Australia's National Science Agency

Opportunities for CO_2 utilisation in the Northern Territory

An exploratory report prepared to inform the development of the Northern Territory Low Emissions Hub Business Case

Citation and authorship

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This report

This report explores opportunities to deploy carbon dioxide (CO_2) utilisation in the Northern Territory, focusing on the Middle Arm Sustainable Development Precinct. It builds on the CSIRO CO_2 Utilisation Roadmap, published in 2021.

The report was commissioned as part of the Northern Territory Low Emission Carbon Capture Utilisation and Storage Hub (NTLEH) business case, led by CSIRO in collaboration with the Northern Territory Government, INPEX, Santos, Woodside Energy, Eni, Xodus, and Total Energies. The NTLEH intends to supply a blueprint for rapid emissions reduction across the NT's natural gas, hydrogen, and energy generation industries.

The project is governed by a Steering Committee consisting of representatives from CSIRO's NTLEH team and the NT Government, and an Advisory Group comprised of representatives from Eni, Santos, Woodside Energy and Xodus Group. The project delivery included a workshop with participants from the Steering Committee, Advisory Group, and representatives from CO_2 Value Australia, the Department of Industry, Science and Resources, and the Department of Climate Change, Energy, the Environment and Water.

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Executive summary

CO_2 utilisation can support the Northern Territory's decarbonisation and economic growth objectives

CO_2 utilisation is the process of using CO_2 captured from industrial emissions or directly from the atmosphere to produce valuable products. Examples of these products include chemicals and fuels, materials for the building sector, food products and plastics. CO_2 utilisation can provide an abatement opportunity by reducing emissions compared to conventional production and, in some cases, even creating net zero or negative emission products.

The Northern Territory (NT) aims to reach net zero emissions by 2050 while growing the gross state product (GSP) to $40 billion by 2030. To achieve its net zero emissions and economic growth targets, the NT will need to grow its low-emission industry activity and support a variety of carbon abatement approaches, such as renewable electricity, carbon capture utilisation and storage (CCUS) and high-quality carbon offsets.

The NT's existing liquefied natural gas (LNG) industry, export links with the Asia-Pacific (APAC) region and high renewable electricity potential could support the development of a CO_2 utilisation industry.

CSIRO is collaborating with industry and government partners to develop a business case for an NT Low Emissions Hub (NTLEH) focusing on CCUS. This report is one input into the development of this business case.

As the NT Government is investigating the Middle Arm Sustainable Development Precinct (MASDP) as a low-emissions industry hub, it is used as a focal point for potential deployments of CO_2 utilisation.

Preliminary assessment identified five CO_2 utilisation opportunities with potential for deployment in the Northern Territory

Methanol

CO_2-derived methanol is a precursor to downstream products, such as plastics, textiles, and a standalone fuel. CO_2-derived methanol production could be a short-term opportunity for the NT because of its diversity in downstream uses and potential for hybrid production using renewable hydrogen and methane. The use of Direct Air Capture (DAC) sourced CO_2 can abate emissions from the use of methanol and downstream products, including jet fuel.

Jet Fuel

The aviation industry has demonstrated interest in decarbonising via sustainable aviation fuels, including CO_2-derived jet fuel. The local military sector in the NT may be willing to pay the premium associated with CO_2-derived jet fuel to support domestic fuel security and decarbonisation targets.

Urea

Urea is the most widely used nitrogen-based fertiliser, and demand is projected to continue to grow. Conventional urea production is a mature application of CO_2 utilisation but a significant contributor to global emissions. Renewable hydrogen and DAC-sourced CO_2 could enable the production of renewable urea in the long term. In the medium term, hybrid urea (using both natural gas and renewable hydrogen inputs) could be manufactured in the NT while the availability and affordability of renewable inputs improve.

Methane

CO_2-derived methane could provide a low to zero-emission alternative to natural gas. Customers may be willing to pay a premium for CO_2-derived methane where alternative solutions (such as hydrogen, ammonia, or electrification) are economically or technically unsuitable – especially when it is derived from DAC or recycled CO_2. The NT would be well positioned to meet this demand due to its well-established LNG export and processing infrastructure and expertise.

Mineral carbonates

CO_2-derived mineral carbonates (such as mineral aggregates for building materials) can abate emissions and even create negative emission products. High-level analysis suggests that suitable mineral feedstocks, such as mafic/ultramafic rock formations, are present in the NT. However, waste from current mining operations is not expected to be suitable for carbonation. New mining projects may create opportunities for mineral carbonation in the NT.

CO_2 utilisation opportunities are comparatively expensive, but cost reductions are expected as the relevant technologies mature

Most CO_2 utilisation applications are not yet commercially mature or cost-competitive with conventional products. However, producers may be able to charge a premium for CO_2-derived products if they support customers' emissions abatement objectives.

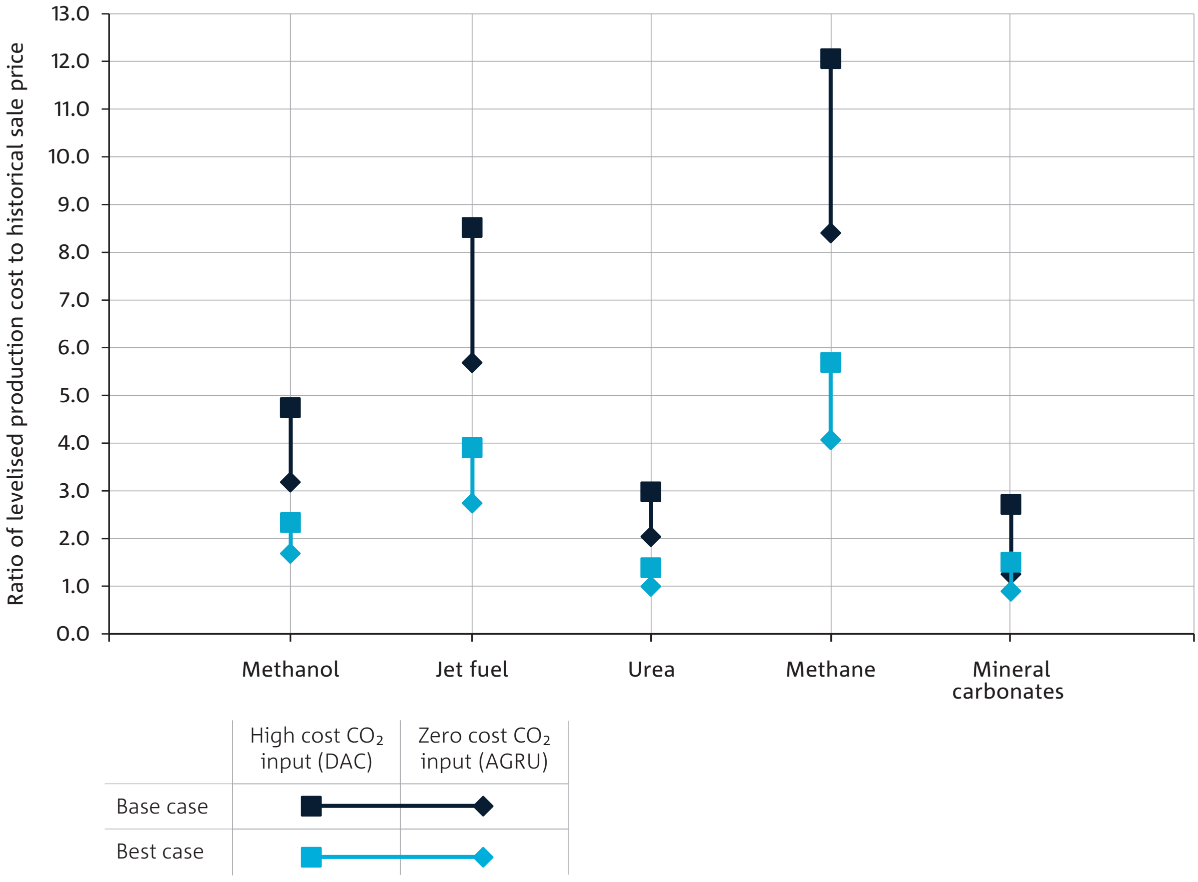
Techno-economic models for five CO_2 utilisation products have been used to calculate the levelised cost of production under base and best case scenarios. The levelised cost of production calculates the lifetime cost of production per tonne of product. To compare the potential commercial feasibility of the five products, the levelised cost of production results have been normalised using a historical sale price (see Figure ES 1). A ratio of 1 indicates that the CO_2 utilisation product has the potential to break-even (with no profit) at a mid-range historical price.

Under the base case scenario, all CO_2-derived products would need to be sold at a significant premium to break even on production costs. Balancing the sustainability and affordability of CO_2 and other input requirements will be critical to attracting customers for CO_2-derived products.

All modelled products have significant cost-reduction potential under the best case scenario due to technological improvements, feedstock affordability, and economies of scale. With a low-cost CO_2 source, mineral carbonates and urea may achieve a break-even price without charging a premium.

The economic feasibility of all CO_2-derived products will depend on a variety of other factors not explored in this report, including their ability to charge a premium for CO_2 abatement, the cost of competing low-emissions products, and cost increases for fossil-fuel-derived products.

Figure ES 1: Best and base case levelised costs of production for five prioritised opportunities as a ratio of conventional sale price



This figure shows the best and base case levelised costs of production for CO_2-derived products expressed as a ratio to historical sale prices for their conventionally produced equivalents. Two different CO_2 feedstocks are shown, acid gas removal unit (AGRU) and direct air capture (DAC), which show the impact of varying CO_2 costs on the levelised cost of production. AGRUs are used for liquefied natural gas (LNG) processes and are a source of near zero-cost CO_2 that is commercially mature. DAC technologies are emerging and have yet to reach commercial scale globally, producing CO_2 at a higher cost.

The scale-up of CO_2 utilisation requires access to large-scale and affordable CO_2 sources, renewable hydrogen and renewable electricity

The deployment plan for the NT describes an indicative scale-up pathway for the five products in this report in the context of expanded CO_2 capture and storage (see Figure ES 2 and Section 4 for further detail). Methanol has the greatest scale-up potential in the short term. Other opportunities including jet fuel and urea production reaching demonstration scale in the medium term. Methane and mineral carbonates could also reach demonstration scale in the medium term if the right customers and mineral feedstocks are identified.

Commercial scale CO_2 utilisation will require large-scale and affordable supply of CO_2, renewable hydrogen and renewable electricity (see Figure ES 3). This will require multiple orders of magnitude increases in the production of each of these inputs. To enable full abatement potential for CO_2 utilisation products, the report assumes:

- That sources of CO_2 will transition over time, with the existing LNG industry providing short term sources of CO_2 in the NT. Sustainable sources of CO_2 (such as direct air capture) can be utilised as they scale up and reach commercial competitiveness.
- That the electricity required in the MASDP will be provided entirely by renewable sources in the long term, supported by energy storage solutions, and upgraded transmission and distribution networks. The NTLEH business case is conducting detailed studies into energy opportunities for the MASDP.

Figure ES 2: Integrated plan for deployment and scale-up in the NT

	Short term (by 2030)	Medium term (2030–2040)	Long term (beyond 2040)
CO_2 CAPTURE	Existing industrial emissions (primarily LNG processing)	Existing industrial emissions + Point source + Demonstration scale DAC	Existing industrial emissions + Point source + Commercial scale DAC
CO_2 UTILISATION: **METHANOL**	Demonstration scale	Commercial scale, potential for hybrid production	Commercial scale for local downstream manufacturing and export
CO_2 UTILISATION: **JET FUEL**	Pilot scale	Demonstration scale for local defence and airport industry	Commercial scale for export
CO_2 UTILISATION: **UREA**		Demonstration scale, potential for hybrid production	Commercial scale, potential for fully renewable urea
CO_2 UTILISATION: **METHANE**		Demonstration scale, if suitable customers are identified	Commercial scale for export
CO_2 UTILISATION: **MINERAL CARBONATES**		Demonstration scale, if appropriate mineral feedstocks are identified	Commercial scale
CO_2 STORAGE	Geological storage	Geological storage	Geological storage

- Large-scale renewable hydrogen production in the medium to long term, enabled by renewable electricity. Naturally occurring hydrogen or low-emission hydrogen produced from natural gas may act as transitionary sources in the NT.
- Access to land, water, natural gas and export infrastructure are also key requirements for scale-up CO_2 utilisation opportunities.

Additional information on requirements for CO_2 utilisation can be found in Section 3.

The development of these inputs and related infrastructure may be relatively low-risk investments for the NT, as carbon capture, renewable electricity and hydrogen are all expected to be increasingly required, even if CO_2 utilisation opportunities do not reach maturity. This can de-risk investment for CO_2 utilisation proponents in the medium to long term.

Figure ES 3: Cumulative CO_2 and hydrogen demand

CO_2 utilisation scale	Methanol	Jet fuel	Urea	Methane	Mineral carbonates
SHORT TERM (BY 2030)					
2% NTLEH CO_2 emissions (0.15 Mtpa from point sources)	**0.05 Mt** Demonstration scale	**0.01 Mtpa** (0.08m bbl/yr) Pilot scale			
	0.02 Mtpa H_2 (equivalent to 0.7 TWh/yr) Requiring 0.6 – 1 GW of hydrogen electrolysers				
MEDIUM TERM (2030-2040)					
6% NTLEH CO_2 emissions (1.15 Mtpa from point sources and DAC)	**0.35 Mtpa** Commercial scale	**0.1 Mtpa** (0.08m bbl/yr) Demonstration scale	**0.1 Mtpa** Demonstration scale	**0.05 Mtpa** (2.8 PJ/yr) Commercial scale	**0.1 Mtpa** Demonstration scale
	0.16 Mtpa H_2 (equivalent to 7.2 TWh/yr) Requiring 0.9 – 4.3 GW of hydrogen electrolysers				Alkaline mineral feedstock
LONG TERM (BEYOND 2040)					
20% NTLEH CO_2 emissions (4.84 Mtpa from point sources and DAC)	**1.0 Mtpa** Commercial scale	**0.25 Mtpa** (2m bbl/yr) Commercial scale	**1.0 Mtpa** Commercial scale	**0.38 Mtpa** (20.9 PJ/yr) Commercial scale	**1.0 Mtpa** Commercial scale
	0.63 Mtpa H_2 (equivalent to 28.3 TWh/yr) Requiring 3.6 – 17 GW of hydrogen electrolysers				Alkaline mineral feedstock

