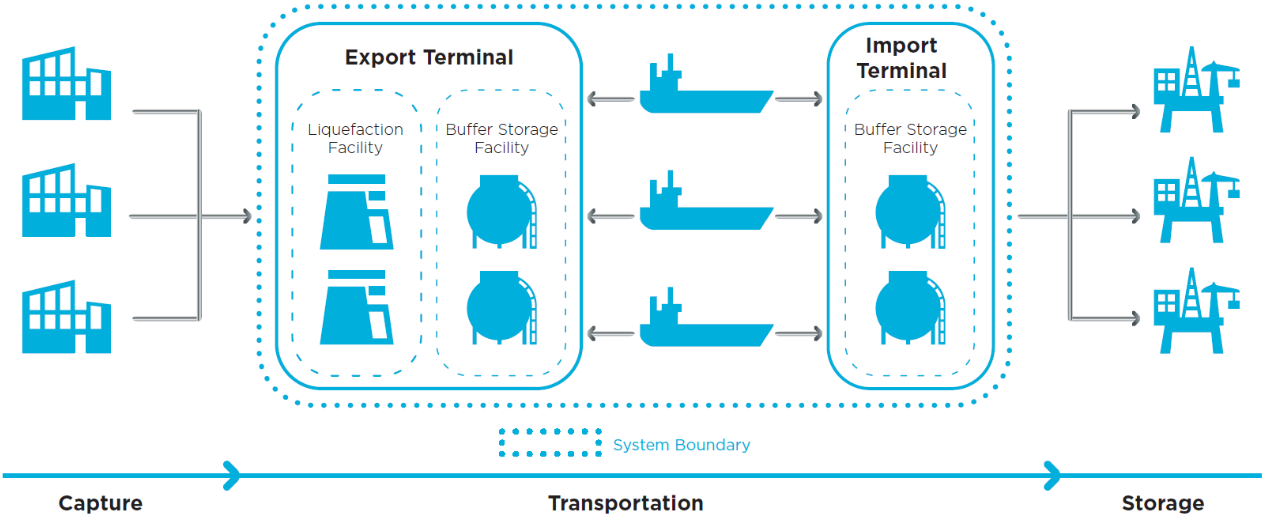

Figure 6: Overview of the CCTS value chain

While the CO_2 capture and gather system (e.g. localised pipelines and compression facilities) is not directly considered in this report, the type of capture and gas conditioning technology used has some bearing on the transportation infrastructure.

There are three main categories of capture technology: (1) pre-combustion capture, (2) post-combustion capture and (3) oxy-fuel combustion with the choice of capture technology determined by the CO_2 source/chemical process or fuel used. Depending on the source of CO_2 and the capture method used, CO_2 streams are likely to require further pre- or post-capture conditioning to reduce impurities, before the CO_2 enters the shared pipeline infrastructure or the export terminal itself. This gas conditioning can include the removal of substances such as water vapour, inert gases, NOx, SOx and heavy metals. These topics are summarised in Porter et al. (2015) and Razak et al. (2023), as they are out of scope for this report. Irrespective of which capture and conditioning technologies are employed, the final gaseous CO_2 stream should have minimal impurities to avoid corrosion, HSE issues and to comply with recognised standards.

A CO_2 stream from multiple facilities may be connected through a shared low-medium-pressure pipeline network to the export terminal (as considered here); alternatively, there may be a need to compress the CO_2 to a dense phase to enable larger volume transport over longer distances. Although it is not evaluated here, extensive onshore pipeline infrastructure will add significantly to the capital component of the CO_2 transport cost and as such would favour the development of large CO_2 transport capacities (e.g., Delta Rhine Corridor) (Gasunie, 2024). The exact configuration of the CO_2 gather system is outside the scope of this report and is not modelled here. However, it is assumed that aggregating emissions from several sources leads to a constant pre-pressurised CO_2 stream entering the export terminal.

The liquefaction of CO_2 is the first activity that occurs within the export facility (and within the system boundaries of the models presented here). Previous studies analysing the shipping of CO_2 assume that it is transported in a low-pressure state (7 barg and –46°C (Roussanaly et al., 2021) see box below for further discussion). At this pressure and temperature range, CO_2 has low vapour pressure and is a liquid, resulting in a higher volumetric density when stored and pumped when compared with the gaseous stream entering the export terminal.

The liquefaction facility progressively compresses the CO_2 and extracts its heat of compression until it is converted to a liquid state at the desired temperature and pressure range. Alternatively, liquefaction can be achieved utilising closed-loop refrigerant systems with a separate working fluid. Either process is energy-intensive, with the cost significantly impacted by whether the incoming CO_2 stream is pre-pressurised (in either the gas or dense phase). Once the CO_2 has been liquefied, it is transferred to a buffer storage facility. This facility contains a series of insulated storage tanks that store the liquid CO_2 prior to loading onto a ship. Depending on the insulation materials and ambient temperature of the facility, a small proportion of the CO_2 will 'boil-off' – that is, convert back to a gaseous state. Part of the operational management of the buffer storage facility involves the transfer and re-liquefaction of gaseous CO_2 to prevent excess pressure buildup within the storage tanks, and thus there is a continual energy demand.

Once a ship is ready for loading, a set of loading arms linked to the buffer storage facility attach to the ship to transfer the liquid CO_2. Depending on the amount and speed of transfer, this process can take several hours and can in principle happen alongside other activities, such as refuelling and crew transfer. Once the ship has been loaded, it will depart the export terminal in transit to the import terminal. While in transit, boil-off management is required to prevent the onboard storage tanks from failing due to excess gasification of the stored CO_2.

Upon arrival, the vessel will dock and the reverse of the process described above will occur, with the unloading arms attaching to the ship and transferring the liquid CO_2 to another buffer storage facility. This facility keeps the CO_2 in its liquid state until it can be sent to a permanent storage location via an export pipeline. This pipeline can be linked to other CO_2 capture facilities – for example, the existing LNG facilities in Darwin – and can also connect to several storage wells. In this report we consider the system boundary to end at the point where the CO_2 exits the buffer storage facility, is reconditioned into a dense form and is then transferred to the export pipeline.

Modes of CO_2 transport via ship

Currently there are three modes of transport that vary according to the temperature and pressure of the stored CO_2. Often it is assumed that CO_2 will be transported in its liquid state due to its higher volumetric density. However, there is no clear consensus as to what pressure/temperature range above the triple point (-56.6°C, 4.17 barg) that CO_2 should be transported. Below are the three ranges often discussed (Orchard et al., 2021):

1. low pressure (5–10 bar between –50° and –40°C)
2. medium pressure (15–20 bar between –30° and –20°C)
3. elevated pressure (35–50 bar between 0° and 15°C).

Each of the proposed pressure ranges has its relative merits. Currently, food-grade CO_2 is transported at medium pressure and uses mature technologies (Al Baroudi et al., 2021). Storing CO_2 at a low pressure results in relatively higher volumetric densities and uses similar technologies as for LPG transportation. High-pressure transportation results in lower energy requirements but it means that the CO_2 is transported at the lowest volumetric density.

There are also drawbacks that relate to the risk of dry-ice (solid CO_2) formation, the cost of materials for tank construction, and the relative technological maturity for handling CO_2 at the proposed pressures.

Based on a review of the literature, transporting CO_2 at a low pressure appears to be the most cost-effective option over longer distances and is therefore the pressure used in the technoeconomic model presented below. However, as research continues and more demonstration projects reach completion, the optimal temperature/pressure combination may change.

The system boundary is relevant for this report as the logistics and technoeconomic model described identifies the costs of the transportation component of the value chain. For completeness, it should be noted that shipping is one of two methods relevant for transnational shipping. Previous studies have considered pipeline networks that connect export and import terminals rather than relying on ships.

A summary review of studies by Al Baroudi et al. (2021) shows that the breakeven distance favouring shipping over both onshore and offshore pipelines is positively associated with the annual quantity of CO_2 transported. While large-scale CO_2 pipeline transport occurs for the purpose of enhanced oil recovery (EOR) in the USA (Global CCS Institute, 2024), no large-scale CO_2 ship transport network exists when considering the transnational shipment of millions of tonnes of CO_2 on an annual basis.

The choice to consider shipping CO_2 rather than using pipelines is a consequence of shipping's potential flexibility with respect to scaling a transnational CO_2 industry, as opposed to determining which transport method is most cost-effective.

2.2 Previous CO_2 shipping models

Prior to developing the logistics and technoeconomic model presented in this report, a review of four past models was conducted.

The first, one of the earliest analyses of shipping CO_2 between capture and storage sites, was performed by the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG, 2004). The report, which was a collaboration with Mitsubishi Heavy Industries, assessed the available technologies, costs and emissions associated with the same components of the value chain analysed in this report. Distances between 200 km and 12,000 km were considered to transport 6.2 Mtpa using ships that could transport between 10,000 and 50,000 tonnes of liquid CO_2 per trip. Adjusted for inflation and exchange rates, the estimated per tonne cost of transporting CO_2 over 6,000 km was between A$62.76 and A$126.77.[2] It was also noted that the additional emissions associated with shipping CO_2 can represent between 8% and 10% of the total volume of CO_2 transported, with most of the emissions being associated with the combustion of heavy fuel oil and ship boil-off during transit.[3] Although this report is relatively dated, it does provide the opportunity to compare against the results of the model developed for this project.

The second study identified was an analysis performed by Element Energy for the UK's Department for Business, Energy and Industrial Strategy (Element Energy Limited, 2018). The purpose of this report was to estimate the costs of shipping CO_2 from terminals within the UK to storage sites within the North Sea. This report has been identified as a key study as it includes a detailed literature review of the capital and operational expenditure associated with key components of the value chain. For example, six studies were reviewed to estimate how the construction cost of ships varies as a function of ship capacity. To date, this report has been identified as the most current comprehensive review of the costs of transporting CO_2, with later studies using inflation-adjusted regressions from this report. In terms of the unit costs of transporting CO_2 the comparability is limited, as the distances considered were less than 1,000 km.