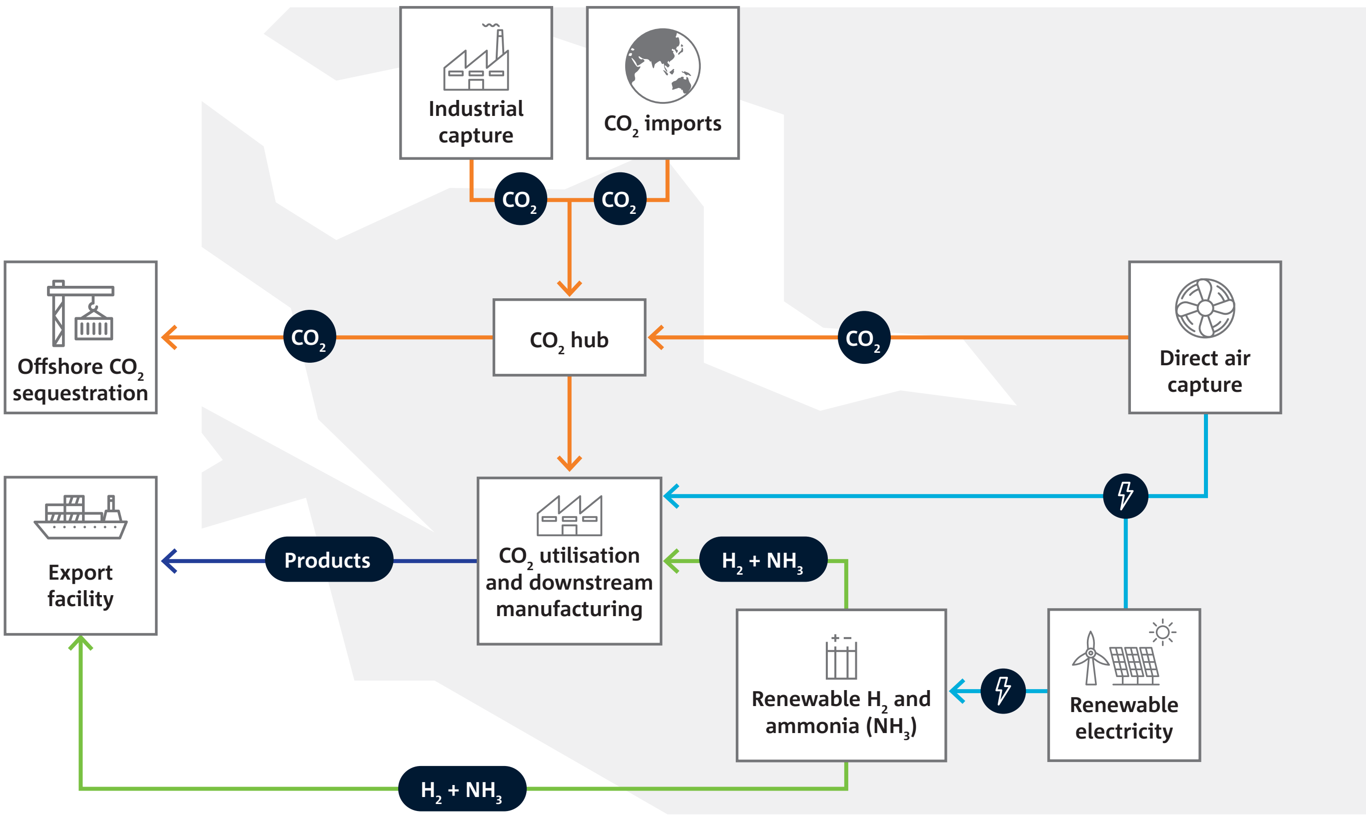
The electrolyser scale varies to account for the different capacity factors modelled for electricity supply (19% and 90%). See Appendix C – Techno-economic for further information.

A CCUS and hydrogen hub in the Northern Territory could support the deployment of CO_2 utilisation opportunities

Developing a hub with shared CCUS and hydrogen production infrastructure can support the deployment and scale-up of CO_2 utilisation opportunities (see Figure ES 4). The hub model could also enable the deployment and scale-up of CO_2 utilisation opportunities by:

- Strategically planning hub activities to identify synergies and efficiencies between CCUS, renewable hydrogen, low-emissions manufacturing and other industrial developments.
- Enabling research, development and demonstration into CO_2 utilisation and related technologies, such as DAC, hydrogen electrolysis and novel utilisation technologies, to reduce utilisation costs.

Figure ES 4: Long-term vision for Northern Territory CCUS hub (not to scale)



1 The opportunity for CO_2 utilisation in the Northern Territory

CO_2 utilisation can produce low-emission products for growing markets

CO_2 utilisation is the process of using CO_2 captured from industrial emissions or directly from the atmosphere to produce valuable products. There are diverse established and emerging uses for CO_2 (see Figure 1), including manufacturing fuels and chemicals, carbonating beverages, enhancing plant growth in greenhouses, and fertiliser production. This report explores opportunities to deploy new CO_2 utilisation applications in the Northern Territory, focusing on carbon abatement opportunities that can be realised by producing products such as chemicals, fuels and bulk materials from CO_2.

The maximum abatement potential of CO_2 utilisation applications depends on both the source of CO_2 and the stability of the CO_2-derived product (i.e., the duration that carbon is stored in the product before it is converted back to CO_2) (see Figure 2). Utilising industrial CO_2 emissions can reduce the emissions intensity of most CO_2-derived products and can enable net zero when the product is stable. This can help reduce the emissions intensity of industries that face barriers to decarbonisation via renewable technologies, known as hard-to-abate industries, such as concrete manufacturing and minerals processing.

Figure 1: Examples of established and emerging CO_2 utilisation applications

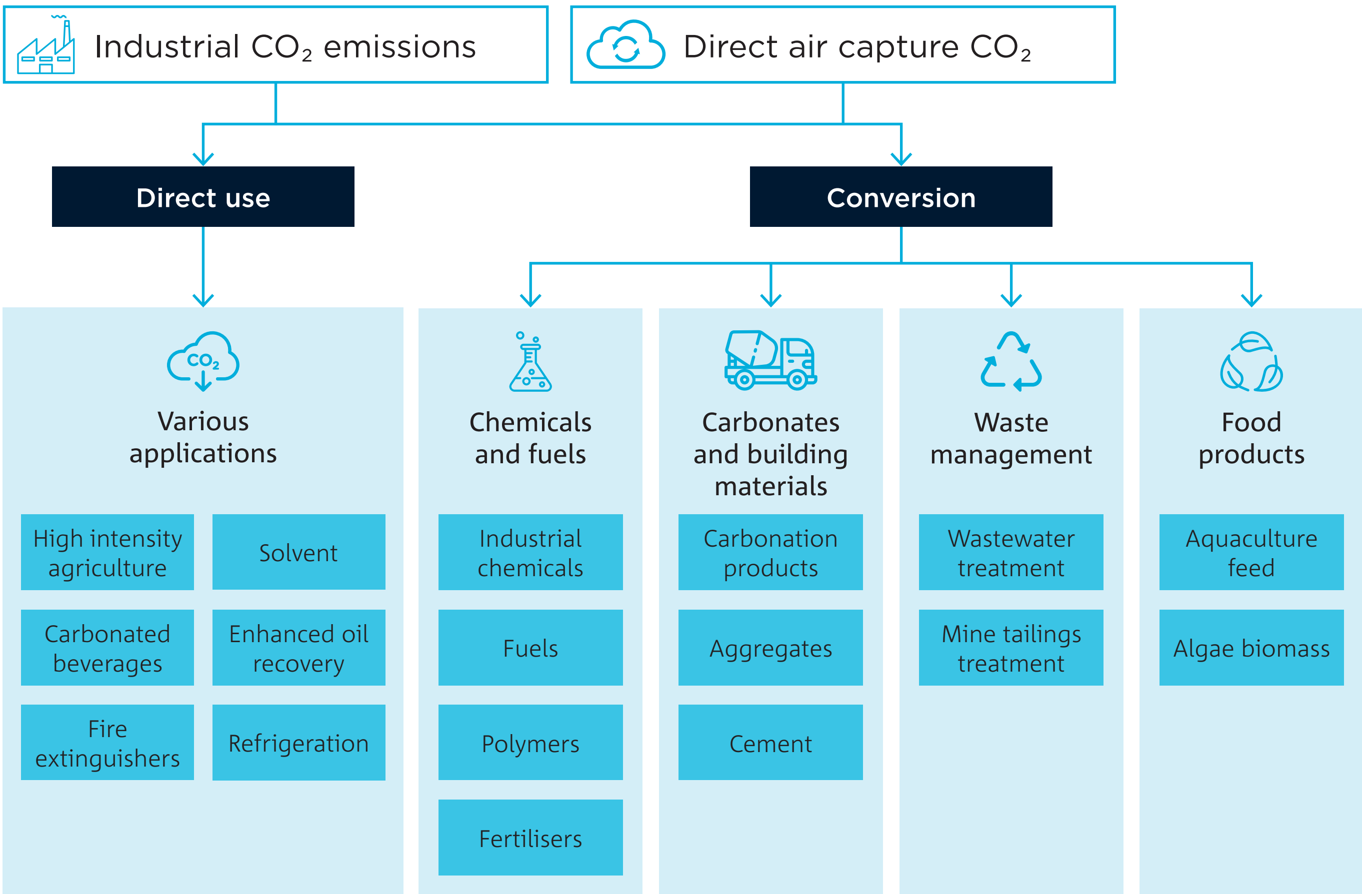


Figure 2: Emissions abatement potential for CO_2-derived products[1]

CO_2 source	Long duration CO_2 storage >100 years (e.g. carbonated aggregates)	Short duration CO_2 storage
Direct Air Capture (DAC)	Negative potential	Net zero potential
Industrial emissions (e.g. Point source or AGRU)	Net zero potential	Reduced emissions intensity

Using DAC can enable net zero emission products, including when use of the product releases CO_2 into the atmosphere. For long-duration CO_2 storage, this can enable negative emissions. However, at the time of writing, DAC technologies have not been widely deployed at commercial scale.

CO_2 utilisation technologies are rapidly maturing with many demonstration and first-of-a-kind plants emerging globally. Examples include:

- Carbon Recycling International (Iceland) has developed a commercial scale (up to 0.11 Mtpa) CO_2-derived methanol production plant that utilises CO_2 from a metallurgical coke production facility in Anyang city, China.
- Norsk e-Fuel (Norway) is developing a first-of-a-kind commercial-scale demonstration plant for CO_2-derived jet fuel production which is planned to commence operations in 2024 and scale up to 0.025 Mtpa (or 0.16m bbl/y) of fuel by 2026.[2]
- INPEX (Japan) plans to develop a methanation demonstration facility in Australia from which CO_2-derived methane will be shipped to Japan with the CO_2 produced from its use captured and returned to Australia in a demonstration of carbon recycling.[3]
- MCi Carbon (Australia) has developed an operational pilot scale CO_2 mineral carbonation plant at the University of Newcastle.[4]

Additional information on CO_2 capture and utilisation technologies and opportunities can be found in CSIRO's CO_2 Utilisation Roadmap.[5]

1 Best case emission outcomes for the production and use of CO_2-derived products with different carbon storage durations. This does not replace a full life cycle assessment which would consider other emissions sources including electricity consumption and transport. Adapted from National Academies of Sciences, Engineering, and Medicine (NASEM) (2022) *Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report*. The National Academies Press.

2 Norsk e-Fuel (n.d.) *Our Technology*. Viewed 17 Jan 2023, https://www.norsk-e-fuel.com/technology.

3 INPEX (2022) *Inpex Vision @2022*. Viewed 02 Feb 2023, https://www.inpex.co.jp/english/company/pdf/inpex_vision_2022.pdf.

4 MCi Carbon (n.d.) *Carbon Platform*. Viewed 16 Jan 2023, https://www.mineralcarbonation.com/carbon-platform.

5 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

The NT has ambitious economic growth and emissions reduction targets

The NT Government has announced an ambitious plan to grow its Gross State Product (GSP) to $40 billion by 2030.[6] Resources, manufacturing, and exports have been identified as critical to growing and future-proofing the NT's economy. However, manufacturing accounted for only 4.2% ($993 million) of GSP and 2.6% of jobs in 2020-21.[7] The NT's exports are reliant on the Liquefied Natural Gas (LNG) industry, demonstrating limited economic complexity in the NT.

The NT Government has also committed to achieving net zero emissions by 2050.[8] The NT's total CO_2 emissions for 2020 were 17.3 Mt CO_2-equivalent.[9] Without abatement, potential economic growth plans in the NT can be expected to increase CO_2 emissions further.

Diversifying and growing the NT's industry and exports while transitioning to net zero emissions will require significant investments in low-emissions technologies such as renewable energy, carbon capture, utilisation and storage (CCUS), and high-quality carbon offsets.

In the context of these challenges, the NT Government is working with industry and the Australian Government to accelerate the development of the Middle Arm Sustainable Development Precinct (MASDP) into a globally competitive and sustainable precinct. The MASDP is approximately 1500 hectares and is undergoing a strategic assessment to streamline approval processes, reduce investment risk and improve regulatory efficiency for prospective proponents.[10] This strategic assessment targets proponents of low-emission petrochemicals, renewable hydrogen, carbon capture and storage (CSS), minerals processing, energy, and advanced manufacturing.[11] The Australian Government is investing $300 million into the NT, including MASDP, offshore CCS projects, and a hydrogen hub.[12]

Alongside the broader MASDP, CSIRO is leading a group of government and industry partners to develop a business case for a Low Emissions CCUS Hub in the Northern Territory (NT) referred to as the Northern Territory Low Emissions Hub (NTLEH). This hub concept aims to reduce the costs of CCUS and hydrogen production through shared infrastructure, aggregation of carbon supply and demand, and economies of scale. CSIRO's analysis indicates that the NTLEH could process over 20 Mtpa of CO_2 for storage and utilisation by 2040. The hub could also play an important role in technology demonstration; supporting decarbonisation, entrepreneurship and job creation.

6 Thompson J (2022) *NT Government says $40-billion economy by 2030 still in reach despite disruptions to Origin and Santos projects*. Viewed 24 Jan 2023, https://www.abc.net.au/news/2022-09-26/nt-santos-gas-future/101471236.

7 NT Government Department of Treasury and Finance (2022) *Northern Territory Economy: Mining and manufacturing*. Viewed 16 Jan 2023, https://nteconomy.nt.gov.au/industry-analysis/mining-and-manufacturing.

8 Northern Territory (NT) Government Department of Environment and Natural Resources (2020) *Northern Territory Climate Change Response: Towards 2050*. Department of Environment and Natural Resources.

9 Australian Government DCCEEW (n.d.) *Emissions by State and Territory, Australia's National Greenhouse Gas Accoun*ts, https://www.greenhouseaccounts.climatechange.gov.au/.

10 Australian Government Department of Climate Change, Energy, the Environment and Water (DCCEEW) (n.d.) *Middle Arm Sustainable Development Precinct Strategic Assessment*. Viewed 24 Jan 2024, https://www.dcceew.gov.au/environment/epbc/strategic-assessments/middle-arm.

11 NT Government (2022) *Middle Arm Sustainable Development Precinct*. Viewed 24 Jan 2023, https://invest.nt.gov.au/investment-opportunities/middle-arm-sustainable-development-precinct.

12 Hynes N & Roberts L (2022) Prime Minister Scott Morrison promises $300 million for Northern Territory energy industry, $14 million to fight crime. 24 April, ABC News. <https://www.abc.net.au/news/2022-04-24/alice-springs-darwin-federal-election-2022-promises/101011700>.

The NT is relatively well positioned to scale-up CO_2 utilisation applications

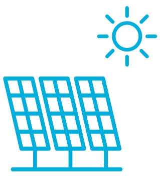
The NT can leverage existing factors to support the scale-up of CO_2 utilisation applications. These include:

Existing LNG industry with expertise in petrochemical processing

Darwin is a globally significant LNG export hub, supplying more than 10% of Japan and Taiwan's annual global gas imports and accounting for more than one-fifth of the NT's GSP.[13]

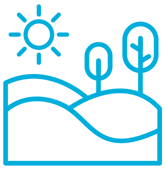
Proximity and established trade links with growing markets in the APAC region

The NT's largest export markets include Japan ($7.1 billion in 2021-22), China ($2.3 billion) and Singapore ($1.7 billion).[14]



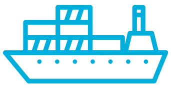
High renewable energy potential

The NT has Australia's strongest solar energy resource with an average annual solar radiation of 22–24 MJ per square metre.[15]



Available land for development

The MASDP has approximately 1,500 hectares available for development.



Deep water port

Darwin's natural deep-water port is Australia's closest port to Asia.[16]

Australian and NT government investment in manufacturing and export infrastructure

The Australian Government has committed $1.5 billion in planned equity for construction of common-use marine infrastructure at MASDP, as well as strategic planning for advanced manufacturing by the NT Government.[17]

13 NT Government (2022) *Expand Darwin's world scale LNG hub.* Viewed 24 Jan 2024, https://territorygas.nt.gov.au/gas-strategy/our-gas-led-growth-story/expand-darwins-world-scale-lng-hub.

14 NT Government Department of Treasury and Finance (2022) *Northern Territory Economy: International trade*. Viewed 16 Jan 2023, https://nteconomy.nt.gov.au/international-trade.

15 NT Government (2022) *Renewable Energy.* Viewed 24 Jan 2023, https://invest.nt.gov.au/infrastructure-and-key-sectors/key-sectors/renewable-energy.

16 Darwin Port (n.d.) *About Darwin Port.* Viewed 31 Jan 2023, https://www.darwinport.com.au/about/about-darwin-port.

17 Minister for Infrastructure, Transport, Regional Development and Local Government (2022) *$2.5 billion infrastructure boost for the Northern Territory*. Viewed 31 Jan 2023, https://minister.infrastructure.gov.au/c-king/media-release/25-billion-infrastructure-boost-northern-territory,

Analysis approach

Objectives

The primary objective of this report is to identify opportunities to deploy CO_2 utilisation applications in the NT and explore the considerations and requirements for their scale-up. This analysis builds on the CO_2 Utilisation Roadmap published by CSIRO in 2021.[18] The report is informed by literature review, techno-economic analysis, and stakeholder consultations (for a list of consulted stakeholders, see Appendix A). This report is designed to inform the development of the NTLEH business case and to be a public resource on CO_2 utilisation opportunities.

Scope

This report is focused on opportunities to utilise CO_2 captured from industrial emissions or directly from the air to reduce the emissions profile of products. Other low-emission manufacturing pathways (including manufacturing using biomass-derived carbon sources and fossil-fuel-based manufacturing coupled with CCS) are out of scope. Natural gas-derived products and feedstocks are out of scope except for the use of CO_2 captured from acid-gas removal units (AGRU) and hybrid production pathways

Approach

This report is the result of three stages of analysis:

1. **Opportunity prioritisation:** A high-level preliminary assessment of eleven CO_2 utilisation applications was used to identify five opportunities (as outlined in Table 1). The five opportunities were prioritised using three criteria: expected availability of critical prerequisites in the NT (including inputs and relevant industry activity), CO_2 utilisation technology maturity, and market readiness (see Table 2 and Appendix B for further information). The six CO_2 utilisation applications that were not prioritised for analysis in this report could become valuable opportunities for the NT in the future.
2. **Opportunity assessment and techno-economic analysis:** A detailed assessment and techno-economic analysis were undertaken to develop an indicative deployment and scale-up plan for the five prioritised applications. This included a literature review, targeted consultations, techno-economic analysis, and the development of individual pathways to deployment and scale-up. The deployment pathways were tested with stakeholders in a workshop. Key considerations that will affect the commercial viability of each opportunity were identified.
3. **Requirements and enablers for CO_2 utilisation:** The cross-cutting requirements for CO_2 utilisation applications were analysed to identify challenges and potential constraints for their deployment and scale-up. High-level actions that could enable CO_2 utilisation to play a role in supporting the NT's economic growth and decarbonisation ambitions were explored.

18 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) CO_2 Utilisation Roadmap. CSIRO.

Table 1: Summary of CO_2 utilisation opportunity assessment, where the blue highlighted applications were prioritised for detailed analysis

APPLICATION	PREREQUISITES	MATURITY	MARKET
Methanol	●	●	●
Jet fuel	◐	◐	●
Urea	◐	●	◐
Methane	●	◐	◐
Mineral carbonates	◐	◐	●
Olefins (Polymer precursors)	◐	◐	◐
Ethanol	◐	◐	◐
Food and beverage manufacturing	○	●	◐
High-value algae products	◐	◐	◐
Animal feed proteins	◐	◐	◐
Carbon-based materials	◐	○	◐

Table 2: Prioritisation criteria

RANKING	PREREQUISITES (INPUTS AND INDUSTRY)	CO_2 UTILISATION TECHNOLOGY MATURITY	MARKET READINESS
● High	Prerequisites likely to be met within five years (by 2028)	Commercial scale demonstration or above (CRI 3+)	Strong demand growth and reasonable prospect of NT supply
◐ Medium	Prerequisites could be met within 10 years if other projects scale effectively (by 2033)	Pilot scale demonstration (TRL 7-9 / CRI 1-2)	Strong demand growth but limited prospect of NT supply OR Low demand growth but reasonable prospect of NT supply
○ Low	Prerequisites are not expected to be met within 10 years	Research and development (TRL <6)	Low demand growth and limited prospect of NT supply

Techno-economic analysis approach

This report uses techno-economic analysis to calculate a levelised cost of production for CO_2-derived products and identify the key cost drivers to reduce barriers to scale-up. A *base case* and *best case* scenario approach was used to capture the current state of technology maturity and costs, and the opportunity for cost reductions due to technological improvements feedstock affordability, and economies of scale.

CSIRO's CO_2 Utilisation Roadmap (2021) set the scale of CO_2 utilisation at 1,000 t/day for the base case and 5,000 t/day for the best case for all modelled applications. For consistency, this project uses the same scales. It should be noted that these scales do not always align with the indicative scale-up pathways for the opportunities discussed in this report. Further information on techno-economic analysis methodology and key assumptions can be found in Appendix C.

All financial assumptions and results are presented in AUD, and all figures are shown in the metric system unless stated otherwise.

2 Assessment of CO_2 utilisation opportunities

This section of the report assesses the opportunity to deploy and scale-up production of CO_2-derived products, including:

- Methanol Section 2.1
- Jet fuel Section 2.2
- Urea Section 2.3
- Methane Section 2.4
- Mineral carbonates Section 2.5

Techno-economic analysis of the levelised cost of production is used to explore the sensitivities and cost premiums for CO_2-derived products. A deployment plan for the five prioritised opportunities is presented in Section 2.6, highlighting the scale-up timelines for different applications.

2.1 Methanol

Key findings

Deployment and scale-up in the NT

Methanol is used for various purposes, including as a solvent, fuel, and feedstock for manufacturing other chemicals and fuels. As such, CO_2-derived methanol production could offer a strategic opportunity for the NT to support the growth of a low emission manufacturing industry and supply international export markets.

Considerations

- CO_2-derived methanol is not expected to compete with conventional methanol on cost alone, but customers could be expected to pay a premium for renewable methanol.
- The international methanol market is crowded, but there is a growing demand in the APAC region for renewable methanol.
- Methanol production in the NT could enable downstream manufacturing and service diverse export markets, which can support local industrial growth and help achieve economies of scale.
- Hybrid methanol production could support the scale-up of CO_2 utilisation with reduced technology risk.

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• Demonstration scale CO_2-derived methanol production (standalone or in a hybrid facility), operating at 0.05 Mtpa	• Commercial-scale CO_2-derived or hybrid production, operating at 0.35 Mtpa	• Commercial scale CO_2-derived production facility for local manufacturing and export use, operating at 1 Mtpa
Enablers	• Explore the prospect of renewable and hybrid methanol production using both natural gas and renewable hydrogen feedstocks	• Secure local offtake agreements for commercial scale methanol production	• Secure international offtake agreements for methanol export

Levelised cost of production and abatement potential

CO_2 SOURCE	BASE CASE LCOP	BEST CASE LCOP	CARBON STORAGE DURATION	ABATEMENT POTENTIAL
DAC	$2349/t (~5 × conventional sale price)	$1155/t (~2.5 × conventional sale price)	>100 years (e.g., polymers)	Negative
			<100 years (e.g., fuels)	Net zero
Industrial emissions	$1576–1711/t (~3–3.5 × conventional sale price)	$835–907/t (~1.5–2 × conventional sale price)	>100 years (e.g., polymers)	Net zero
			<100 years (e.g., fuels)	Reduced emissions intensity

2.1.1 Overview

Methanol is an alcohol used to synthesise a wide variety of chemicals and fuels, such as plastics, textiles, medical equipment, insulation, and paints. It is also used as a fuel and fuel additive.[19] Methanol is conventionally produced from synthesis gas (syngas) derived through steam methane reforming (SMR) or steam gasification of coal.

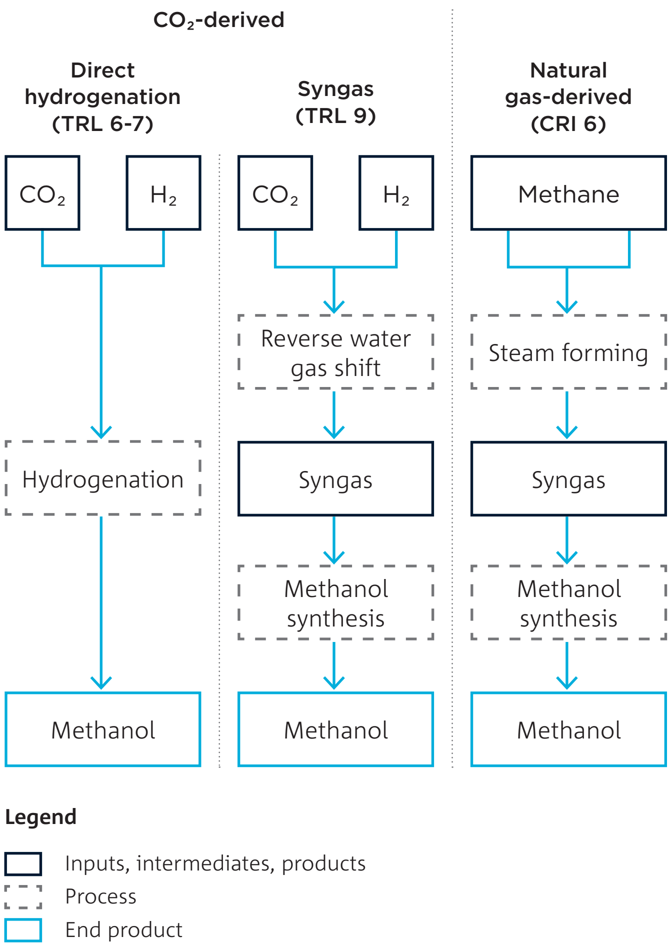
CO_2-derived methanol can be produced using syngas as an intermediary or by direct hydrogenation of CO_2 (see Figure 3). Production of methanol via syngas (utilising a reverse water gas shift) is technologically mature and has been an area of growing global commercial interest. However, uptake depends on the availability of low-cost, renewable hydrogen and catalyst improvements to drive cost competitiveness.[20]

Direct hydrogenation has not been demonstrated at scale but could enable improved process efficiency once the technology matures. While pilot direct hydrogenation plants are in operation, longer-term studies are required to optimise catalyst use, identify ideal operating conditions, and increase methanol yield.[21]

Current emissions from methanol production and use are around 300 Mt CO_2 per annum (approximately 10% of the chemical sector's global emissions).[22] If fossil-fuel-derived methanol products are used to meet projected global demand in 2050, this would increase to 1,500 Mt of CO_2-equivalent emissions.[23]

Depending on the end use of CO_2-derived methanol, CO_2 may be stored for a short (e.g., fuel) or long time (e.g., polymers). Short duration storage of CO_2 sourced from industrial emissions can reduce overall emissions through substitution. However, methanol produced from renewable hydrogen and CO_2 sourced from DAC would be effectively net zero for these applications.

Figure 3: Simplified production processes for CO_2-derived and conventional (natural gas-derived) methanol



19 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

20 Bown RM, Joyce M, Zhang Q, Reina TR, Duyar MS (2021) Identifying Commercial Opportunities for the Reverse Water Gas Shift Reaction. Energy Technology.

21 Dieterich V, Buttler A, Hanel A, Spliethoff H, Fendt S (2020) *Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review*. Energy & Environmental Science.

22 International Renewable Energy Agency (IRENA), Methanol Institute (2021) *Innovation Outlook: Renewable Methanol*. International Renewable Energy Agency.

23 IRENA, Methanol Institute (2021) *Innovation Outlook: Renewable Methanol*. International Renewable Energy Agency.

2.1.2 Deployment and scale-up in the NT

Competitive, commercial-scale CO_2-derived methanol production could stimulate the NT economy by enabling diverse, sustainable manufacturing applications and export opportunities. Table 3 outlines an indicative pathway to achieving commercial scale production beyond 2040 and the scale of inputs required to achieve this. Additional detail on the shared, critical requirements for CO_2 utilisation can be found in Section 3.

Table 3: CO_2-derived methanol scale-up pathway for the NT

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• Demonstration scale CO_2-derived methanol production (standalone or in a hybrid facility)	• Commercial-scale CO_2-derived or hybrid production	• Commercial scale CO_2-derived production facility for local manufacturing and export use
Enablers	• Explore prospect of renewable and hybrid methanol production using both natural gas and renewable hydrogen feedstocks	• Secure local offtake agreements for commercial scale methanol production	• Secure international offtake agreements for methanol export
Scale of production	0.05 Mtpa	0.35 Mtpa	1 Mtpa
CO_2 utilised	0.08 Mtpa	0.55 Mtpa	1.57 Mtpa
Hydrogen required	0.01 Mtpa	0.07 Mtpa	0.21 Mtpa

2.1.3 Considerations for deployment and scale-up in the NT

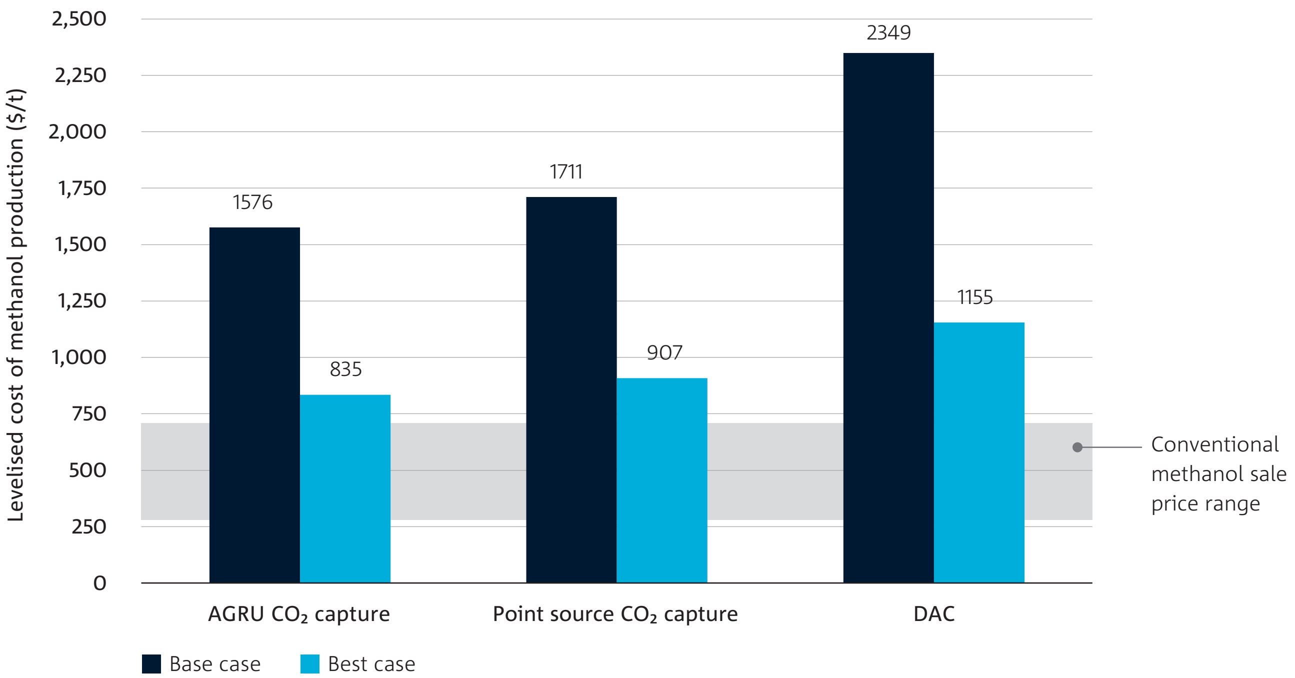
CO_2-derived methanol is not expected to compete with conventional methanol on cost alone, but customers could be expected to pay a premium for renewable methanol.