The third study reviewed was the HySupply Shipping Tool developed by Daiyan et al. (2021) to estimate the costs of shipping hydrogen and hydrogen derivatives from Australia to ports in Europe and Asia. The model is an Excel workbook that enables users to calculate shipping costs for various distances across the different hydrocarbon types. Relative to the previous studies reviewed, a significant number of parameters specific to the ship are included, but the costs relate to a single ship, not multiple ships. In addition, an accompanying manual describes a list of sources that are used to justify the chosen parameters within the model.

The final model identified was the CCTS levelised cost model developed by Rystad Energy. This model enables the calculation of unit costs for the transportation component of the value chain, comparing between shipping and both onshore and offshore pipelines. A selection of model parameters can be modified to analyse the costs assuming different scenarios. A description of key

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[2] The original per tonne estimates of US$24.90 and US$50.30 were inflated using at cumulative inflation rate of 61.30% between 2004 and 2023 and an exchange rate of US$1: A$1.56.

[3] Both sources of emissions can be mitigated, for example by switching to lower emissions fuels, onboard capture systems, or the installation of insulation to minimise boil-off rates.

model inputs and assumptions is also provided, but a significant number of parameters and assumptions are not disclosed, which makes comparison with this study limited.

Based on the models reviewed, the approach has been to use the tool developed by Daiyan et al. (2021) as a template for this study's logistics and technoeconomic model. Given that none of the previous models explicitly described the logistics model in detail, this is described in the methodology in Section 3 below, and additional necessary functions have been added to the model. Formulas and data sources noted in the previous reports have also been included where appropriate.

2.2.1 Other relevant studies

Since Element Energy's report (2018), several studies have analysed various issues related to the value chain. Some of these studies are useful for justifying the parameters included in the model in this study, and others are relevant for describing qualitative factors that should be considered alongside the main findings.

Determining what size ships should be considered is a critical parameter for this study. Previously, it had been assumed that LCO_2 ships are similar to LPG carriers due to the same type of storage tanks being used onboard (Pérez-Bódalo et al., 2024). However, prior to 2024 there were only four LCO_2 vessels in operation with capacities between 1,000 and 2,000 m^3 (Oxford Institute for Energy Studies, 2024). Note that LCO_2 is about twice as dense as LPG, which in turn is denser than LNG.

Table 1 includes a list of several studies that have described the storage volume, ship length and draught for larger LCO_2 vessels. A recent report by the American Bureau of Shipping (2024) identified that as of January 2024 there were six orders for new LCO_2 vessels with capacities of 7,500m^3 and 22,000 m^3. With the exception of Larsen et al. (2022), there are few studies that consider the design characteristics of larger LCO_2 vessels. This is a qualitative risk factor, as the design characteristics could constrain certain ship sizes from entering ports.

Table 1: Review of ship design studies

Study	Volume transported (m^3)	Ship length (m)	Ship draught (m)
Ministry of Petroleum and Energy (2016)	6,000–7,700	114–150	Not stated
Kokubun et al. (2013)	3,000	94.2	6.9
Bjerketvedt et al. (2020)	3,750–7,500*	90–110	Not stated
IEAGHG (2004)	10,000–50,000	116–220	9.5–11
Vermeulen (2011)	30,000	210	11
Larsen et al. (2022)	150,000	316	19

*Volume transported is measured in tonnes.

Although previous studies have assumed that CO_2 will be transported at low pressures, there has been research into alternative pressures. Work by Roussanaly et al. (2021) analysed the impact that alternative storage pressures have on the cost of shipping CO_2, highlighting that low pressure (7 barg) is the most cost-efficient option (see box above). Trædal et al. (2021) experimented with alternative mixtures of CO_2/N_2 and pure CO_2 to identify how low the operational pressures can be before dry-ice formation becomes an operational issue. They identified that pure CO_2 can be safely liquefied at 5.8 bar, while higher pressures are required for CO_2/N_2 mixtures to prevent dry-ice formation.

Related to the issue of dry-ice formation are the depressurisation operations that may be required in emergencies to prevent equipment failure. Drescher et al. (2023) performed several experimental tests to address data gaps related to the depressurisation of low-pressure CO_2 storage tanks, as well as evaluating existing depressurisation modelling software tools.

Finally, the management of boil-off for larger ships is the focus of work by Lu et al. (2023), who find that liquid ammonia could be used to lower the energy and emissions associated with onboard CO_2 liquefaction.

Various studies have explored how current carbon capture technologies can be used to reduce shipping emissions and therefore maximise the net amount of CO_2 transported. A recent review (Tavakoli et al., 2024) suggests that onboard carbon capture systems could achieve a 70–90% reduction in vessel-based emissions, although this would come at the cost of increased energy consumption. Visonà et al. (2024) estimated the CO_2 avoidance cost of these systems to range from €64 to €149 (A$104 to A$244) per tonne of CO_2 captured, which is similar to the minimum capture and liquefaction cost of €98 (A$161) per tonne calculated by Feenstra et al. (2019). Additionally, Ros et al. (2022) reported a cost of €119 (A$195) per tonne, but emphasised other important factors in choosing the optimal capture system, such as solvent selection, heat integration and the impact of ship motion during transit.

Case study: CO2next, Rotterdam

The CO2next project is developing an open-access multi-user liquid CO_2 import-export terminal at Maasvlakte in the port of Rotterdam (Figure 7).

The terminal has been designed to service the supply and dispatch of liquid CO_2 by inland and seagoing barges and vessels, and future plans incorporate rail transport of liquid CO_2. CO_2 imports are anticipated from Austria, The Netherlands, Spain, Germany, Belgium, France and Switzerland, and the terminal will have direct access to pipelines for CO_2 storage facilities such as Aramis.

In June 2024 the CO2next partners (Vopak and Gasunie, Shell and TotalEnergies) entered into the front-end engineering design (FEED) phase for a 5.4 Mtpa two-jetty facility. A final investment decision (FID) is anticipated in 2025, with proposed facility startup in 2027 (subject to offtake agreements and permitting). The project has been granted Project of Common Interest (PCI) status and Connecting Europe Facility (CEF) subsidy. Future expansion envisages a four-jetty facility with a 15 Mtpa capacity (CO2next, 2024)

In August 2024, the Northern Territory Government and Royal Vopak signed a memorandum of understanding to cooperate on the development of common-user infrastructure including a CO_2 import terminal in the MASDP (Vopak, 2024).

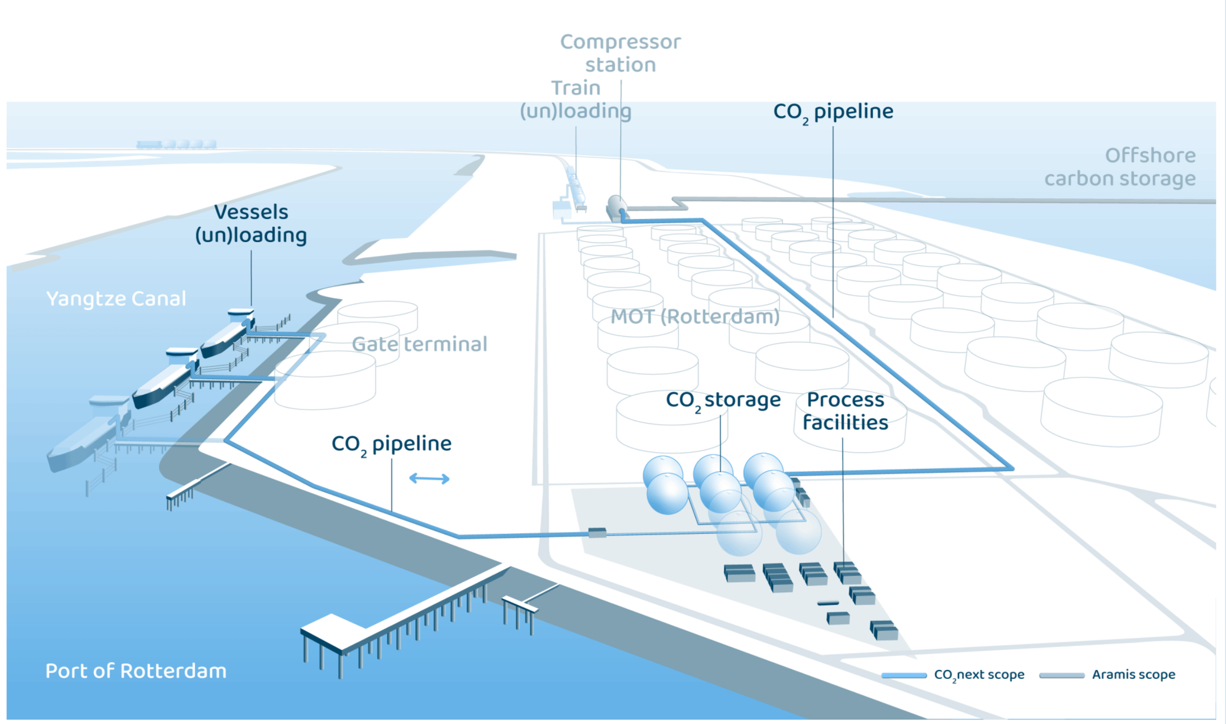

Figure 7: Schematic of the CO2next CO_2 import-export facility

(Copyright © 2024 CO2next https://co2next.nl/about/).