Modelling indicates that the levelised cost of methanol production (based on direct hydrogenation of CO_2) exceeds typical sale prices of conventional methanol in both the base and best case (as shown in Figure 4).

Under the best-case scenario, the levelised cost of production is $835–907/t using industrial CO_2 emissions, and $1155/t when using DAC. This improvement is primarily driven by a reduction in the cost of hydrogen from $5.47 to $2.62/kg, as shown in Figure 4. Low-cost CO_2 capture can also have a notable impact on production costs. As such, CO_2 captured from natural gas processing facilities and other industrial processes could help demonstrate and scale CO_2 utilisation while DAC reaches commercial scale. A detailed breakdown of cost reduction drivers between the base and best cases can be seen in Figure 25 in Appendix D.

Future increases in methanol sale prices or the introduction of a carbon price could increase the competitiveness of CO_2-derived methanol. However, proponents will need to charge premiums for CO_2-derived methanol to break even on production costs under most scenarios. The techno-economics of hybrid production using a syngas intermediary (see below) are beyond the scope of this analysis and require further exploration.

Figure 4: Levelised cost of methanol production using different CO_2 feedstocks



The modelled CO_2 sources were acid gas removal unit (AGRU) capture (assumed zero cost), high partial pressure point source capture ($86/t CO_2 in the base case and $46/t CO_2 in the best case) and direct air capture ($490/t CO_2 in the base case and $200/t CO_2 in the best case). The base case scale assumes utilisation of 1,000 t/d of CO_2 (equivalent to a production scale of 0.23 Mtpa methanol). The best case assumes a five-fold increase in the scale of CO_2 utilisation and methanol production. The conventional methanol sale price range is based on historical market prices between 2015 and 2019. See Appendix C for all assumptions.

The cost of hydrogen (driven by the price and capacity factor of renewable electricity) is the most significant driver of the levelised cost of CO_2-derived methanol production (see Figure 25 in Appendix D for a breakdown of the primary cost reduction drivers between base and best case). Figure 5 shows the impact of different hydrogen costs on the levelised cost of methanol production. Achieving a stretch target of $2/kg of hydrogen would make CO_2-derived methanol significantly more cost competitive. However, recouping production costs would require a significant premium when using DAC-sourced CO_2.

The international methanol market is crowded, but there is a growing demand in the APAC region for renewable methanol.

Global methanol production capacity has exceeded demand in recent years (2021 global production capacity reached 160 Mtpa while demand was approximately 85 Mtpa). Production capacity is also forecast to grow by more than 80% from 2021 to 2030 due to planned plants in Russia, the Middle East and China.[24]

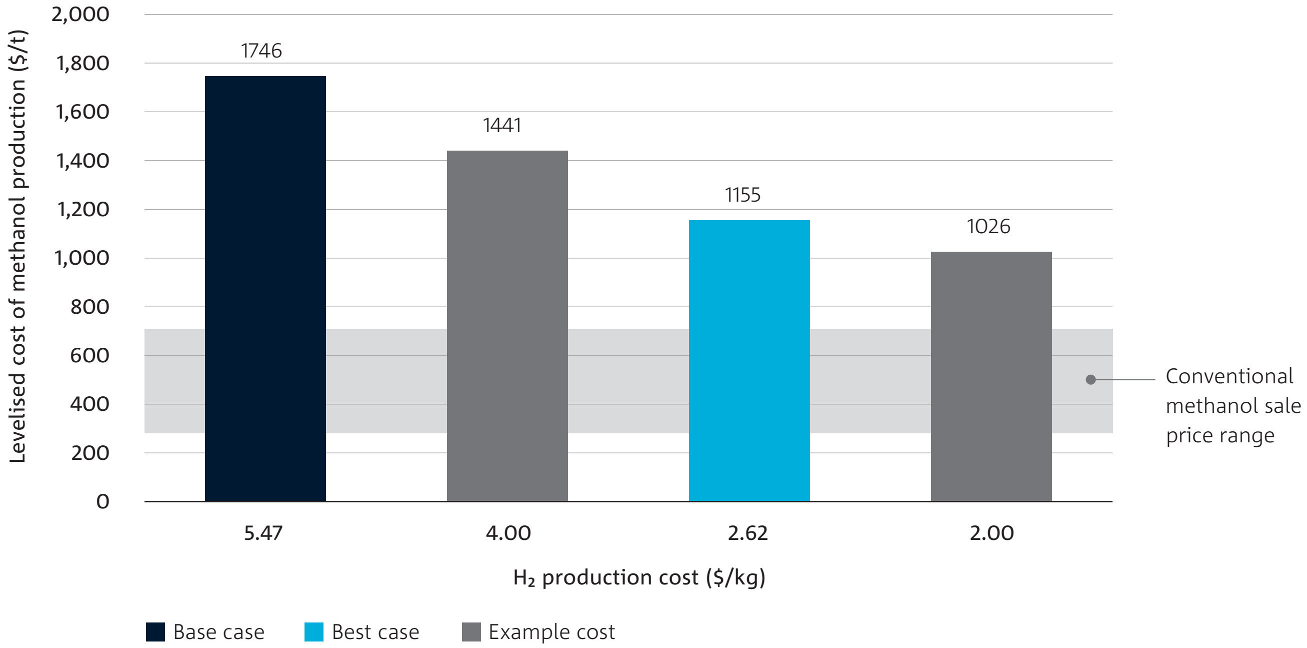
China has many dormant conventional production facilities, the world's largest methanol consumer and producer.[25] Around 80% of China's methanol production facilities are coal-based,[26] but China has also invested in CO_2-derived methanol production.

24 Fernández L (2022) Global production capacity of methanol 2018-2021. Viewed 17 Jan 2023, https://www.statista.com/statistics/1065891/global-methanol-production-capacity/.

25 Methanol Institute (2021) *Methanol Fuel in China 2020*. China Association of Alcohol and Ether Fuel and Automobiles.

26 Xue Y (2022) *Beijing to accelerate deployment of methanol vehicles under carbon-neutral drive*. Viewed 17 Jan 2023, https://www.scmp.com/business/article/3193161/beijing-accelerate-deployment-methanol-vehicles-under-carbon-neutral-drive.

Figure 5: Impact of hydrogen feedstock cost on the levelised cost of methanol production



Sensitivity analysis shows the effect that the modelled base ($5.47/kg H_2) and best case ($2.62/kg H_2) hydrogen production costs have on the levelised cost of methanol. A midpoint of $4.00/kg and a stretch goal of $2.00/kg were also modelled. This modelling assumes that CO_2 is sourced from DAC and uses the best case option for all other variables.

Carbon Recycling International has developed a commercial-scale CO_2-derived methanol production plant that utilises CO_2 from a metallurgical coke production facility in Anyang, China. This plant started production in late 2022 and has a capacity of up to 0.11 Mt of low-carbon intensity methanol produced from approximately 0.16 Mt of CO_2 yearly.[27] Carbon Recycling International is also designing a similarly sized CO_2-to-methanol facility for construction in a petrochemical industrial park Jiangsu, China.[28]

Local and global demand for methanol is projected to grow significantly. Australian demand was 4.9 Mtpa in 2020 and is projected to grow at a compound annual growth rate (CAGR) of 4.60% until 2030.[29] Similarly, global demand was 85 Mtpa in 2021 and is projected to grow at a CAGR of 4.24% until 2032. Much of this demand is from the APAC region.[30] Demand for renewable methanol is projected to grow faster than the broader market, at a CAGR of 5.8%, reaching a total market value of $5.3 billion by 2027.[31]

Darwin's proximity to Asia is favourable, as trade links established for the export of LNG can be leveraged to supply large volumes of methanol to this market in the coming decades.[32 33 34] China and Korea both have high projected growth for methanol demand and pre-existing trade links with the NT. Similarly, India is a robust growth market, and Japan is a key trade partner of the NT,[35 36] making each country a possible target export market.

27 Carbon Recycling International (n.d.) *Projects*. Viewed 17 Jan 2023, https://www.carbonrecycling.is/projects.

28 Carbon Recycling International (n.d.) *Projects*. Viewed 17 Jan 2023, https://www.carbonrecycling.is/projects.

29 ChemAnalyst (2021) *Australia Methanol Market Analysis*. Viewed 23 Jan 2023, https://www.chemanalyst.com/industry-report/australia-methanol-market-201.

30 ChemAnalyst (2022) *Methanol Market Analysis*. Viewed 23 Jan 2023, https://www.chemanalyst.com/industry-report/methanol-market-219.

31 Ayushi C (2020) *Renewable Methanol Market*. Viewed 16 Jan 2023, https://www.alliedmarketresearch.com/renewable-methanol-market.

32 EnergyQuest (2022) *Record June LNG exports end a record year but big fall in China exports*. Viewed 16 Jan 2023, https://www.energyquest.com.au/record-june-lng-exports-end-a-record-year-but-big-fall-in-china-exports/.

33 NT Government Department of Treasury and Finance (2022) *Northern Territory Economy: International trade*. Viewed 16 Jan 2023, https://nteconomy.nt.gov.au/international-trade.

34 Technavio (2021) *Methanol Market*. Viewed 24 Jan 2023, https://www.technavio.com/report/methanol-market-industry-analysis.

35 BrandEssence Market Research and Consulting Private Limited (2022) *Methanol Market Size, Share, Industry Growth by 2028*. Viewed 16 Jan 2023, https://brandessenceresearch.com/chemical-and-materials/methanol-market.

36 NT Government Department of Treasury and Finance (2022) *Northern Territory Economy: International trade*. Viewed 16 Jan 2023, https://nteconomy.nt.gov.au/international-trade.

Countries with existing or planned petrochemical manufacturing facilities that utilise methanol as a feedstock are also expected to grow demand in the region. These include Indonesia, Malaysia, Singapore, Korea and India.[37] Examples include Indonesia's Cilacap Refinery, the country's largest, responsible for 34% of total domestic fuel production[38]; Malaysia's Pengerang Integrated Complex, housing petroleum, petrochemicals, electricity and gas production capabilities[39]; and Singapore's Jurong Island, a $5.82 billion petrochemical hub[40].

With the abundance of conventional production facilities and growing demand for renewable methanol, new investments in the NT should consider whether CO_2 utilisation can enhance their ability to compete in this global market. Focus should be placed on the rapidly evolving methanol markets of countries with aggressively legislated interim emissions reduction targets, such as Japan and South Korea.[41] [42]

Methanol production in the NT could enable downstream manufacturing and service diverse export markets, which can support local industrial growth and help achieve economies of scale.

Production at Australia's only methanol plant (a 0.07 Mtpa plant operated by Coogee Chemicals in Victoria) ceased in 2016 because of high gas prices in the east coast market.[43] [44] Australia is now reliant on imported methanol, primarily sourced from the United States, Singapore, and the United Arab Emirates.[45]

Proponents are exploring the feasibility of new domestic methanol production, including in the NT. However, these projects still need plans for CO_2 utilisation. Projects include:

- Coogee Chemicals is undertaking pre-feasibility studies on a 0.35 Mtpa conventional methanol plant using natural gas in Darwin.[46]
- HAMR Energy and Bingo Industries are conducting feasibility studies with CSIRO to assess if methanol can be synthesised from renewable hydrogen and carbon from unrecyclable waste.[47]
- ABEL Energy is conducting feasibility studies into an integrated renewable hydrogen and methanol production facility in Tasmania. This facility would utilise forestry harvest residues as the carbon source, which could be supplemented with atmospheric CO_2 captured onsite in the long term. While the study was initially based on a production capacity of 0.075 Mtpa of biomethanol, ABEL is now considering a capacity of 0.2 Mtpa, with operations to begin in 2025.[48]

Methanol is both an exportable product and a potential feedstock for local manufacturing. As methanol production may support downstream manufacturing opportunities, it may be a compelling opportunity for the NT. The strong expected growth in renewable methanol demand and diversity of downstream markets may support project proponents to secure offtake agreements. Olefins (polymer precursors) and propylene are expected to be the fastest growing downstream products of the methanol market in the short-term (to 2025), with this demand driven by China.[49] Methanol is also expected to be increasingly used as a sulphur-free maritime fuel,[50] which may further increase demand.

37 BrandEssence Market Research and Consulting Private Limited (2022) *Methanol Market Size, Share, Industry Growth by 2028*. Viewed 16 Jan 2023, https://brandessenceresearch.com/chemical-and-materials/methanol-market.

38 Djuang J (2021) *Top Five Refineries in Indonesia*. Viewed 24 Jan 2023, https://oilandgascourses.org/top-five-refineries-in-indonesia/.

39 Petronas (n.d.) *Pengerang Integrated Complex (PIC): The Regional Petrochemical Park*. Viewed 24 Jan 2023, https://www.petronas.com/pic/.

40 PCS (n.d.) *Jurong Island.* Viewed 24 Jan 2023, https://www.pcs.com.sg/singapore-petrochemical-complex/jurong-island/.

41 Agency of Natural Resources and Energy (2021) *Outline of Strategic Energy Plan*. Viewed 23 Jan 2023, https://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/6th_outline.pdf.

42 United Nations Framework Convention on Climate Change (2021) *The Republic of Korea's Enhanced Update of its First Nationally Determined Contribution.* Viewed 31 Jan 2023, https://web.archive.org/web/20220519144111/https:/www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Republic%20of%20Korea%20First/211223_The%20Republic%20of%20Korea's%20Enhanced%20Update%20of%20its%20First%20Nationally%20Determined%20Contribution_211227_editorial%20change.pdf.

43 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

44 Coogee (n.d.) *Manufacturing & Supply*. Viewed 16 Jan 2023, https://www.coogee.com.au/manufacturing-and-supply.

45 Volza (2022) *Methanol Imports in Australia - Import data with price, buyer, supplier, HSN code*. Viewed 16 Jan 2023, https://www.volza.com/p/methanol/import/import-in-australia/.

46 Macdonald-Smith A (2019) *Coogee examines $500m methanol plant in NT*. Viewed 16 Jan 2023, https://www.afr.com/companies/energy/coogee-examines-500m-methanol-plant-in-nt-20190904-p52nr9.

47 Victorian Government Department of Energy, Environment and Climate Action (n.d.) *Business Ready Fund*. Viewed 16 Jan 2023, https://www.energy.vic.gov.au/grants/business-ready-fund.

48 ABEL Energy (2022) *Knowledge Sharing Report.* Viewed 24 Jan 2023, https://recfit.tas.gov.au/__data/assets/pdf_file/0011/367877/ABEL_Energy_-_Knowledge-Sharing_Report_-Bell_Bay_-_Jun2022.pdf.

49 ReportLinker (2020) *Methanol Market - Growth, Trends, and Forecast (2020 – 2025)*. Viewed 16 Jan 2023, https://www.reportlinker.com/p05778197/Methanol-Market-Growth-Trends-and-Forecast.html.

50 Methanol Institute (n.d.) *Marine Fuel*. Viewed 16 Jan 2023, https://www.methanol.org/marine-fuel/.

If complementary downstream projects that provide additional value by upgrading methanol to other products can be identified, production in NT could help to catalyse the creation of a low-emissions manufacturing hub. Jet fuel is an example of a critical product that could be produced from methanol (see Section 2.2). Demand from multiple downstream markets may also support large-scale methanol production in the medium term, improving economies of scale and lowering production costs.

Hybrid methanol production could support the scale-up of CO_2 utilisation with reduced technology risk.

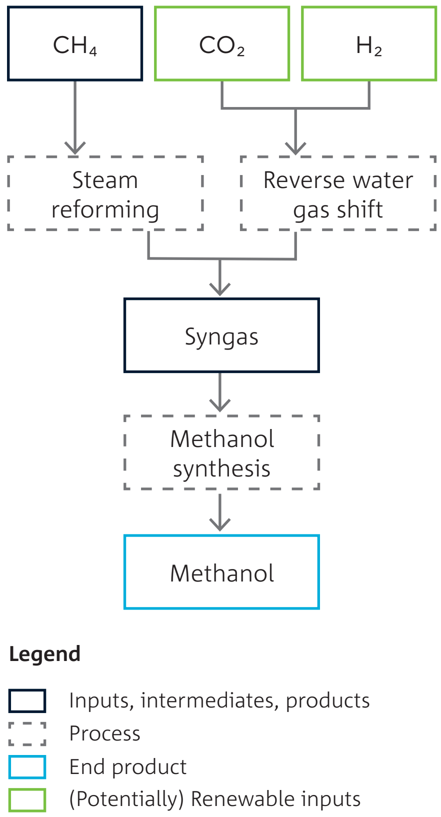
Globally, the CO_2-derived methanol industry is at early commercial maturity.[51] A hybrid approach that combines conventional and CO_2-derived methanol production could support the demonstration of CO_2 utilisation while renewable hydrogen production scales up.

Renewable hydrogen is required for CO_2-derived methanol production.[52] Investment will likely be constrained by renewable hydrogen supply in the short term, so aligning methanol scale-up with hydrogen industry development will be critical.

In the near-term, hybrid production models that blend renewable syngas (derived from renewable hydrogen and captured CO_2) into conventional methanol production could be explored (see Figure 6). The NT's natural gas industry could enable the development of hybrid methanol production facilities. Gas is projected to be cheaper in Australia's northern regions (projected at $8.70/GJ in 2030[53]) than in the east coast states where methanol manufacturing has ceased due to high gas prices.[54] The hybrid production model could scale its renewable inputs as renewable hydrogen becomes readily available and increasingly affordable.

Demonstration of methanol production in a hybrid facility can act to test and refine the CO_2-derived methanol process. This will provide an opportunity to identify any operational and engineering challenges associated with integrating and scaling CO_2-utilising production methods. Future-proofing new conventional methanol facilities to integrate CO_2 utilisation can improve their sustainability and social license while renewable hydrogen production scales. This hybrid approach could also support CO_2-derived methanol production as the local industry builds chemical manufacturing expertise, transport, and logistical support.

Figure 6: Simplified hybrid methanol production process in which natural gas, sustainable CO_2 and renewable hydrogen are used to produce syngas for methanol production



51 CRI (n.d.) *CO_2 & Methanol*. Viewed 16 Jan 2023, https://www.carbonrecycling.is/co2-methanol#.

52 Borisut P, Nuchitprasittichai A (2019) Methanol Production via CO_2 Hydrogenation: Sensitivity Analysis and Simulation—Based Optimization. Frontiers in Energy Research.

53 EnergyQuest (2021) *New report highlights growing divide in east coast gas market*. Viewed 16 Jan 2023, https://www.energyquest.com.au/new-report-highlights-growing-divide-in-east-coast-gas-market/.

54 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

2.2 Jet fuel

Key findings

Deployment and scale-up in the NT

Net zero emission targets and domestic fuel security drivers for the civil and military aviation sectors may support the production of CO_2-derived jet fuel in the NT, despite its cost premiums.

Considerations

- CO_2-derived jet fuel comes at a significant cost premium, with a high sensitivity to hydrogen input costs.
- Biofuels are currently more mature and cost-competitive, but CO_2-derived jet fuel is expected to play a critical role in the longer term.
- CO_2-derived jet fuel could support the NT civil and military aviation sectors to improve their fuel security and reduce emissions.
- Export-scale production could enable economies of scale and drive production cost reductions.
- Early investments in CO_2-derived jet fuel may remain process agnostic while new production processes are certified and standardised.

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• Pilot scale production to validate the process and secure accreditation operating at 0.01 Mtpa (0.08 million bbl)	• Demonstration scale production for defence and local airports, operating at 0.1 Mtpa (0.8 million bbl)	• Commercial scale production for local and export markets, operating at 0.25 Mtpa (2.0 million bbl)
Enablers	• Secure certification for methanol-derived jet fuel production • Demonstrate blending of CO_2-derived jet fuel into conventional fuel supply chains	• Secure process certification for the facility • Secure local offtake agreements for commercial scale jet fuel production	• Secure international certification and offtake agreements for export

Levelised cost of production and abatement potential

CO_2 SOURCE	BASE CASE LCOP	BEST CASE LCOP	CARBON STORAGE DURATION	ABATEMENT POTENTIAL
DAC	\$724/t (~8.5 × conventional sale price)	\$332/t (~4 × conventional sale price)	<100 years	Net zero
Industrial emissions	\$483–525/t (~5.5–6 × conventional sale price)	\$233–255/t (~2.5–3 × conventional sale price)		Reduced emissions intensity

2.2.1 Overview

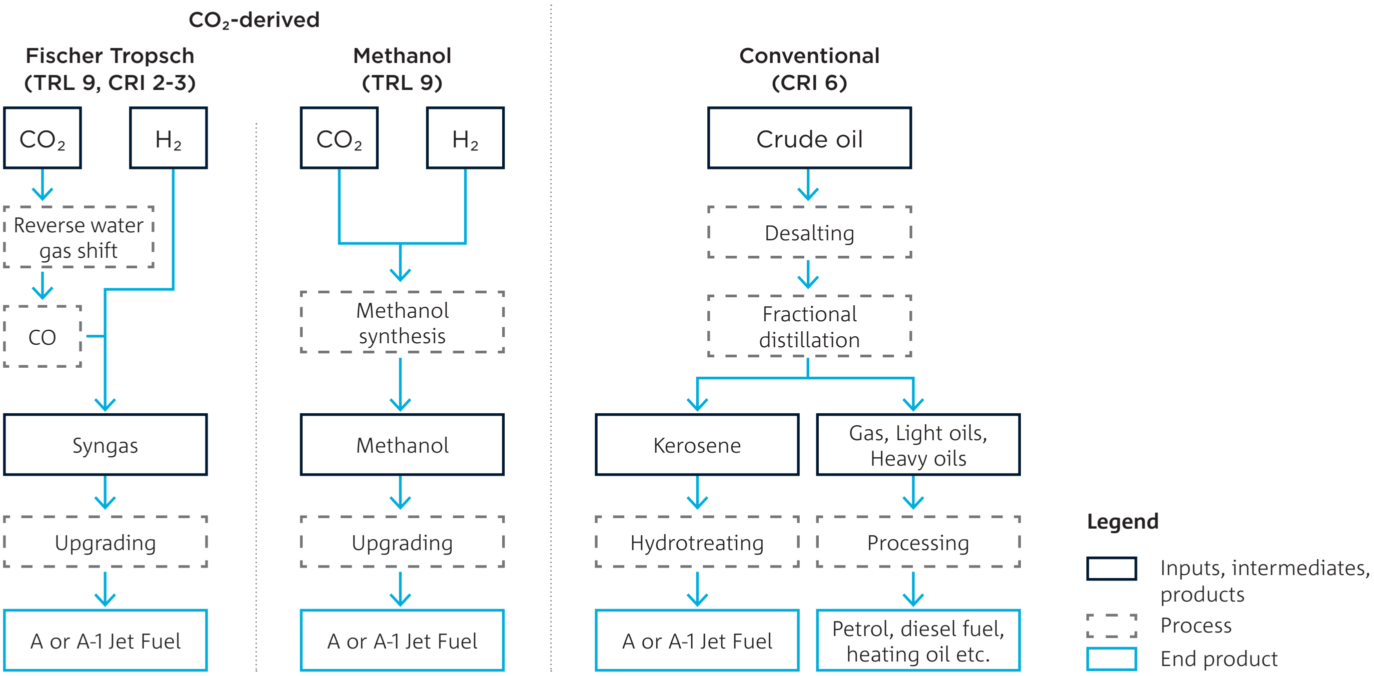
Renewable hydrocarbon fuels can be produced using captured CO_2 and a source of renewable hydrogen. Because this process is driven by electricity, this type of renewable fuel production is called power-to-liquid. Power-to-liquid applications can substitute the fossil-fuel-derived energy-dense fuels used in long-distance and heavy-load transport (e.g. aviation, shipping and long-haul transport).

This report focuses on the opportunity to manufacture CO_2-derived jet fuel (a refined kerosene-based fuel) because of its high maturity, the presence of a civil and military (domestic and international) aviation sector in the NT, and significant interest in this opportunity from industry.[55] CO_2-derived jet fuel can be produced using the Fischer Tropsch (FT) process syngas as an intermediary or by direct hydrogenation of CO_2 (see Figure 7).

The aviation sector handled approximately 2.5% (or 1.025 billion tonnes[56]) of annual global CO_2 emissions in 2018. As a hard-to-abate industry, this proportion is expected to grow.[57] The International Air Transport Association (IATA) and Airports Council International have committed to cap net carbon emissions from 2020 and to achieve net zero by 2050.[58] [59] However, the industry faces significant barriers to decarbonising using electrification or other fuel alternatives (e.g. hydrogen) due to long asset lifespans, battery limitations, and the complexity of the required engine, aircraft, and infrastructure modification.[60] Producing and using sustainable aviation fuels (including both biofuels and CO_2-derived fuels) will be critical to achieving the sector's emissions abatement objectives. It will also reduce other forms of air pollution, including particulate matter emissions and sulphur oxides (SOx).[61]

CO_2-derived jet fuel stores CO_2 until it is used. Jet fuel produced from industrial emissions would reduce overall emissions through substitution. To achieve carbon net zero, jet fuel produced from renewable hydrogen and DAC-sourced CO_2 would be effectively carbon neutral for these applications.

Figure 7: Simplified jet fuel production processes



55 Sherwin ED (2021) Electrofuel Synthesis from Variable Renewable Electricity: An Optimization-Based Techno-Economic Analysis. Environmental Science and Technology; Gray N, McDonagh S, O'Shea R, Smyth B & Murphy JD (2021) Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Advances in Applied Energy.

56 Ritchie H, Roser M, Rosado P (2020) *CO_2 and Greenhouse Gas Emissions*. Viewed 17 Jan 2023, https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

57 Ritchie H (2020) *Climate change and flying: what share of global CO_2 emissions come from aviation?*. Viewed 17 Jan 2023, https://ourworldindata.org/co2-emissions-from-aviation.

58 International Air Transport Association (IATA) (2021) *Net-Zero Carbon Emissions by 2050*. Viewed 17 Jan 2023, https://www.iata.org/en/pressroom/pressroom-archive/2021-releases/2021-10-04-03/.

59 Airports Council International (2021) *Net zero by 2050: ACI sets global long term carbon goal for airports*. Viewed 17 Jan 2023, https://aci.aero/2021/06/08/net-zero-by-2050-aci-sets-global-long-term-carbon-goal-for-airports/.

60 Schwab A, Thomas A, Bennett J (2021) *Electrification of Aircraft: Challenges, Barriers, and Potential Impacts*. National Renewable Energy Laboratory.

61 Argonne National Labs (2012) Life Cycle Analysis of Alternative Aviation Fuels in GREET. US DOE.

2.2.2 Deployment and scale-up in the NT

Scaling up CO_2-derived jet fuel production in the NT in the short to medium term will require a source of affordable renewable hydrogen (or methanol) and local customers willing to pay a significant premium for the fuel. Table 4 outlines a potential pathway to achieving commercial-scale production beyond 2040 and the scale of inputs required to achieve this. Additional detail on the shared, critical requirements for CO_2 utilisation can be found in Section 3.

Table 4: CO_2-derived jet fuel scale-up pathway for the NT

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• Pilot scale production to validate the process and secure accreditation	• Demonstration scale production for defence and local airports	• Commercial scale production for local and export markets
Enablers	• Secure certification for methanol-derived jet fuel production • Demonstrate blending of CO_2-derived jet fuel into conventional fuel supply chains	• Secure process certification for the facility • Secure local offtake agreements for commercial scale jet fuel production	• Secure international certification and offtake agreements for export
Scale of production	0.01 Mtpa (0.08m bbl/yr)	0.1 Mtpa (0.8m bbl/yr)	0.25 Mtpa (2.0m bbl/yr)
CO_2 utilised	0.04 Mtpa	0.38 Mtpa	0.95 Mtpa
Hydrogen required	0.005 Mtpa	0.05 Mtpa	0.125 Mtpa

2.2.3 Considerations for deployment and scale-up in the NT

CO_2-derived jet fuel comes at a significant cost premium, with a high sensitivity to hydrogen input costs.

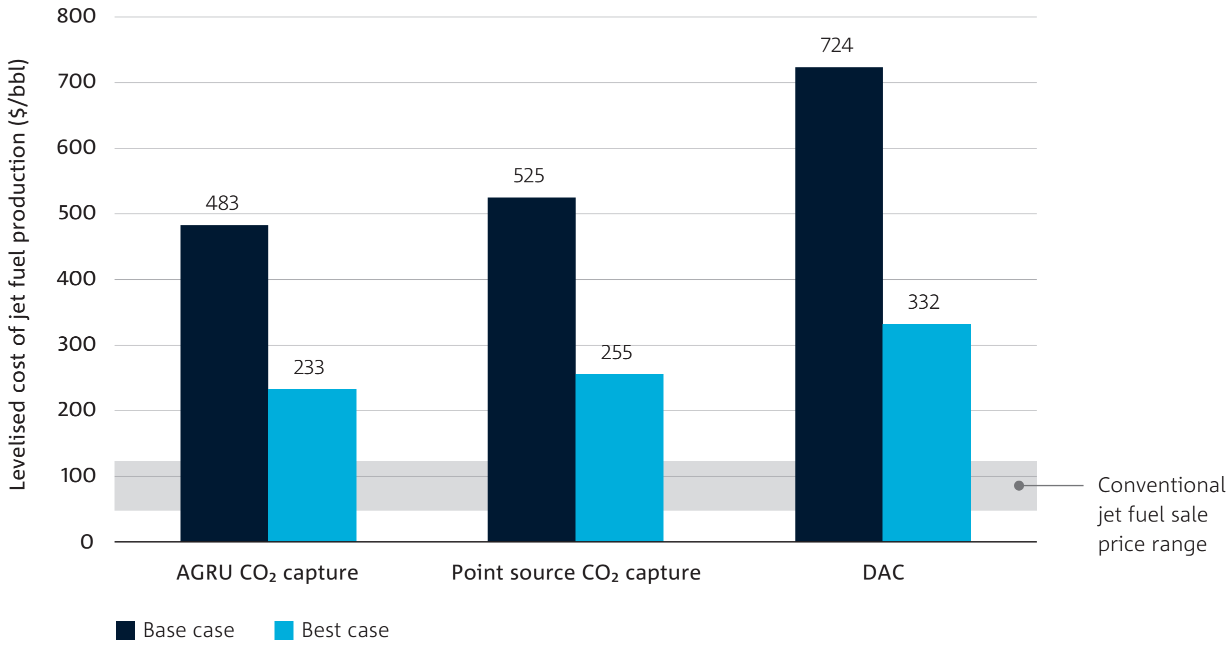
Modelling indicates that the levelised cost of CO_2-derived jet fuel production from upgrading methanol significantly exceeds typical sale prices of conventional jet fuel under both the base and best case scenarios (as shown in Figure 8). The methanol-based production process was modelled because it is expected to be more economically competitive than the FT process in the long term.[62]

Under the best case scenario, the levelised cost of production was $233–255/bbl using industrial CO_2 emissions and $332/bbl when using DAC. This improvement is primarily driven by a reduction in the cost of hydrogen from $5.47 to $2.62/kg. Low-cost CO_2 sources can also significantly reduce the levelised production costs, especially in the base case scenario, with a trade-off in the emissions abatement potential. As such, AGRU or other industrial emissions could be used to help demonstrate and scale CO_2 utilisation while DAC reaches commercial scale. A detailed breakdown of cost reduction drivers between the base and best case can be seen in Figure 26 in Appendix D.