3 Methods

3.1 Overview

Based on a review of the literature, a combined logistics and technoeconomic model was developed to estimate the levelised cost of shipping CO_2 from the Port of Kawasaki in Japan to the Port of Darwin. The modelling involved two steps:

1. calculating the number of ships required to ship a desired volume of CO_2 each year
2. calculating the levelised costs, using the logistic model outputs.

The various equations used to estimate the costs for each component of the value chain build upon the work described in Element Energy's report (2018), with formulas and results from other studies used as a robustness check. In addition, cost estimates from recent Northern Territory Government reports (GHD, 2023; Royal HaskoningDHV, 2021) – for example, the costs of constructing an import terminal within the Middle Arm – have also been used and are described below.

3.2 Logistics model

The first component of the shipping model determines the minimum number of ships required to transport a given annual volume of liquid CO_2. The formula used to calculate the round-trip duration is shown in equation (1). Based on an inputted distance and ship speed, the number of required one-way sailing days is calculated. Next, the time taken to transit through the port is added to the total, which can then be scaled by a weather uncertainty parameter. This parameter is set to a value between 0 and 1, with a lower number representing increased delays due to adverse weather events.

$$\textbf{Round trip duration} = \mathbf{2} \times \left(\frac{\textbf{Sailing days} + \textbf{Port transit}}{\textbf{Weather uncertainty}} + \frac{\textbf{Port operations}}{\textbf{Opertations uncertainty}}\right) \tag{1}$$

The second component accounts for port operations. Based on the per-trip volume of CO_2 shipped and the inputted flow rate, the number of hours required to load or unload the ship can be calculated. The operations uncertainty parameter is analogous to the weather uncertainty parameter, adjustable to account for delays in operations. It is assumed that other activities, such as refuelling and crew changes, occur simultaneously while the ship is being loaded or unloaded.

Next, the maximum number of trips that can occur each year is calculated using equation (2):

$$\textbf{Maximum number of trips} = \frac{\mathbf{365} \times \textbf{Ship working capacity}}{\textbf{Round-trip duration}} \tag{2}$$

The ship working capacity is an adjustment factor that accounts for the days each year that the ship would be in dry-dock or port for maintenance. To calculate the total volume that each ship can transport, the maximum number of trips is multiplied by each ship's volume, which is the product of its maximum capacity in tonnes and a volume adjustment factor. Finally, to determine the minimum quantity (Q) of ships required, the optimisation problem in equation (3) is solved:

$$\mathbf{Minimimise\ Q_{Ships}\ subject\ to\ Q_{Ships}} \times \mathbf{Volume_{Per\ ship}} \geq \mathbf{Annual\ volume\ (Mtpa)} \tag{3}$$

Often, the calculated amount of CO_2 that can be transported exceeds the desired quantity – for example, 2.3 Mtpa can be transported when only 2 Mtpa is required. When this is the case, two additional calculations occur. First, the maximum number of trips is reduced for all ships until the annual volume shipped is just above the annual required volume. Second, if possible, the number of trips for one of the ships is reduced until again just enough volume is transported each year. The reduced number of per annum trips impacts later cost calculations but also indicates the degree of utilisation with respect to the fleet of ships required.

3.3 Technoeconomic model

Following the calculation of the required number of ships, the levelised cost of transportation (LCOT) for an annual quantity of CO_2 to transport is calculated, as shown in equation (4). The LCOT is a unit cost measure that aggregates the operating expenditure (OpEx) and upfront CapEx incurred prior to a project commencing operations (Friedl et al., 2023).

$$\mathbf{LCOT} = \frac{\mathbf{Liquefaction_{CapEx}} + \mathbf{Liquefaction_{OpEx}} + \sum_{\mathbf{n=0}}^{\mathbf{N}}\left[\mathbf{Ship_{CapEx}} + \mathbf{Ship_{OpEx}}\right] + \mathbf{Storage_{CapEx}} + \mathbf{Storage_{OpEx}}}{\mathbf{Annual\ quantity\ of\ CO_2\ transporte}\square\square} \tag{4}$$

For each infrastructure category, previous studies and reports have been used to estimate the associated CapEx and OpEx. Often the costs reported, and the equations used for their estimation, are expressed in different currencies and need to be adjusted to account for inflation. Table 2 lists the 2023 exchange rates and inflation-adjustment factors used, as well as the discount rate and economic life parameters needed to calculate annualised CapEx.[4] It should be noted the shorter economic life associated with ships reflects the additional uncertainty associated with acquiring ships of the sizes considered in this report. The economic life's chosen do not necessarily reflect when replacement decisions would occur.

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[4] Alternatively, uncertainty could be reflected in a higher discount rate. Either adjustment would increase the annual capital expense. Assumptions regarding which specific risks would justify adjusting either parameter are beyond the scope of this study.

Table 2: Economic and financial parameters

Economic variable	Parameter
£ to US$ 2023 exchange rate	1.243
US$ to A$ 2023 exchange rate	1.563
UK inflation adjustment 2017–2023	1.242
Discount rate	7.00%
Economic life (ships)	20 years
Economic life (liquefaction and storage)	30 years

In this study it is assumed that all required infrastructure and ships are constructed and ready to be used in the first year that CO_2 is transported. This assumption allows for the conversion of all CapEx totals to annualised expenses using a capital recovery factor (CRF). This expense represents the annual interest and principal repayments required to repay all CapEx by the end of the asset's economic life. Based on partner feedback, the economic life of the ships modelled in this study has been reduced to reflect the uncertainty associated with constructing ships that can transport tens of thousands of tonnes of liquid CO_2. Consequently, the annualised capital expense associated with ships is larger than what it would be assuming a longer economic life.

The following sections discuss how each of the various infrastructure costs is calculated. Unless stated otherwise, no location-specific cost adjustments are modelled. Depreciation expenses and contingency adjustments are also not included.

3.3.1 Liquefaction

The first step of the CCTS value chain involves gaseous CO_2 from multiple capture sources entering the export facility, before it is liquefied within the facility. There are three main cost components associated with liquefaction:

1. CapEx required to construct the facility
2. fixed OpEx, often expressed as a percentage of CapEx
3. variable OpEx related to electricity consumption, as liquefaction is an energy-intensive process.

Equations (5–7) are based on the literature review of liquefaction costs reported by Element Energy (2018), adjusted for inflation and exchange rates.

$$\mathbf{Annual\ cost\ of\ liquefaction} = \mathbf{CAPEX} + \mathbf{Fixed\ OpEx} + \mathbf{Electricity\ OpEx} \tag{5}$$

$$\mathbf{CapEx} = \mathbf{8.06\%_{CRF}} \times \mathbf{\$31.03_{tCO_2}} \times \mathbf{Annual\ quantity} \tag{6}$$

$$\mathbf{Electricity\ OpEx} = \$\mathbf{71.13}_{\mathbf{kWh}} \times\ \mathbf{104.20\ kWh}_{\mathbf{tCO_2}} \times \mathbf{Annual\ quantity} \tag{7}$$

For the CapEx formula, the technologies employed are assumed to exhibit constant returns to scale. This assumption is based on the idea that liquefaction processes are mature technologies and have been used for liquefying more energy-intensive compounds (e.g. methane) at capacities exceeding several Mtpa (Zhang et al., 2020). Several studies published after Element Energy's report (2018) have estimated the per-tonne costs of liquefaction for quantities between 1 and 4 Mtpa, also assuming a linear increase in costs (Aliyon et al., 2020; Chen and Morosuk, 2021; Deng et al., 2019). This study does not model increasing returns to scale due to a lack of evidence of new technologies, leading to a fall in average costs as the size of the liquefaction plant increases.[5]

The choice of which coefficients to use for both CapEx and electricity OpEx is determined by whether the CO_2 gas is pressurised prior to liquefaction. Non-pressurised CO_2 represents using low-concentration flue gas streams – for example, flue gas from thermal power stations (Koytsoumpa et al., 2018; Madejski et al., 2022). Consequently, additional energy is required to liquefy the stream, raising the costs of liquefaction. Combining flue gas streams from multiple capture sites or using several concentrated streams – for example, CO_2 streams from steam methane reformers – results in a pressurised stream of CO_2 that has a lower relative cost to liquefy. In this study it is assumed that the CO_2 stream is not pressurised, in effect assuming that liquefaction is adjacent to a CO_2 source (Element Energy Limited, 2018). Later sensitivity analysis shows the decrease in cost associated with the CO_2 stream pressurised between 70 and 100 bar (Element Energy, 2018).[6]

The fixed OpEx associated with liquefaction relates to the necessary labour, administration and maintenance expenses required to operate the liquefaction facility and was set to 10% of CapEx (Element Energy, 2018). Finally, the cost of electricity was set to US$71.16 per MWh[7], and an emissions factor of 436 grams of CO_2 per kWh was used to calculate the emissions associated with liquefaction (Japan Electric Power Information Center, 2023).

3.3.2 Ship expenditure

CapEx

The unit investment costs associated with purchasing fit-for-purpose ships can represent a significant component of the LCO_2 value chain. Several factors determine the per-ship CapEx, including: the desired capacity, the vessel type, the technologies required and associated design complexity, the cost of raw materials and labour, the degree of competition between shipbuilders, current regulatory requirements and the existing demand for new ships. Ideally, costs would be obtained via quotes from shipbuilders for ships capable of transporting LCO_2 at different capacities. Currently, however, no ships have been constructed to transport LCO_2 at the capacities

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[5] This is in part due to previously reviewed studies assuming both a fixed electricity cost and consumption rate, irrespective of the quantity of CO_2 liquefied.

[6] The cost of conditioning CO_2 is assumed to be incurred at the capture stage of the value chain and is therefore not considered as part of the cost of liquefaction.

[7] The cost per MWh was calculated using the 2023 system price of 10.74¥ per kWh for electricity generation (Japan Electric Power Exchange, 2024) and converted to US$ using the average 2023 Japanese Yen:US$ exchange rate (Exchange-Rates.org, 2024).

examined here. To address this shortcoming, two methods were identified in the literature that can be used to estimate the CapEx required. Each method assumes that the cost of constructing an LNG/LPG tanker is a reasonable estimate due to the similar technologies and engineering expertise required for ship construction (Aspelund et al., 2006).

The first method relates to that used in the HySupply shipping model, which reports the cost of a 160,000m³ LNG vessel to be US$192 million. This cost is calculated using the linear function described in Al-Breiki and Bicer (2020) whereby ship CapEx for LNG ships increases at a constant rate of US$1200/m³.[8]

One limitation of this method is that constant returns to technology are assumed. It may be the case that economies of scale can be achieved as ship capacity increases. The second method relates to a literature review of the capital costs in Element Energy's report (2018) which led to the following inflation and currency adjusted equation being used:

$$\mathbf{Ship_{CapEx(US\$M)}} = \mathbf{0.3152} \times \mathbf{Ship_{Capacity(t)}}^{\mathbf{0.5369}} \tag{8}$$

This equation, focused on estimates for low-pressure ships, accounts for economies of scale as capacity increases. In this report, equation 8 is used to calculate the CapEx associated with three capacities (40,000 m³, 60,000 m³ and 80,000 m³).

Regardless of which estimation method is used, there is significant uncertainty with respect to the true cost of estimating ships that have yet to be constructed at the capacities proposed. Therefore, as part of the sensitivity analysis performed, after presentation of the main results alternative costs are modelled in Section 4. Based on feedback from collaborators this study assumes a US$160 and US$200 million per ship cost for the 40,000 m³ capacity. The cost of the larger capacity ships is then scaled using the six-tenths rule (Tribe and Alpine, 1986).[9]

Another limitation on ship size relates to the maximum draught of the ships considered. Noting that LCO_2 is more than twice as heavy LNG and has a similar density to water. A preliminary traffic assessment of Darwin Harbour by Royal HaskoningDHV (2021) reported that having a draught of 13 m or less should not impact ship navigation since the channel depth exceeds 15.6 m 90% of the time. In this report a maximum capacity of 80,000 m³ is assumed as the maximum-sized vessel that can enter the port without dredging activities. If further dredging was to occur in Darwin Harbour, it is possible that ships with deeper draughts, larger capacities and therefore lower cost per m³ capacity could be realised.

The useful life of each ship is assumed to be 20 years, 10 years lower than the storage and liquefaction infrastructure. The choice to lower the useful life is based on feedback from collaborator organisations. On the assumption that there is greater investment risk associated with CO_2 ships relative to other ships such as LNG or LPG, a reduced useful life results in a larger amortised expense, increasing the levelised cost.

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[8] This relationship appears to be first described in Seddon (2006) but the cost has also been reported elsewhere (Bainbridge, 2004; Cho et al., 2005).

[9] Using the higher ship costs represents a cost markup of between 60–67% and 100–109%. This report makes no claims as to which cost figure is most likely to occur. Rather, the intent is to model how sensitive the levelised cost is to changes in a relatively important parameter that is subject to significant uncertainty.

OpEx

This report considers two broad categories of OpEx for shipping. The first category includes fixed expenditure, often expressed as a percentage of CapEx. The second comprises expenditure modelled as a function of parameters. Table 3 summarises these categories, and they are discussed below.

Table 3: Classification of operational expenditure

Expenditure category	Calculation method
Fuel consumption	Modelled
Insurance	% of OpEx
Maintenance	% of CapEx
Labour	Modelled
Port costs	Modelled

Fuel consumption

To model fuel consumption, three models in the literature were reviewed, acknowledging that a wide variety of models are available (Fan et al., 2022).

The first model developed by Mitsubishi Heavy Industries for the IEAGHG (2004) included reporting the daily fuel cost for several ship capacities and speeds. Using these data, several regressions were estimated that could be used to predict the average daily fuel consumption as a function of the ship's deadweight tonnage, holding speed constant. The results of these regressions are shown in equations (9) and (10):

$$\mathbf{Daily\ fuel\ consumption}_{\mathbf{15\ knots}} = \mathbf{2.6456} \times {\mathbf{Ship}_{\mathbf{Capacity(T)}}}^{\mathbf{0.2295}} \tag{9}$$

$$\mathbf{Daily\ fuel\ consumption}_{\mathbf{18\ knots}} = \mathbf{6.4309} \times {\mathbf{Ship}_{\mathbf{Capacity(T)}}}^{\mathbf{0.2041}} \tag{10}$$

A review of fuel consumption models was included in Element Energy's report (2018) with a regression linking the daily MWh requirement against ship capacity.

Here only LNG is considered as a fuel, noting the move away from heavy and medium fuel oil usage towards low-emissions intensity marine fuels. Assuming an energy density of 48.6 MJ/kg for methane, the MWh estimate was converted to a daily quantity of fuel required measured in tonnes.

The final method to calculate daily fuel consumption involves estimating the required main engine total power (maximum continuous rating, or MCR) requirement for tanker vessels using the regression estimated by Cepowski (2019) shown in equation (11):

$$\mathbf{MCR(kW)} = \mathbf{2.66} \times \mathbf{DWT}^{\mathbf{0.6}} \times \mathbf{V}^{\mathbf{0.6}} \tag{11}$$

where DWT is the deadweight tonnage of the vessel and V is the vessel speed.

The MCR can then be multiplied by the specific fuel consumption to obtain the hourly fuel consumption. The specific fuel consumption of LNG engines varies with engine type, with a range reported between 148 and 156 g/kWh (International Maritime Organisation, 2020), corresponding to an engine efficiency of 47–50%. For the main results of the study, a speed of 15 knots and a SFC rate of 148 g/kWh was used. In later sensitivity analysis the ship speed is increased to 18 knots with a SFC rate of 197 g/kWh.[10]

A summary of the estimated daily fuel requirements using all three methods is reported in **Error! Reference source not found.**Table 4. There is a similarity between the methods, but Cepowski's method (2019; equation 11) was chosen as the baseline method for calculating daily fuel consumption.

Table 4: Comparison of daily fuel requirements in tonnes

	IEAGHG (2004)		Element Energy (2018)		Cepowski (2019)	
Capacity\Speed	**15 kn**	**18 kn**	**15 kn**	**18 kn**	**15 kn**	**18 kn**
40,000 m³	31	57	30	51	30	45
60,000 m³	34	62	36	62	38	57
80,000 m³	36	66	42	73	45	68

Forecasting the price of LNG is beyond the scope of this study as long-term supply and demand fundamentals will drive prices. However, this parameter has been benchmarked against the 5-year median average price for East Asia equal to US$10.20 MMBTU (~US$467 per tonne) (Australian Competition & Consumer Commission, 2024). As such, for simplicity a cost of US$500 per tonne of LNG is assumed in the model. Given the potential for fuel costs to have a significant impact on costs, a 25% increase in the per tonne price of fuel was also included as part of the sensitivity analysis.

Insurance and maintenance

The cost of insurance and maintenance expenditure for each ship is assumed to be a fixed operational expenditure. It is assumed that insurance premiums equivalent to 10% of the total OpEx of the ship are levied each year (Raab et al., 2021). The cost of annual maintenance is assumed to be equal to 4% of the total capital cost (Al-Breiki and Bicer, 2020).

Labour

Using LNG vessels as a guide, each ship will require crew, deck officers and engineers who have specific training in maintaining liquefied chemicals. The costs of training when vessels are commissioned have been estimated to be US$750,000 per ship, with subsequent refresher training equal to US$100,000 per ship per annum (Poten and Partners, 2015). This cost is in

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[10] Here we assume that the MCR of the vessel is equal to 75% of maximum ship power when sailing at 18 knots.

addition to the cost of salaries and insurance for the crew. Public data for the annual cost of crew are limited, but one study by Al-Breiki and Bicer (2020) uses a per ship annual cost of US$2.5 million. In the absence of a better cost estimate, this figure has been used here too.

Port costs

To model port costs, two sets of costs based on location have been calculated. For the export side, the equation included in Element Energy's report (2018), adjusted for inflation and exchange rates, has been used, as shown in equation (12):

$$\textbf{One-way trip port fees}(\mathbf{US\$}) = \mathbf{0.5} \times (\mathbf{0.4365} \times \textbf{Ship capacity}_{\mathbf{T}} + \mathbf{5,559.30}) \tag{12}$$

For the import side, the various charges that would be levied based on public information provided by the Port of Darwin (2023) have been estimated. Table 5 lists the various charges included in the model, expressed in A$. As a final step, the unloading charges are converted to US$ and summed together with the loading port costs to estimate the per-ship round-trip port costs.

Table 5: Summary of Port of Darwin fees

Fee category	Calculation
Port dues	A$0.04 per gross tonne
Berthage/moorings	Fixed fee A$2,682.76 Variable cost A$0.40 per gross tonne
Pilotage (inwards and outwards)	A$0.2004 per gross tonne
Wharfage – other bulk liquids	A$7.86 per kilolitre

3.3.3 Storage

To estimate the costs of operating the export terminal storage facility, the low-pressure CapEx costs detailed in Element Energy's report (2018) are used. The per tonne of CO_2 CapEx costs are an average of low-pressure costs described in Seo et al. (2016) and Skagestad et al. (2014), equal to £516 (US$821 in 2023 dollars) per tonne of CO_2. The amount of storage required is calculated as shown in equation 13:

$$\textbf{Buffer storage}(\mathbf{T}) = \mathbf{150}\% \times \textbf{Ship capacity}_{\mathbf{T}} \times \mathbf{Q}_{\mathbf{Ships}} \tag{13}$$

The 150% storage requirement follows previous studies that argue that the rate allows for operational flexibility that may be required, for example to account for delays of ships in transit (Al Baroudi, 2021).