Future increases in jet fuel sale prices or the introduction of a carbon price could increase the competitiveness of CO_2-derived jet fuel. However, a significant green premium can be expected under most scenarios.

62 Bruce S, Temminghoff M, Hayward J, Palfreyman D, Munnings C, Burke N, Creasey S (2020) *Opportunities for hydrogen in aviation*. CSIRO.

Figure 8: Levelised cost of CO_2-derived jet fuel production from different CO_2 feedstocks



The modelled CO_2 sources were AGRU capture (assumed zero cost), high partial pressure point source capture ($86/t CO_2 in the base case and $46/t CO_2 in the best case) and direct air capture ($490/t CO_2 in the base case and $200/t CO_2 in the best case). The base case scale assumes utilisation of 1,000 t/d of CO_2 (equivalent to a production scale of 0.43m bbl/yr or 0.096 Mtpa jet fuel). Best case assumes a five-fold increase in the scale of CO_2 utilisation (and jet fuel production). The conventional jet fuel sale price range is based on historical market prices between 2016 and 2020. See Appendix C – Techno-economic for all assumptions.

The cost of hydrogen (driven by the price and capacity factor of renewable electricity) is the primary cost driver of the levelised cost of jet fuel (see Figure 26 for a breakdown of the primary cost reduction drivers between the base and best cases). Figure 9 shows the impact of different hydrogen costs on the levelised cost of jet fuel production. Achieving a stretch target of $2/kg hydrogen would not make CO_2-derived jet fuel economically competitive compared to typical sale prices for conventional jet fuel.

Biofuels are currently more mature and cost-competitive, but CO_2-derived jet fuel is expected to play a critical role in the longer term.

No CO_2-derived jet fuel production was identified in Australia, but pilot-scale projects are operating internationally. First-of-a-kind commercial scale projects are expected to be operational by 2024.[63]

Examples of commercial-scale projects include:

- Norsk e-Fuel is planned to be the world's first industrial-size demonstration of the power-to-liquid process, launching in 2024 and scaling up to produce 25 ML of CO_2-derived jet fuel annually by 2026. It will use solid oxide electrolyser cells (SOEC), alkaline electrolysers, and direct air capture technology, to create renewablesustainable aviation fuel (SAF).[64]
- Green Fuels for Denmark aims to produce 0.275 Mtpa of combined SAF, CO_2-derived methanol and renewable hydrogen by 2030.[65]
- ExxonMobil announced in June 2022 that they are developing SAF production capabilities using the methanol process, expanding their existing biofuel SAF production capabilities. The solution also provides the flexibility to use a mix of alcohols as feedstock and produce renewable diesel and lower-carbon chemical feedstocks.[66]

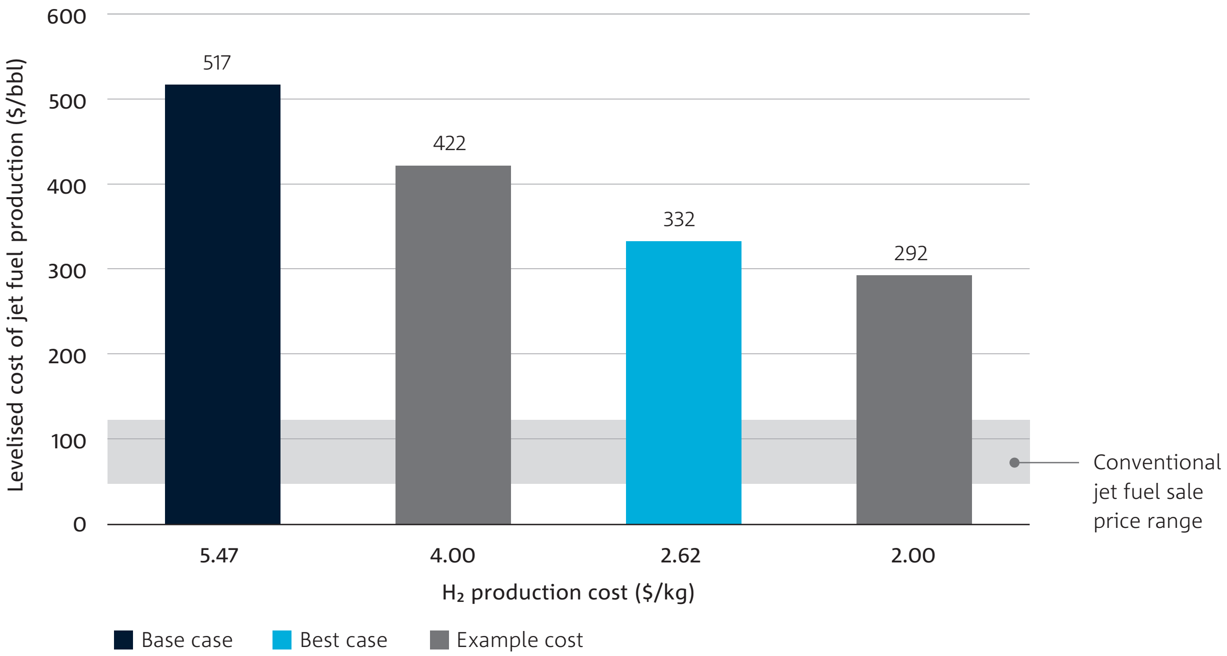
63 Igini M (2022) *4 Sustainable Aviation Fuel Companies Leading the Way to Net-Zero Flying*. Viewed 17 Jan 2023, https://earth.org/sustainable-aviation-fuel-companies/.

64 Norsk e-Fuel (n.d.) *Our Technology*. Viewed 17 Jan 2023, https://www.norsk-e-fuel.com/technology.

65 Orsted (2022) *Green Fuels for Denmark receives IPCEI status*. Viewed 17 Jan 2023, https://orsted.com/en/media/newsroom/news/2022/07/20220715544411.

66 ExxonMobil (2022) *ExxonMobil methanol to jet technology to provide new route for sustainable aviation fuel production*. Viewed 17 Jan 2023, https://www.exxonmobilchemical.com/en/resources/library/library-detail/101116/exxonmobil_sustainable_aviation_fuel_production_en.

Figure 9: Impact of hydrogen feedstock cost on the levelised cost of jet fuel production utilising DAC CO_2 feedstock and best-case scenario assumption



Sensitivity analysis shows the effect that the modelled base ($5.47/kg H_2) and best case ($2.62/kg H_2) hydrogen production costs have on the levelised cost of jet fuel. A midpoint of $4.00/kg and a stretch goal of A$2.00/kg were also modelled. This modelling assumes that CO_2 is sourced from DAC and uses the best case option for all other variables.

SAFs can also be renewably produced using biomass as a carbon feedstock. These biofuel-based SAFs are currently more economically competitive and commercially mature. As such, current SAF production is almost entirely biofuel-based, typically producing hydro-processed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK).[67]

The pre-COVID Australian demand for jet fuel was approximately 59 million bbl per year.[68] Global SAF production in 2022 (estimated at 1.89 million bbl[69]) would only meet about 3% of Australia's demand alone. SAF production is expected to rise sharply after 2025 as multiple new plants come online in the US, following government investment via the Inflation Reduction Act.[70] The world's largest HEFA-SPK producer, Neste, plans to produce up to 12.26 million bbl per annum by the end of 2023, following upgrades to refineries in the Netherlands and Singapore.[71] [72]

There are constraints on the ability of biofuels to scale, including access to arable land and competition from the food sector (when suitable waste products are not readily available). While there is limited arable land in the NT, there is significant forestry industry (over 47,000 hectares) that could support the production of oil crops or waste biomass feedstocks for biofuel production.[73]

Because of the vast global demand for SAFs and the constraints on biofuel production, a combination of biofuels and CO_2-derived jet fuel will likely be required to meet the world's SAF needs. In the long-term, CO_2-derived jet fuel can offer a SAF process that does not create competition for land with the food and agriculture industry and may offer more significant CO_2 abatement potential.

67 Feuvre P (2019) Commentary: Are aviation biofuels ready for take off?. International Energy Agency.

68 2019 data. TheGlobalEconomy.com (2021) *Australia: Jet fuel consumption*. Viewed 17 Jan 2023, https://www.theglobaleconomy.com/Australia/jet_fuel_consumption/.

69 IATA (2022) *2022 SAF Production Increases 200% - More Incentives Needed to Reach Net Zero*. Viewed 17 Jan 2023, https://www.iata.org/en/pressroom/2022-releases/2022-12-07-01/.

70 S&P Global (2022) *DG Fuels' SAF plant in Louisiana sells full production capacity four years before open*. Viewed 17 Jan 2023, https://www.spglobal.com/commodityinsights/en/oil/refined-products/jetfuel/111422-dg-fuels-saf-plant-in-louisiana-sells-full-production-capacity-four-years-before-open.

71 NESTE (n.d.) *The Future of Aviation: SAF reduces GHG emissions by up to 80%*. Viewed 17 Jan 2023, https://www.neste.com/products/all-products/saf/key-benefits#1752ff82.

72 NESTE (2021) *Neste to enable production of up to 500,000 tons/a of Sustainable Aviation Fuel at its Rotterdam renewable products refinery*. Viewed 17 Jan 2023, https://www.neste.com/releases-and-news/renewable-solutions/neste-enable-production-500000-tonsa-sustainable-aviation-fuel-its-rotterdam-renewable-products.

73 Northern Territory Government (2022) *Forestry*. Viewed 8 Feb 2023, https://nt.gov.au/industry/agriculture/food-crops-plants-and-quarantine/forestry.

CO_2-derived jet fuel could support the NT civil and military aviation sectors to improve their fuel security and reduce emissions.

Due to the Australian Defence Force's commitments to reducing greenhouse gas emissions and the strategic importance of fuel security,[74 75] the military is a prospective customer for locally produced CO_2-derived jet fuel in the short-medium term, compatible with both the Air Force's gas-turbine powered aircraft and the Army's M1 Abrams tanks.[76]

Globally, defence forces are often a significant contributor to national emissions, typically accounting for at least 50% of governments' carbon emissions and are, therefore, essential to achieving emission reduction targets for many countries and avoiding reliance on expensive offsets.[77] The Australian Department of Defence has matched the Federal Government's overall commitment to reach a 43% emissions reduction target by 2030 and net zero emissions by 2050 as part of their strategy.[78]

Military industries may be willing to pay a premium for CO_2-derived jet fuel that meets emissions targets and stringent fuel requirements, such as the inclusion of corrosion inhibitors and anti-icing additives.[79] The United States Department of Defence, for example, has emissions commitments[80] and has invested in power-to-liquids for their aviation fleet[81]. They also have a strong alliance with Australia's Defence Force, utilising Darwin as a training base during their dry season.[82]

Domestic production of CO_2-derived jet fuel can reduce reliance on imports, improving domestic fuel security for defence applications. Australia's reliance on imported aviation fuel almost doubled between 2010–11 and 2017–18 due to declining domestic crude oil production. Due to declining domestic crude oil production, Australia's dependence on imported aviation fuel almost doubled between 2010–11 and 2017–18.[83] Three domestic refineries have closed in the past 13 years due to a reduction in domestic demand following the global financial crisis and the strength of the Australian dollar following the mining boom.[84]

The importance of domestic fuel security has been emphasised recently due to pressures on global supply chains and international geopolitical tension.[85] For example, New Zealand is dependent on imported jet fuel with the recent closure of its remaining domestic refinery. When the country received a contaminated jet fuel shipment in late 2022, they were forced to ration available fuel, with Auckland Airport operating at 75% capacity.[86]

The NT is home to two Royal Australian Air Force (RAAF) bases, including the 45-hectare Darwin base, used as a staging base for transitioning aircraft and training exercises, and the Tindal base, located outside of Katherine, which is home to five squadrons.[87 88] The United States is constructing a 1.89 million bbl (300 ML) jet fuel storage facility by September 2023 that will be used for transferring, managing, and storing military specification jet fuels.[89]

74 Blenkin M (n.d.) *Fuel security concerns endanger Australia's defensive capabilities*. Viewed 17 Jan 2023, https://www.themandarin.com.au/200207-fuel-security-concerns-australia-defensive-capabilities/.

75 Australian Government DCCEEW (n.d.) *Australia's Fuel Security*. Viewed 17 Jan 2023, https://www.energy.gov.au/government-priorities/energy-security/australias-fuel-security.

76 Yildirim U (2022) Special report: The Australian Defence Force and its future energy requirements. Australian Strategic Policy Institute.

77 Bowcott H, Gatto G, Hamilton A, Sullivan E (2021) *Decarbonizing defense: Imperative and opportunity*. Viewed 17 Jan 2023, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/decarbonizing-defense-imperative-and-opportunity.

78 Leben W, Yildirim U (2022) *Aggressive action required to meet Defence's ambitious emissions-reduction target*. Viewed 17 Jan 2023, https://www.aspistrategist.org.au/aggressive-action-required-to-meet-defences-ambitious-emissions-reduction-target/.

79 Shell Global (n.d.) *Military Jet Fuel*. Viewed 17 Jan 2023, https://www.shell.com/business-customers/aviation/aviation-fuel/military-jet-fuel-grades.html.

80 U.S. Department of Defense (n.d.) *Tackling the Climate Crisis*. Viewed 17 Jan 2023, https://www.defense.gov/spotlights/tackling-the-climate-crisis/.

81 Poland C (2021) *The Air Force partners with Twelve, proves it's possible to make jet fuel out of thin air*. Viewed 17 Jan 2023, https://www.af.mil/News/Article-Display/Article/2819999/the-air-force-partners-with-twelve-proves-its-possible-to-make-jet-fuel-out-of/.

82 Australian Government Department of Defence (n.d.) *Marine Rotational Force – Darwin*. Viewed 17 Jan 2023, https://defence.gov.au/Initiatives/USFPI/Home/MRF-D.asp.