The OpEx, which represents maintenance and repair costs, is assumed to be 5% of CapEx (Metz et al., 2005). Costs are assumed to increase linearly with quantity, in effect assuming constant returns to scale.

Included in the storage costs for the export terminal is the cost of loading arms. The Element Energy report (2018) includes a CapEx cost equal to £1.4 (US$2.23 in 2023 dollars) per tonne of CO_2 and an OpEx rate of 3%. This cost is noted to relate to having sufficient infrastructure to facilitate a loading time of 15 hours. We model two loading arm capacities, 3,000 m^3 and 6,000 m^3 per hour, which can lead to loading times above and below 15 hours, however the differences do not have a significant impact on costs therefore no adjustments are applied.

For the import terminal, a detailed concept design study was developed by GHD for the Northern Territory Department of Infrastructure, Planning and Logistics (GHD, 2023). This study describes the relevant engineering and technoeconomic considerations to enable the importation of up to 6 Mtpa. The infrastructure requirements include provisions for unloading liquid CO_2 from ships and transferring it to a buffer storage facility. There, it is held until it is reconditioned for export through a tie-in export pipeline to long-term storage sites. The study details the electricity requirements as well as location-specific Class 4 engineering cost estimates for the terminal. These costs have been used in this model but are not explicitly disclosed; however, they do include cost adjustments to account for Darwin's remote location. Later sensitivity analysis lowers the buffer storage requirement to 120%, scaling costs using the six-tenths rule.

3.3.4 Emissions and carbon price

For each of the key components of the CCTS value chain, emissions are estimated. In scenarios where a carbon price is included, the cost of carbon emitted forms part of the total levelised cost. For the liquefaction process at the export terminal, 2023 average emissions intensity for Japan's electric power industry was used, which was 436 kg CO_2 per MWh (Japan Electric Power Information Center, 2023). Emissions associated with the ships relate to the combustion of LNG. It is assumed that for every tonne of LNG combusted, 2.78 tonnes of $CO_{2\text{-e}}$ (CO_2 equivalent) is released (Australian Government, 2023).[11] No onboard capture systems are assumed to be installed. Onboard CO_2 is assumed to boil off at a rate of 0.2 %/day and is reliquefied onboard (Awoyomi et al., 2019). Finally, for the emissions associated with energy used for LCO_2 storage in the importation terminal, the 2023 scope 2 emissions factor for the Northern Territory of 540 kg CO_2 per MWh was applied (Australian Government, 2023).

Due to a lack of data, it is assumed that the electricity required for the export terminal LCO_2 storage facility is the same as the electricity required to operate the import terminal LCO_2 storage facility. In scenarios where a non-zero carbon price occurs, the total per annum emissions value is multiplied by the carbon price and is assumed to be the same price in both countries. The carbon price modelled is equal to A$75[12] per tonne, which is the maximum price ACCUs could be purchased from the government in 2023–24 (DCCEEW, 2024). This represents a conservative

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[11] To arrive at a rate of 2.78 tonnes, the energy content of LNG (0.0253 GJ/L) was multiplied by the scope 1 emissions factor of 51.53 kg $CO_{2\text{-e}}$/GJ. Afterwards, the figure was converted to kg $CO_{2\text{-e}}$/t, assuming the density of LNG to be 0.463 kg/L.

[12] This is the price before any consumer price index (CPI) and other adjustments are applied.

emissions cost as average purchase costs of ACCUs across the same period were between A$25 and A$35 (Clean Energy Regulator, 2024). As of August 2024, the Japanese government has implemented a voluntary emissions trading scheme that is expected to transition to a mandatory scheme in February 2026; a carbon levy is also planned to be implemented in 2028 (Nomura Research Institute, 2023).

4 Results and discussion

4.1 Logistics model

To evaluate the shipping logistics, a baseline scenario was selected. This report considers the scenario whereby CO_2 captured within the Port of Kawasaki is exported, shipped and stored at the Port of Darwin prior to being injected into available subsurface geological reservoirs. lists the relevant parameters for determining the optimal number of ships required based on a one-way distance of 6,231 km.

Table 6: Key parameters for the logistics model

Parameter	Value	Source
Ship speed	15 kt	Seo et al. (2016)
Distance	6,231 km	
Ship working capacity	90% (328.5 days per annum)	Model assumption
Port approach/mooring	8 hours	Model assumption
Load/unload rate	3,000m³ - 6,000m³ per hour	Model assumption
Volume capacity	95%	Al Baroudi et al. (2021)
Weather uncertainty	95%	Model assumption
Operations uncertainty	95%	Model assumption

The majority of parameters noted in Table 6 represent conservative assumptions rather than being linked to previous studies. The justification for being conservative reflects the fact that the ships being modelled in this study have not been constructed at the capacities considered. For example, setting both the weather and operations uncertainty parameters to 95% adds an additional 1.11 days to the per-trip duration relative to a scenario where no uncertainty is modelled. Most of the additional time is due to longer transit times between ports, with the operational uncertainty adding an extra 2 hours to the loading and unloading process. Finally, the modelled load/unload rates are consistent with the rates discussed in *Task 6* (Joodi et al., 2024b).

Table 7 details the required number of ships based on capacity and the desired quantity of million tonnes of CO_2 transported per annum. Across the range of ship sizes (40,000–80,000 m^3) and required transport capacities (16 Mtpa) a maximum of 11 ships would be required using the smallest ship size considered, or six ships for the largest size. As expected, the annual quantity of port arrivals falls with larger capacity vessels at a constant rate. The change in total round-trip duration across the different capacities is due to the longer load/unload times. If the rate was doubled to 6,000 m³, the duration would reduce from 22.72 days to 21.55 days for the largest capacity ship.

Table 7: Shipping and logistics model results

Mtpa	Number of ships	Port arrivals per annum	Capacity utilisation	Frequency unload (days)	Berth utilisation
Capacity = 40,000 m^3					
1	2	26	98.30%	14.04	3.96%
2	4	52	98.30%	7.02	7.91%
3	6	77	99.58%	4.74	11.72%
4	7	103	99.26%	3.54	15.68%
5	9	128	99.84%	2.85	19.48%
6	11	154	99.58%	2.37	23.44%
Ship fuel consumption (t LNG /day) 30		**One-way emissions[13] (t)** 770		**Total round trip duration (days)** 21.55	
Capacity = 60,000 m^3					
1	2	18	94.66%	20.28	4.11%
2	3	35	97.37%	10.43	7.99%
3	4	52	98.30%	7.02	11.87%
4	5	69	98.78%	5.29	15.75%
5	7	86	99.07%	4.24	19.63%
6	8	103	99.26%	3.54	23.52%
Ship fuel consumption (t LNG/day) 38		**One-way emissions (t)** 982		**Total round trip duration (days)** 22.13	
Capacity = 80,000 m^3					
1	1	13	98.30%	28.08	1.98%
2	2	26	98.30%	14.04	3.96%
3	3	39	98.30%	9.36	5.94%
4	4	52	98.30%	7.02	7.91%
5	5	64	99.84%	5.70	9.78%
6	6	77	99.58%	4.74	11.72%
Ship fuel consumption (t LNG /day) 46		**One-way emissions (t)** 1,168		**Total round trip duration (days)** 21.55	

At all capacities there is spare capacity within the fleet to ship greater volumes. Capacity utilisation refers to the proportion of CO_2 transported as a ratio of the total volume that could be transported if every vessel was at full capacity and completed the maximum feasible number of trips per annum. Focusing on the most extreme example, two 60,000m^3 ships could complete 15 round trips transporting approximately 1.76 Mtpa; however, they are constrained in the model to only transport 1 Mtpa. To account for this underutilisation in the model the actual number of trips made is reduced to the minimum required, lowering the associated fuel costs. Reducing the number of trips leads to ships that are being utilised between 94.66–99.58%. Each ship is transporting close to its maximum capacity, however there is still spare capacity to expand the number of trips if the actual quantity of CO_2 to be transported exceeds the modelled annual volumes.

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[13] Refers to the per-ship emissions only.

4.2 Technoeconomic model

Using the results from the logistics model, the levelised cost of transportation for three ship sizes across different annual volumes of CO_2 is reported in Figure 8**Error! Reference source not found.**. The variation in costs across different ship capacities is most pronounced at lower annual volumes. This is due to the CAPEX related to export storage rising as ship capacity increases. This variation decreases as economies of scale are realised, with the average cost falling from between A$184/t and A$224/t with 1 Mtpa transported to between A$122/t and A$128/t with 6 Mtpa transported.

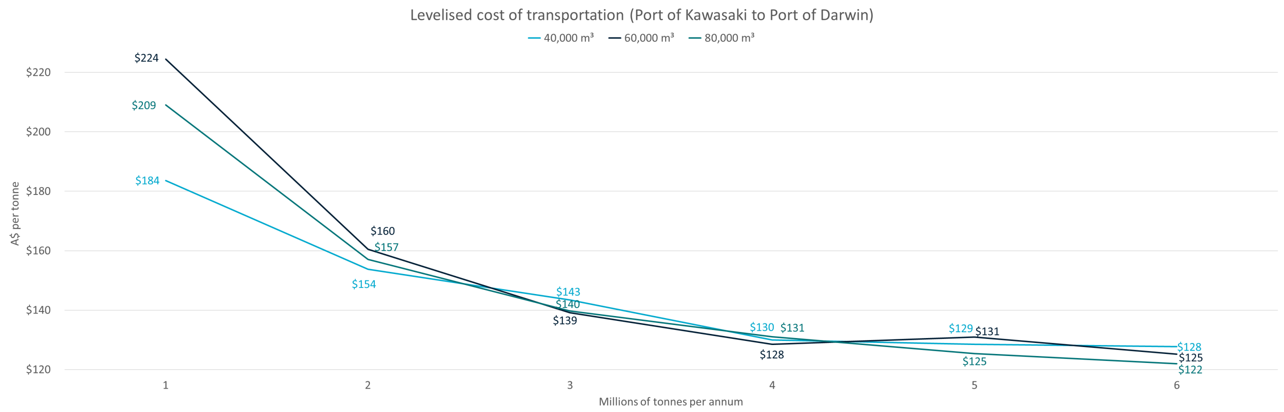

Figure 8: Levelised cost of transportation in A$ per tonne

This result is unsurprising given that the assumptions associated with the technologies employed consider either constant or increasing economies of scale. These results do not imply that 80,000 m^3 is the capacity for which the LCOT is minimised (larger ship sizes have not been modelled). Larger sizes might result in lower costs; however, economies of scale may be exhausted beyond a certain capacity. Constraints regarding vessel size could limit port access, and other unmodelled constraints might also prevent lower levelised costs.

A more detailed breakdown of each cost component is shown in Figure 9 and 10. For low volumes of CO_2 transported and the largest ship size considered, most of the cost (A$209/t) is attributable to the fixed costs of infrastructure, with approximately 58% of the costs related to CapEx. At this volume, the import storage assets are underused. When up to 6 Mtpa are shipped with the largest ship size, the costs associated with liquefaction and storage represent a relatively small proportion of the total cost (A$122/t).

The most significant component of the cost is related to the ship's OpEx. The largest component relates to port costs, particularly the costs of operating within the Port of Darwin. Other costs, such as maintenance and insurance costs, are set as a proportion of the ship's CapEx. Fuel costs represent 7.0% of the total cost; however, the fuel is assumed to be a fixed requirement and costs would be expected to vary according to market conditions.

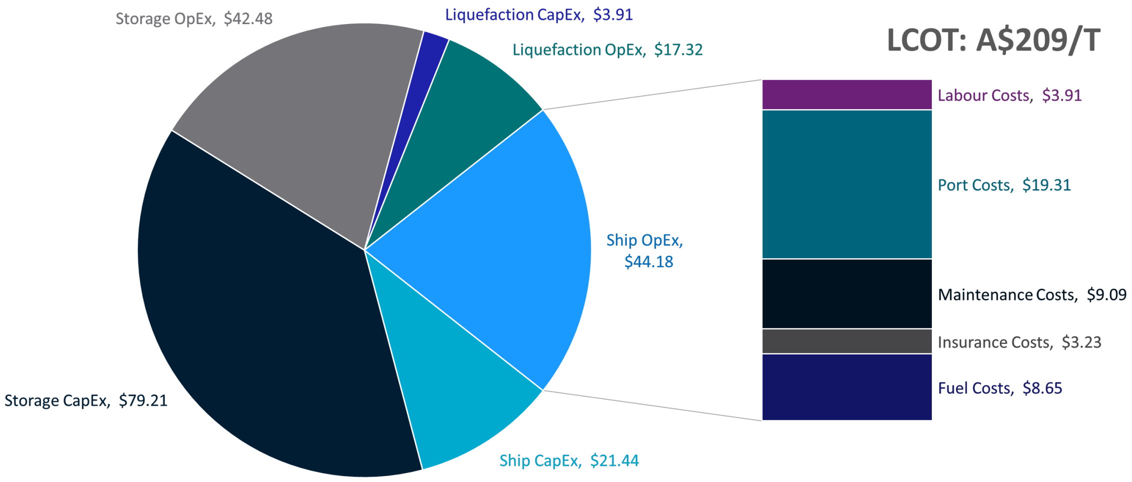

Figure 9: Cost breakdown for shipping 1 Mtpa CO_2 using 80,000 m³ capacity ships

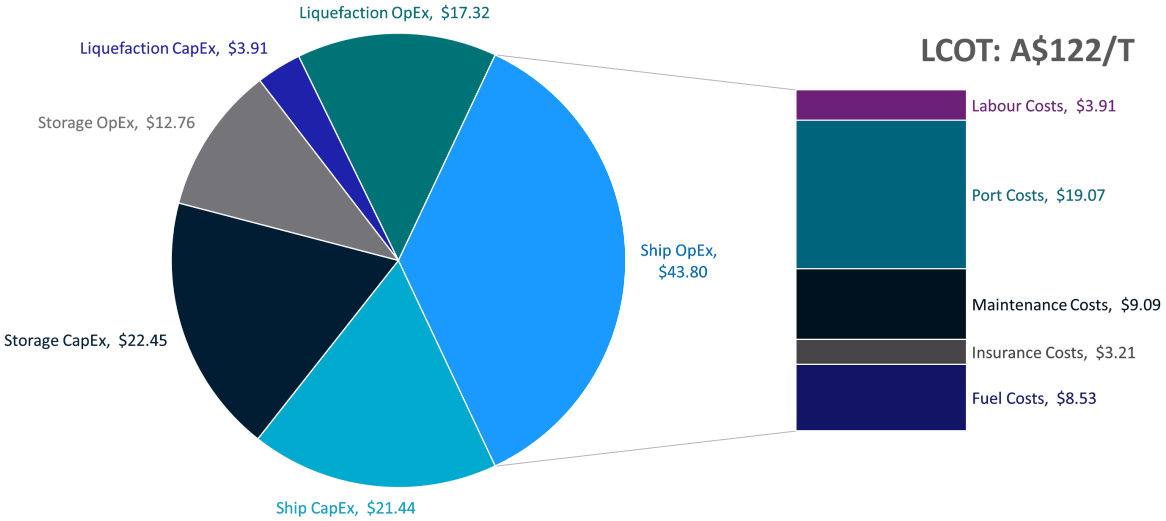

Figure 10: Cost breakdown for shipping 6 Mtpa CO_2 using 80,000 m³ capacity ships

4.2.1 Emissions

Figure 11 shows the emissions for varying technologies and annual volumes transported using an 80,000 m³ capacity ship. The largest proportion is attributable to liquefaction, representing approximately 50% of annual emissions within the system boundaries discussed. This result stems from the assumption that the CO_2 stream is not pressurized before liquefaction. Combining multiple capture sites could result in a pre-pressurised stream being feasible, lowering the energy requirement and associated emissions.

The next largest source of emissions is attributable to shipping (33%), followed by storage (17%).As discussed above, only LNG has been considered as a fuel in this report; however, with the emergence of alternative low-emissions fuels such as ammonia and e-methanol ((International Energy Agency, 2023) these emissions could be reduced. These emissions relate to the combustion of fuel and are understated on account of auxiliary power requirements – for example, electrical energy required for heating and lighting – not being modelled.

The emissions associated with the generation of electricity supplied to both export and import terminals in the Port of Kawasaki and the Port of Darwin, respectively, are expected to fall over time, reducing the per kWh emissions intensity. Furthermore, terminal operators may enter into power purchase agreements (PPAs) with electricity generators for the provision of renewable electricity.

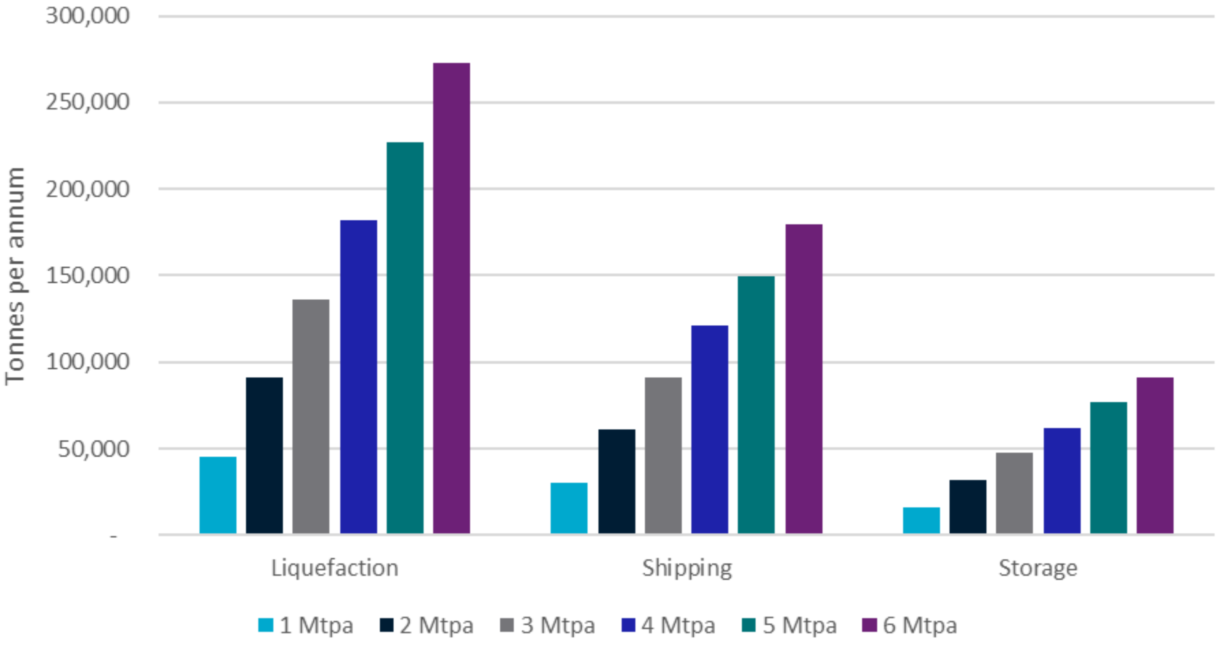

Figure 11: Emissions by technology and volume (excluding any vented boil-off emissions) using 80,000 m³ capacity ships

Throughout this report it is assumed that a consistent boil-off rate applies across all ships, regardless of their specific parameters. It is also assumed that all CO_2 that boils off will be reliquefied. However, if any CO_2 boil-off is not reliquefied and is instead vented, it could significantly impact both shipping logistics and costs,[14] although this is unlikely as past studies focusing on this issue have concluded that the CO_2 will indeed be reliquefied (Awoyomi et al., 2019; Lee et al., 2017).