83 Carter L, Quicke A, Armistead A (2022) *Over a barrel*. The Australia Institute.

84 Carter L, Quicke A, Armistead A (2022) *Over a barrel*. The Australia Institute.

85 Sustainable Aviation Fuel Alliance of Australia and New Zealand (2020) *Future of Australia's Aviation Sector*. BioEnergy Australia.

86 Hardiman J (2022) *New Zealand Has Started Rationing Jet Fuel To Airlines*. Viewed 18 Jan 2023, https://simpleflying.com/new-zealand-jet-fuel-rationing/.

87 Royal Australian Air Force (RAAF) (n.d.) *RAAF Base Darwin*. Viewed 18 Jan 2023, https://www.airforce.gov.au/about-us/bases/raaf-base-darwin; Australian Government Department of Defence (n.d.) *RAAF Base Darwin Aircraft*. Viewed 18 Jan 2023, https://defence.gov.au/aircraftnoise/Darwin/Aircraft.asp.

88 RAAF (n.d.) *RAAF Base Tindal*. Viewed 18 Jan 2023, https://www.airforce.gov.au/about-us/bases/raaf-base-tindal; Australian Government Department of Defence (n.d.) *RAAF Base Tindal*. Viewed 18 Jan 2023, https://defence.gov.au/aircraftnoise/Tindal/Default.asp.

89 Mackay M (2022) *Work begins on $270 million US fuel storage facility on Darwin's outskirts*. Viewed 18 Jan 2023, https://www.abc.net.au/news/2022-01-19/work-begins-on-us-jet-fuel-facility-outside-darwin/100764194.

Export-scale production could enable economies of scale and drive production cost reductions.

Local demand driven by national security and net zero commitments could enable the demonstration of CO_2-derived jet fuel production. However, commercial scale production in the order of 2.0 million bbl per year would exceed the NT's demand for jet fuel. Expanding into international export markets will be necessary to achieve more significant economies of scale.

Domestic sales of jet fuel in Australia were in the order of 21.7 million bbl (3,457 ML) in 2019. Both domestic and international sales in the NT amounted to only 1.2 million bbl (191.8 ML).[90] The global commercial jet fuel market is expected to grow from 2.52 billion bbl in 2019 to over 5.48 billion bbl by 2050.[91]

Japan and Singapore have high potential to be suitable trading partners for CO_2-derived jet fuel. Japan has a significant demand for jet fuel (pre-COVID demand in the order of 82 million bbl per year[92]) and is committed to developing public-private partnerships to promote SAF production.[93] Similarly, Singapore is a large user of aviation fuel for civilian and military purposes (pre-COVID demand in the order of 67 million bbl per year), with consistent growth in recent years.[94]

Early investments in CO_2-derived jet fuel may remain process agnostic while new production processes are certified and standardised.

Jet fuels are defined by their performance specification rather than molecular composition, meaning CO_2-derived jet fuels can be drop-in substitutes for their replace fossil-based incumbents, provided they meet and are covered by appropriate certification standards.[95 96]

While ASTM International has developed a standard for blended use (up to 50%) of FT-produced jet fuel in commercial aviation,[97] the methanol-derived production process is not yet covered by appropriate standards. However, ExxonMobil's recent investments in methanol-based production suggest that it expects the process to be viable.

Any early investments in CO_2-derived jet fuel production in the NT may focus on the FT process while the inputs and certification standards to enable the methanol process are developed. While both processes are technically mature (TRL 9), the FT process is more commercially mature. This suggests that short-term investments in CO_2-derived jet fuel will utilise the FT process. In addition to commercial maturity, FT processes produce lubricants as a by-product. As Australia has no domestic lubricant production and most machines with moving parts require these, this may present an additional opportunity to capture value from FT-based production.

In the long term, the methanol process is expected to be more economical than FT.[98] This is because CO and CO_2 can produce methanol, which means a reverse water gas shift (RWGS) reaction is unnecessary. The removal of the RWGS reaction can significantly increase production efficiency.[99 100] Additionally, the methanol upgrading process produces more of the the shorter chain hydrocarbons used to produce jet fuel. This means it requires considerably less feedstock to produce the same volume of jet fuel than the FT process. Access to scaled and affordable CO_2-derived methanol (see Section 2.1) is critical to enabling this production process and achieving the best-case modelled costs.

90 Australian Government DCCEEW (2022) *Australian Petroleum Statistics 2022*. Viewed 18 Jan 2023, https://www.energy.gov.au/publications/australian-petroleum-statistics-2022.

91 Converted from gallons (106bn in 2019, 230bn in 2050); 1 gallon (US) = 0.0238095238 barrel (oil): U.S. Department of Energy (2020) *Sustainable Aviation Fuel: Review of Technical Pathway*. Viewed 18 Jan 2023, https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf.

92 2019 data, converted from bbl/day. TheGlobalEconomy.com (2021) *Japan: Jet fuel consumption*. Viewed 17 Jan 2023, https://www.theglobaleconomy.com/Japan/jet_fuel_consumption/.

93 Sasatani D (2022) Japanese Government and Industry Partner to Develop SAF Capacity. U.S. Department of Agriculture, Foreign Agricultural Service.

94 2019 data, converted from bbl/day. TheGlobalEconomy.com (2021) *Singapore: Jet fuel consumption*. Viewed 17 Jan 2023, https://www.theglobaleconomy.com/Singapore/jet_fuel_consumption/.

95 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

96 bp (2022*) What is sustainable aviation fuel (SAF) and why is it important?*. Viewed 18 Jan 2023, https://www.bp.com/en/global/air-bp/news-and-views/views/what-is-sustainable-aviation-fuel-saf-and-why-is-it-important.html.

97 IATA (n.d.) Sustainable Aviation Fuel: Technical Certification. IATA.

98 Bruce S, Temminghoff M, Hayward J, Palfreyman D, Munnings C, Burke N, Creasey S (2020) *Opportunities for hydrogen in aviation*. CSIRO.

99 Dieterich V, Buttler A, Hanel A, Spliethoff H, Fendt S (2020) *Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review*. Energy & Environmental Science.

100 Zang G, Sun P, Elgowainy A, Bafana A, Wang M (2021) Life Cycle Analysis of Electrofuels: Fischer–Tropsch Fuel Production from Hydrogen and Corn Ethanol Byproduct CO_2. Environmental Science and Technology.

2.3 Urea

Key findings

Deployment and scale-up in the NT

Renewable urea production is a long term opportunity that requires both renewable ammonia production and DAC to reach commercial scale. In the medium term, the NT could consider manufacturing hybrid urea with reduced emissions intensity while the availability and affordability of renewable inputs improve.

Considerations

- Renewable urea could become cost-competitive with conventional urea.
- Domestic production of urea could reduce exposure to international prices while supporting the decarbonisation of fertiliser manufacturing.
- Hybrid production of urea could increase CO_2 utilisation and lower the emissions intensity of urea production while renewable ammonia and DAC-sourced CO_2 scale.
- Targeting export markets that favor renewable urea production will be critical to capturing market share and enabling commercial-scale production.

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• No significant advancement expected in the short term	• Demonstration of hybrid or renewable urea production	• Commercial scale production using renewable feedstocks
Enablers	• Test the market and explore the economic viability of renewable and hybrid ammonia production in the NT • Validate technical design and economic feasibility of renewable and hybrid urea production	• Hybrid or renewable ammonia production using renewable hydrogen feedstock	• Commercial scale renewable ammonia production • Commercial scale DAC • Secure offtake agreements for commercial scale urea exports

Levelised cost of production and abatement potential

PRODUCT DESCRIPTION	CO_2 SOURCE	HYDROGEN SOURCE	BASE CASE LCOP	BEST CASE LCOP	CARBON STORAGE DURATION	ABATEMENT POTENTIAL
Renewable urea	DAC	Renewable	$1142/t (~3.0 × conventional sale price)	$531/t (~1.5 × conventional sale price)		Net zero
Industry emissions urea	Industrial emissions	Renewable	$781–844/t (~2 × conventional sale price)	$381–415/t (Comparable to conventional sale price)	<100 years	Reduced emissions intensity
Hybrid urea	Methane or blended	Blended (methane coupled with CCS and renewable)	Not modelled			Reduced emissions intensity (least abatement potential)

2.3.1 Overview

Urea is the most widely used nitrogen-based fertiliser, accounting for more than 70% of worldwide fertiliser usage.[101] In the NT, urea is commonly applied to grass hay crops.[102] Urea is also used as feedstock in melamine and urea-formaldehyde resin production, as a dietary supplement in ruminant diets, and in AdBlue (a diesel exhaust fluid used in some vehicles to reduce harmful gases being released into the atmosphere).

Urea is conventionally derived from fossil fuels where methane (from natural gas), atmospheric nitrogen, and water react together at high temperature (400–500°C) and pressure (150–300 bar) to produce ammonia (NH_3) and CO_2.[103] [104] This is known as the Haber-Bosch process. The ammonia and some of the CO_2 generated are then reacted to produce urea (see Figure 10). Conventional urea production is a commercially mature CO_2 utilisation application. However, the process is a net emitter of CO_2, responsible for around 2% of global CO_2 emissions.[105] Additionally, urea's common uses (e.g., fertiliser) are short-term stores of carbon that release CO_2 after use. CCS can be applied to conventional urea production to reduce the emissions intensity, but this is beyond the scope of this report.

To increase the amount of CO_2 utilised in urea production and reduce the overall CO_2 intensity of urea production, renewable hydrogen can be used to replace some of the methane used in conventional ammonia production. This is described as hybrid urea production (see Figure 11 and Section 2.3.3).

In the longer term, commercial-scale production of renewable hydrogen and ammonia could create an opportunity to replace methane and utilise more sustainable sources of CO_2 for urea production.[106] A sustainable source of CO_2 (e.g., DAC) is essential to approach net zero lifecycle emissions for urea.[107] Biomass can also be used as a sustainable source of CO_2. Commercial plans to produce fully renewable urea have yet to be identified in Australia. However, Strike Energy has announced plans for a possible hybrid urea production facility using natural gas, renewable hydrogen, and CCS in WA.[108]

Renewable ammonia is the critical precursor to renewable urea. Renewable ammonia production has been successfully demonstrated at pilot scale (CRI 2–3), and some commercial plants are in development in Australia.[109] These include the BP-led Australian Renewable Energy Hub project in WA, planned to operate by 2025;[110] ENGIE, Mitsui and Yara's Project Yuri in WA, planned to operate in 2024;[111] and Origin Energy's renewable hydrogen and ammonia project in Tasmania, planned to operate by 2025.[112]

101 International Fertilizer Association (2018) *Statistics: Production & International Trade*. Viewed 18 Jan 2023, https://www.ifastat.org/.

102 Richter P, Bristow M (2015) Reducing Nitrous Oxide Emissions when Fertilising Hay Crops with Nitrogen Fertiliser. Northern Territory Government.

103 Incitec Pivot Fertilisers (2021) *Fact Sheet – Urea*. Viewed 18 Jan 2023, https://www.incitecpivotfertilisers.com.au/~/media/Files/IPF/Documents/Fact%20Sheets/32%20Urea%20Fact%20Sheet.pdf.

104 Ghavam S, Vahdati M, Wilson I, Styring P (2021) *Sustainable Ammonia Production Processes*. Frontiers in Energy Research.

105 Osorio-Tejada J, Tran N, Hessel V (2022) Techno-environmental assessment of small-scale Haber-Bosch and plasma-assisted ammonia supply chains. The Science of the Total Environment.

106 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO

107 Milani D, Kiani A, Haque N, Giddey S, Feron P (2022) *Green pathways for urea synthesis: A review from Australia's perspective*. Sustainable Chemistry for Climate Action. https://doi.org/10.1016/j.scca.2022.100008

108 Bennet M (2022) *Strike Energy pivots urea plant plans into new low-carbon precinct*. Viewed 23 Jan 2023, https://www.afr.com/companies/energy/strike-energy-pivots-urea-plant-plans-into-new-low-carbon-precinct-20220607-p5arrc.

109 Milani D, Kiani A, Haque N, Giddey S, Feron P (2022) *Green pathways for urea synthesis: A review from Australia's perspective*. Sustainable Chemistry for Climate Action. https://doi.org/10.1016/j.scca.2022.100008

110 CSIRO (2022) Australian Renewable Energy Hub. Viewed 2 Feb 2023, https://research.csiro.au/hyresource/australian-renewable-energy-hub/

111 Engie & Yara (2020) *YURI Phase 0: Feasibility Study Public Report*. Viewed 18 Jan 2023, https://arena.gov.au/assets/2020/11/engie-yara-renewable-hydrogen-and-ammonia-deployment-in-pilbara.pdf.

112 Origin Energy Limited (2020) *Origin to investigate export scale green hydrogen project in Tasmania*. Viewed 18 Jan 2023, https://www.originenergy.com.au/about/investors-media/origin_to_investigate_export_scale_green_hydrogen_project_in_tasmania/.

Figure 10: Simplified production process for renewable and conventional (natural gas-derived) urea

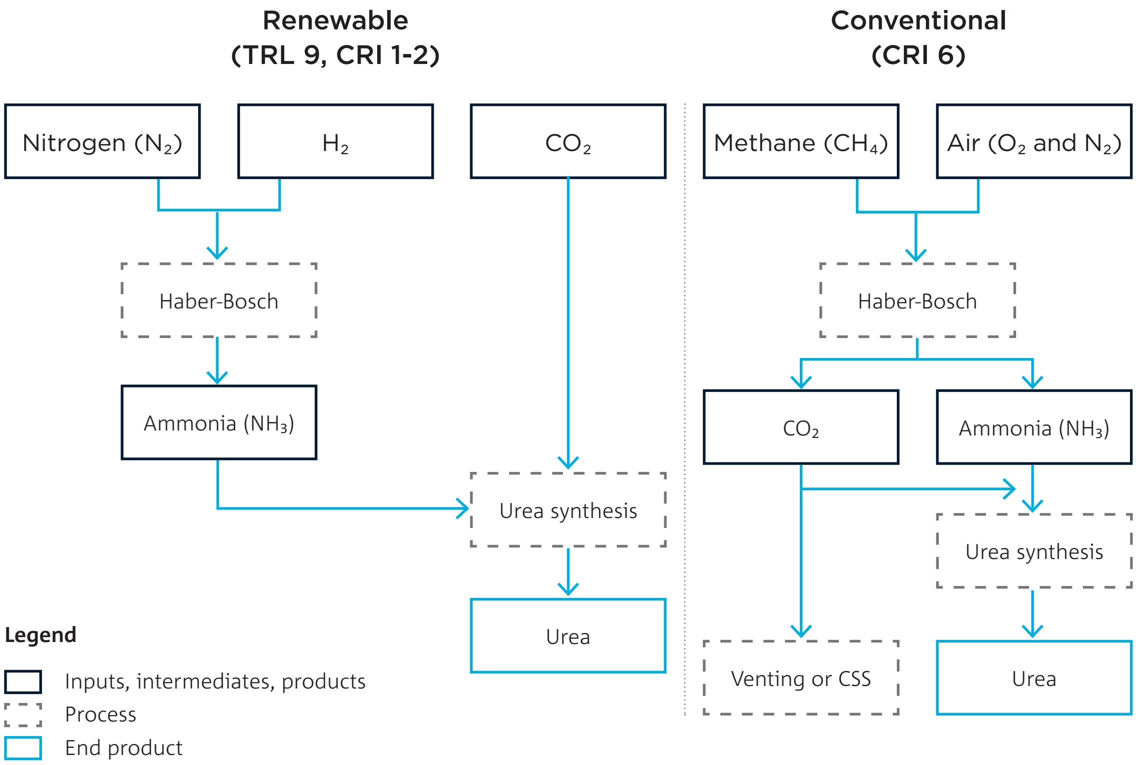
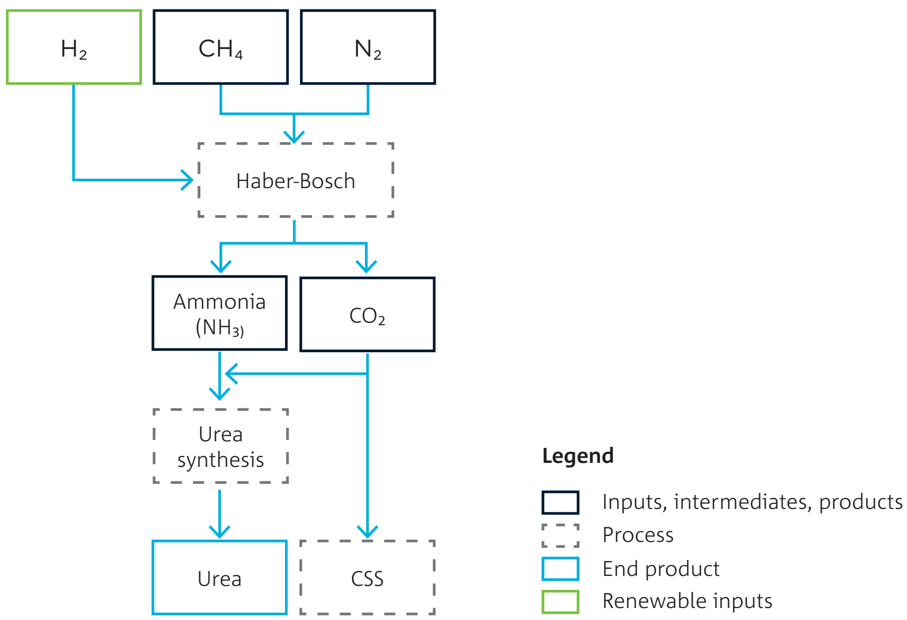