However, until CO_2 transport ships of the size discussed in this report are built, uncertainties remain regarding the average boil-off rate and the effectiveness of onboard liquefaction processes. To understand the impact of this uncertainty, the costs of venting all boil-off CO_2 were explored by varying the average daily boil-off rate. The baseline boil-off rate is 0.2% per day, with the other rates examined reflecting a 20% increase or decrease from this baseline. This modelling of uncertainty is exploratory and simply highlights the potential impact of not accounting for boil-off rates. Table 8**Error! Reference source not found.** summarises the key differences in the results

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[14] To account for CO_2 venting, the net quantity of CO_2 shipped would be reduced and there is the potential that a carbon price would be payable on the quantity vented.

when CO_2 boil-off is vented. It focuses on the largest ship size and 6 Mtpa, but the trends identified apply irrespective of capacity. A A$75 CO_2 emissions price is also assumed for the numbers presented, which represents the maximum price before adjustments in 2023–24.[15]

Table 8: Boil-off emissions analysis

Boil-off rate	0.16%/day	0.2%/day	0.24%/day
Baseline levelised cost (Carbon tax included)	A$128.79		
Baseline emissions	543,610 tonnes (9.06% of 6 Mtpa)		
Per annum increase (relative to no boil-off CO_2 release scenario):			
Levelised cost	A$6.90 (5.36%)	A$7.59 (5.89%)	A$7.87 (6.11%)
Emissions	122,801 (22.59%)	147,663 (27.16%)	170,191 (31.31%)

The boil-off rates modelled show that the levelised cost of transportation increases between 5.36 % and 6.11% due to the additional CO_2 emission levees paid for the vented CO2. In addition, slightly more trips are required to ensure the net volume of CO2 is transported, further increasing emissions. The additional emissions associated with any CO_2 vented increase the total emissions by 9.06% of the gross volume of CO_2 transported to between 11.11% and 11.90%. If reliquefying the CO_2 onboard was not an option, additional trips could make up for the shortfall, as could a slight increase in processing capacity at the export side of the value chain. Evaluating the trade-offs associated with accounting for the costs of boil-off is beyond the scope of this report but could be useful for future analysis.

4.2.2 Sensitivity analysis

Model sensitivity analysis was performed for different sets of parameters, with the results reported in Figure 12 and 13.

In part 1 of the sensitivity analysis (Figure 12), The first parameter concerns imposing a A$75 cost per tonne of CO_2 emissions results in an average cost increase of between A$6.78 and A$7.52 per tonne of CO_2 shipped. It should be noted that this charge is applied to all emissions in the value chain, including liquefaction-related emissions in Japan as well as combustion emissions in transit. Including the emissions related only to the storage facility in Australia results in minimal changes in cost.

The second parameter concerns port charges being increased by 25%, with the average cost increase being between 2.42% and 4.20% for the larger ship capacities. The percentage increase is

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[15] With no carbon price the change in levelised cost is on average less than A$1 per tonne. This situation could represent the status quo, whereby CO_2 emitted to the atmosphere within international waters is not covered by any regulatory scheme.

proportionally larger when considering larger annual volumes shipped as most of the port charges are based on the frequency of visits. The percentage increase is also slightly higher for larger ships as the wharfage charges are based on capacity.

The next parameter considered relates to increasing the per tonne fuel costs by 25%. The impact is relatively minor in that increasing the cost per tonne from US$500 to US$625 leads to on average a A$2.07–A$2.82 increase in cost per tonne of CO_2 shipped. Finally, reductions in the working capacity from 90 to 85% have a minimal impact on costs. The increase is between A$0.51–$1.27 and is the result of slightly more trips being required, however the change is minimal.

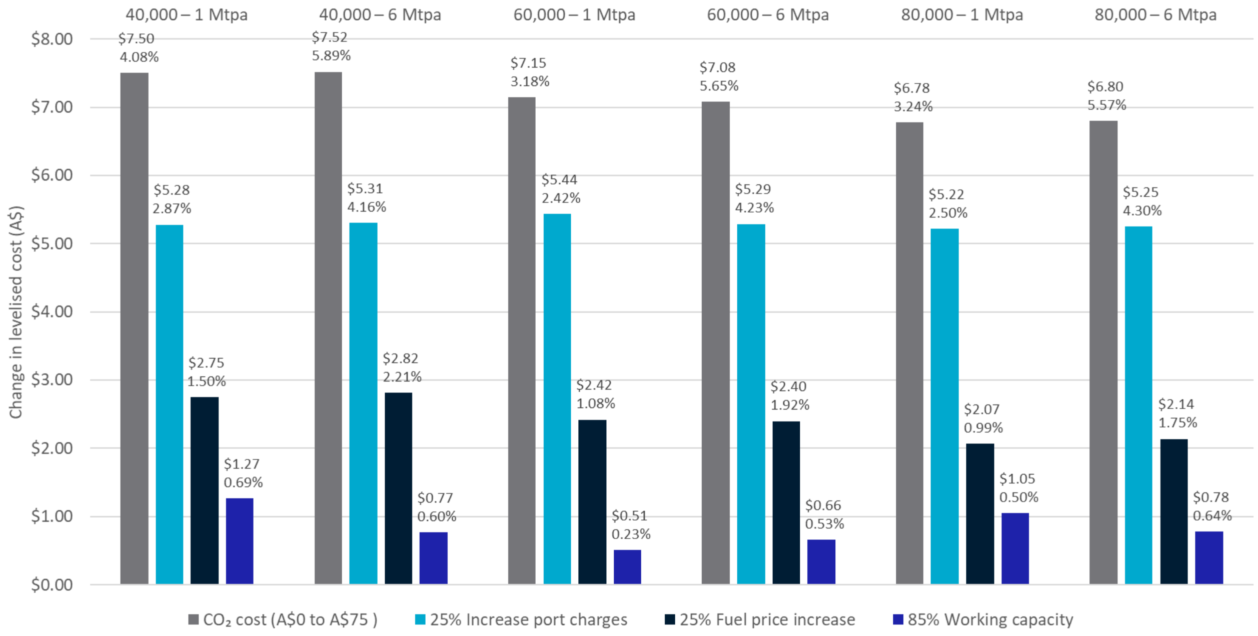

Figure 12: Sensitivity analysis part 1 – for variations in port charges, CO_2 costs, fuel price and working capacity (A$)

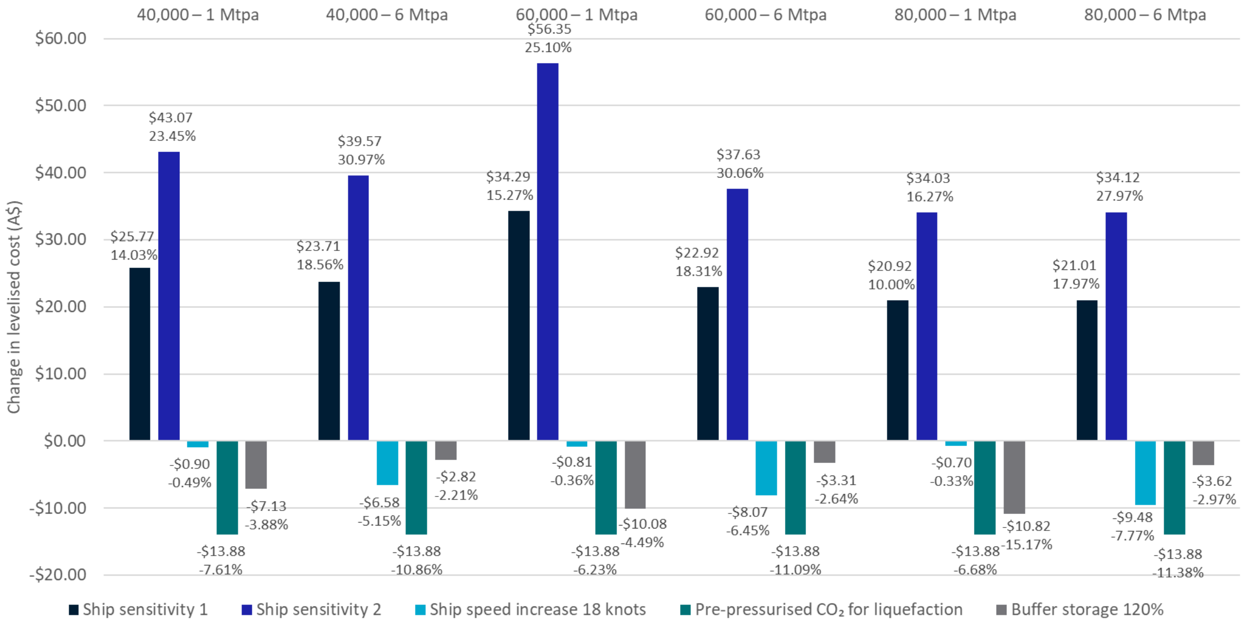

Figure 13 Sensitivity analysis part 2 – for variations in ship volume and speed, liquefaction and buffer storage costs (A$)

Part 2 of the sensitivity analysis (Figure 13) examined two parameters that could have a significant impact on cost, as well as three that could lead to cost savings.

The first parameters included as part of the sensitivity analysis relate to the CapEx associated with ship construction. Based on feedback from collaborators there was concern as to the estimated costs identified in the literature. Although the technologies used for storing CO_2 onboard ships are relatively mature, with comparisons often made to LNG and LPG vessels, to date no ships have been constructed transporting the volumes considered in this study and therefore the costs of LCO_2 vessels may be underestimated.

In contrast to the above the first cost saving discussed, increasing the ship speed, can lead to significant cost reductions. Faster speeds enable more trips to be completed, which increases the total volume transported. If the annual transport volume remains the same, faster speeds may reduce the number of ships required. At lower volumes this impact is not as significant as the ships are already underutilised, with minimal change in the number of trips required each year. When considering 6 Mtpa though, the size of the fleet is reduced across each of the capacities considered, lowering the amount of CapEx required.

The sensitivity analysis also highlights that significant cost savings could be realised by liquefying pre-pressurised CO_2 and reducing the amount of buffer storage required. Utilising the lower energy requirements noted in the Element Energy Report (2018) leads to a cost reduction between 6.68% and 11.09%. Both the associated CapEx and OpEx reduce due to the lower energy requirements. Whether these cost savings can be realised is in part dependent on whether sufficient captured CO2 can be transport to the liquefaction facility.

Compared with the formulas used in previous studies, the cost of buffer storage in Darwin results in it being a non-trivial component of the overall cost of CO_2 transportation. Part of the reasoning for this cost being so significant relates to the fact that this terminal would be a greenfield development in the Northern Territory, where construction costs have historically been more expensive due to its relatively remote location and small workforce. Another factor is the assumption that 150% of a ship's volume is required for buffer storage. Assuming a 120% buffer storage requirement leads to a cost reduction of between 2.21% and 15.17%. We return to this point later in the discussion section below.

4.3 Discussion

Focusing on the logistics component of the modelling, there are several areas where utilisation can be increased to lower costs. For the various annual capacities modelled, in almost all instances the ships are underutilised due to not being filled to maximum capacity. This is partly due to the technical limitation that a proportion of the onboard storage volume is reserved to account for boil-off, but future research into alternative storage materials and boil-off management systems could address this limitation.

Practically speaking, it is highly unlikely that ship operators will not fully load each vessel. Exceptions could arise due to below-average flow rates or other operational issues impacting either terminal. Over time, these issues could be addressed through having a fleet of vessels with varying capacities or developing a spot fleet market. Such flexibility presumes an established CO_2 transportation market and therefore, in the short term, the focus will be maximising utilisation to minimise costs.

Another way to maximise utilisation would be to progressively scale up the infrastructure, including the number of ships required. The desired quantity of CO_2 transported each year assumes that there are sufficient capture volumes and accessible storage capacity outside of the system boundaries considered in this study. This is a strong assumption to make, and it may be more conservative to assume that project-specific quantities will be made available for transportation. To minimise costs, it is important to forecast these volumes accurately and then gradually expand the fleet to match growing demand over time.

As the volume transported increases, the number of port calls will grow, potentially impacting traffic flows at each port. Modelling the impact of traffic flows at the export terminal is outside the scope of this report, but analysis has been undertaken with respect to the Port of Darwin. Forecast modelling by Royal HaskoningDHV (2021) estimates that by 2030–40, 830 port calls per annum will be made to the Middle Arm Terminal. The report's authors conclude that additional port calls can be accommodated within the relevant river channels, but LCO_2 vessels were not considered in this forecast.

Based on this report's analysis the number of port calls could increase by up to 19%, assuming the maximum volume and smallest ship size modelled were used. This outcome is unlikely, as the results indicate that lower costs can be achieved by using larger ships and reducing the number of port calls required. There is a trade-off in opting for larger ships, as port depth may eventually become a constraint, necessitating further dredging activities to accommodate the larger vessels.

Other related logistics issues pertain to the speed of the vessels travelling between terminals as well as loading/unloading operations. In the sensitivity analysis it was shown that faster speeds can lead to reduced fleet sizes, reducing the levelised cost despite higher rates of fuel consumption. Note this result only applies to the ship sizes modelled, and the impact may not be as significant for alternative ship sizes.

Increasing flow rates during loading and unloading operations does not significantly affect costs. However, from a logistics standpoint, the construction of additional loading arms could reduce the time ships spend at the berth, provided that other factors, such as ship refuelling, do not negate the time savings from faster loading and unloading.

One of the most significant factors in the technoeconomic model is the cost associated with the import terminal's buffer storage facility. As noted in GHD's report (2023), significant cost savings could be realised if the number of onsite storage vessels is reduced, leading to lower CapEx. Currently it is assumed that the LCO_2 is unloaded off the site to the buffer storage facility and then progressively converted to a dense state before being transferred to an export tie-in pipeline. Greater conversion capacities and associated downstream capacities could reduce the amount of buffer storage required.

Alternative methods of storage – for example, a second ship stored adjacent to the Middle Arm terminal – could be used in lieu of a dedicated storage terminal. A further option would be to increase the time on the wharf for the vessels and thus reduce the need for storage capacity, but this would need to be balanced with vessel utilisation and the associated cost implications. A second vessel option may be applicable as the size of the fleet increases and older ships form part of the spot fleet market.

There are several limitations and underlying assumptions in the reported costs for each key asset. The CapEx equations often assume constant or increasing returns to scale, but this assumption may not hold true since facilities and ships have not yet been constructed at the proposed scales. While storage and liquefaction technologies are relatively mature, reducing the risk of failing to achieve cost efficiencies, the design and construction of larger LCO_2 ships are more uncertain. Few shipyards currently specialise in building liquefied gas container ships, and existing orders for other vessels could delay the expansion of the required fleets. Therefore, purchasing adequately sized vessels is identified as a key risk factor for minimising the costs of developing an LCO_2 value chain.

Determining both the desired pressure/temperature and the tolerance of impurities will be critical for derisking the value chain and evaluating alternative methods to lower costs. Over time, there may be an opportunity to develop additional terminals within Australia, especially in the north of the country. Agreeing on a common set of standards could enable a short-term market that mitigates the risks associated with delays throughout the value chain. These standards would also need to consider international trends. This is especially the case when deciding tolerances for impurities within the CO_2 stream. The modelling presented in this report does not consider differences in CO_2 stream specifications between jurisdictions and any additional gas conditioning steps required, so any deviations may lead to higher costs or present a barrier to transnational CO_2 shipping (See *Task 6 report* for a more detailed discussion (Joodi et al., 2024b)).

From an emissions perspective, there are opportunities to further decarbonise the value chain. In the short term, reducing the emissions intensity of electricity generation will reduce the impact of emissions associated with liquefaction and storage. This will be especially important if the CO_2 entering the export terminal is not pressurised, resulting in more electricity being required for liquefaction.

Reducing the emissions associated with shipping is relatively more challenging. Currently, the shipping industry is considering a range of alternatives to decarbonise shipping, including increasing energy efficiencies, alternative ship designs and lower-emission fuels. Ammonia-fuelled engines are being considered alongside hydrogen due to the lack of CO_2 emissions associated with combustion. These technologies are relatively immature and are at a cost disadvantage compared with conventional fuels. This is also the case for onboard capture systems, which as noted earlier in the literature review are relatively costly methods for emissions abatement. In the absence of carbon pricing for this part of the value chain, the overall effectiveness of shipping CO_2 is reduced as long as CO_2 emissions persist throughout the chain.

5 Conclusion

As countries pursue their net-zero ambitions, permanent CO_2 storage will be a component of their decarbonisation strategies. For countries without suitable geology for CO_2 storage, achieving this will require international cooperation to establish value chains capable of transporting captured CO_2 to suitable storage sites. Transnational shipping could provide a suitable option for the Asia-Pacific region where distances are large between CO_2 emissions sources and storage locations. Given Australia's significant storage resources and established relationships with key trade partners aiming to decarbonise their hard-to-abate sectors, this report estimates the cost of shipping CO_2 from the Port of Kawasaki to the Port of Darwin. Given the relative proximity of other major ports, the results present an approximate estimate of shipping CO_2 from Japan/South Korea to Darwin.

To conduct this analysis, the CO_2 transport value chain was described, starting from the point where CO_2 enters the export terminal to its transfer to a long-term storage site beyond the import terminal. The value chain includes three key components: the liquefaction process, intermittent storage and the ships used for transportation. After detailing the value chain, the report reviewed several previous and related studies that have estimated the costs of transnational CO_2 shipping. Building on this work, an integrated logistics and technoeconomic model was developed to estimate the levelised cost of shipping CO_2 from Japan to Darwin. This allowed the modelling of several scenarios, varying both the size of the ships and the annual volume of CO_2 to be transported.

When considering annual volumes between 1 and 6 Mtpa, the levelised cost of shipping CO_2 was estimated to range from A$122 to $224 per tonne. Achieving the lower end of this cost range requires using the largest ships modelled and leveraging economies of scale by spreading the fixed infrastructure costs over larger CO_2 volumes.

The model uses formulas and parameters from existing literature, but the costs reflect a single set of assumptions about the value chain and represent a best-case scenario. It is not an optimisation model, and other parameters or uncertainties could lead to more accurate cost estimates. However, the model does highlight areas where costs could be reduced through optimisation, such as by reducing the required buffer storage size or using faster ships to minimise the fleet size and lower capital requirements.

The reported CO_2 shipping costs represent only one part of the three-part value chain associated with carbon capture and storage. To determine the total cost of CCTS, the costs of capture and storage must also be considered. Policymakers across multiple jurisdictions will need to compare this aggregate cost with alternative decarbonisation methods (if they are available in their jurisdictions) to identify the most effective allocation of government funds for achieving least-cost emissions reductions.

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