Figure 11: Simplified hybrid urea production process in which both natural gas and renewable hydrogen are used to produce ammonia for urea production



2.3.2 Deployment and scale-up in the NT

Renewable urea production is a long-term opportunity that requires both renewable ammonia production and DAC to reach commercial-scale. However, Australia requires a secure supply of urea for agricultural and chemical applications, and project proponents should assess whether the NT is well-placed to address this need through hybrid production while the availability and affordability of renewable inputs improve. Table 5 outlines a pathway to achieving commercial-scale production beyond 2040 and the scale of inputs required to achieve this. Additional detail on the shared, critical requirements for CO_2 utilisation can be found in Section 3.

Table 5: Renewable and hybrid urea scale-up pathway for the NT

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• No significant advancement expected in the short term	• Demonstration of hybrid or renewable urea production	• Commercial scale production using renewable feedstocks
Enablers	• Test the market and explore the economic viability of renewable and hybrid ammonia production in the NT • Validate technical design and economic feasibility of renewable and hybrid urea production	• Hybrid or renewable ammonia production using renewable hydrogen feedstock	• Commercial scale renewable ammonia production • Commercial scale DAC • Secure offtake agreements for commercial scale urea exports
Scale of production	-	0.1 Mtpa	1 Mtpa
CO_2 utilised	-	0.073 Mtpa	0.73 Mtpa
Hydrogen required	-	0.01 Mtpa	0.1 Mtpa

2.3.3 Considerations for deployment and scale-up in the NT

Renewable urea could become cost-competitive with conventional urea.

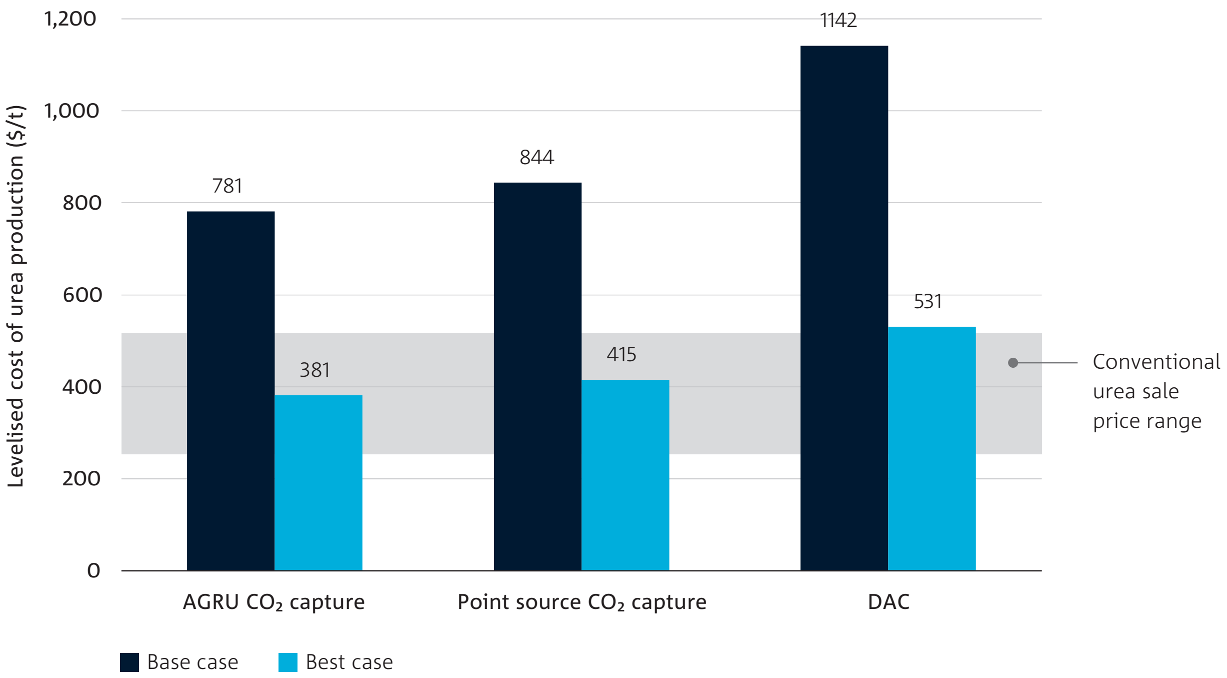
Modelling indicates that the levelised cost of renewable urea, using DAC and renewable ammonia production, may approach conventional urea sale prices under the best case scenario (as shown in Figure 12). Base case levelised production costs for renewable ($1,142/t) and semi-renewable urea produced from renewable H_2 and industrial CO_2 emissions ($781–844/t) exceed the assumed conventional sale price range.

Under the best case scenario, the levelised production cost for renewable urea decreases by over 50% to $531/t, suggesting that it may become economically competitive under realistic market conditions. The utilisation of industrial CO_2 feedstocks instead of DAC can also reduce production costs by up to 32%. As such, AGRU or other industrial emissions may have a role in helping to scale up the production of reduced emissions intensity urea produced from renewable ammonia. However, sustainable CO_2 sources are critical to the production of net zero-emission urea. Once DAC-sourced CO_2 becomes increasingly available and affordable, customers may be willing to pay a premium for fully renewable urea.

While a more stable, long-term term sale price range for conventional urea has been used as a comparison in Figure 12, Australia's recent urea import prices have exceeded $1,000/tonne in 2022.[113] Renewable urea may become increasingly competitive if conventional urea prices do not return to pre-COVID levels or if a carbon price is placed on urea production and use.

113 Cameron, A (2022) *Agricultural overview: September quarter 2022*. Viewed 18 Jan 2023, https://web.archive.org/web/20221108033104/https:/www.agriculture.gov.au/abares/research-topics/agricultural-outlook/agriculture-overview#high-inflation-for-food-and-inputs-clouding-outlook.

Figure 12: Levelised cost of urea production from renewable ammonia and different CO_2 feedstocks



The modelled CO_2 sources were AGRU capture (assumed zero cost), high partial pressure point source capture ($86/t CO_2 in the base case and $46/t CO_2 in the best case) and direct air capture ($490/t CO_2 in the base case and $200/t CO_2 in the best case). The base case scale assumes utilisation of 1,000 t/d of CO_2 (equivalent to a production scale of 0.49 Mtpa urea). Best case assumes a five-fold increase in the scale of CO_2 utilisation (and urea production). The conventional urea sale price range is based on typical historical market prices between January 2015 and January 2020. See Appendix C – Techno-economic analysis assumptions for all assumptions.

The cost of hydrogen (primarily driven by the price and capacity factor of renewable electricity) is the largest driver of the levelised cost of renewable urea (see Figure 27 in Appendix D for a breakdown of the primary cost reduction drivers between the base and best cases). Figure 13 shows the impact of different hydrogen costs on the levelised cost of urea production. Achieving a stretch target of $2/kg hydrogen would reduce the production cost of urea derived from DAC CO_2 to within the range of historic sale prices for conventional urea.

Domestic production of urea could reduce exposure to international prices while supporting the decarbonisation of fertiliser manufacturing.

Growing demand for urea and declining local production will increase Australia's reliance on imports, increasing the nation's exposure to price and supply fluctuations in the international market. The global demand for urea was approximately 166 Mtpa in 2021[114] and is expected to continue growing at 0.8–2.7% (CAGR) until 2027.[115] [116] [117]

Australia imports most of its urea needs, with the remainder currently produced by Incitec Pivot at Gibson Island, Queensland,[118] which has announced that this plant

114 Converted from 183,000-kilotons (1 ton = 0.907 tonnes): Mordor Intelligence (n.d.) *Urea Market – Growth, Trends, COVID-19 Impact, and Forecasts (2023 – 2028)*. Viewed 18 Jan 2023, https://www.mordorintelligence.com/industry-reports/urea-market.

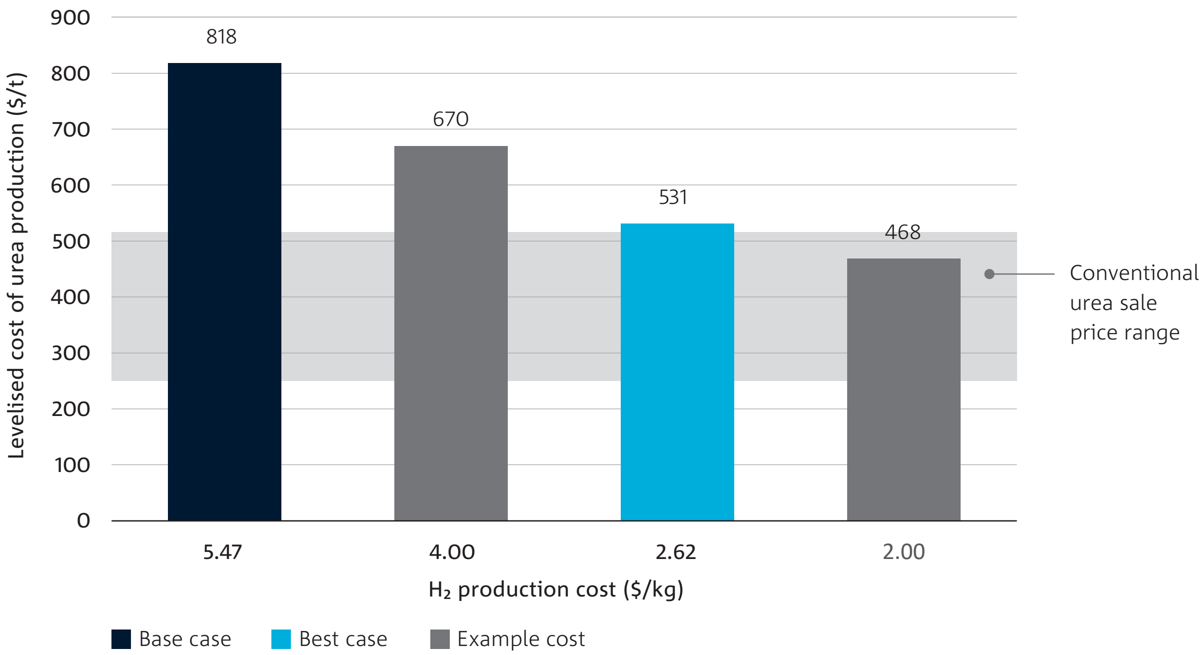
115 Expert Market Research (n.d.) *Urea Market*. Viewed 23 Jan 2023, https://www.expertmarketresearch.com/reports/urea-market.

116 Fortune Business Insights (2022) *Urea Market*. Viewed 23 Jan 2023, https://www.fortunebusinessinsights.com/urea-market-106850.

117 IMARC (n.d.) *Urea Market*. Viewed 23 Jan 2023, https://www.imarcgroup.com/urea-market.

118 Reuters (2021) *Australia to ramp up local urea production to avert trucking crisis*. Viewed 18 Jan 2023, https://www.reuters.com/markets/commodities/australia-ramp-up-local-urea-production-avert-trucking-crisis-2021-12-19/.

Figure 13: Impact of hydrogen feedstock cost on the levelised cost of urea production utilising DAC CO_2 feedstock and best-case scenario assumptions



Sensitivity analysis shows the effect that the modelled base ($5.47/kg H_2) and best case ($2.62/kg H_2) hydrogen production costs have on the levelised production cost of urea. A midpoint of $4.00/kg and a stretch goal of $2.00/kg were also modelled. This modelling assumes that CO_2 is sourced from DAC and uses the best case option for all other variables.

will cease operations in early 2023. Australia imported 2.4 Mtpa of urea in 2021 for use in the agriculture industry,[119] and its demand for urea-based fertiliser imports is expected to rise.[120] [121] This may be disrupted in the long term by a high global market price and unprecedented weather conditions.

Significant recent increases in urea prices, mainly due to increased shipping costs and international geopolitical tensions, have highlighted Australia's exposure to fertiliser shortages and price shocks. These factors make a compelling argument for domestic urea production when considering the urgency of decarbonisation in the agricultural industry. Fertiliser prices have risen almost 30% during 2022, followed by an 80% increase in 2021.[122]

These high prices are likely to impact farm margins and, in turn, food prices. Australia's major suppliers of urea are China, the Middle East, and Southeast Asia.[123] The majority of Australia's urea was previously imported from China, which in late 2021 banned the export of nitrogen and phosphate fertiliser products to lower prices domestically, causing sudden disruption in the supply chain.[124]

Some plans to resume urea fertiliser production within Australia have been announced. However, while manufacturers have shown interest in more sustainable production methods[125] no renewable urea projects have been proposed.

119 Grain Central (2022) *Green light for WA plant to shore up Australia's urea supply*. Viewed 18 Jan 2023, https://www.graincentral.com/logistics/green-light-for-wa-plant-to-shore-up-australias-urea-supply/.

120 Cameron A (n.d.) *Agricultural overview: December 2022*. Viewed 18 Jan 2023, https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/agriculture-overview.

121 Mordor Intelligence (n.d.) *Urea Market – Growth, Trends, COVID-19 Impact, and Forecasts (2023 – 2028)*. Viewed 18 Jan 2023, https://www.mordorintelligence.com/industry-reports/urea-market.

122 Baffes J, Koh WC (2022) *Fertilizer prices expected to remain higher for longer*. Viewed 18 Jan 2023, https://blogs.worldbank.org/opendata/fertilizer-prices-expected-remain-higher-longer.

123 NeuRizer (n.d.) *About Urea*. Viewed 18 Jan 2023, https://neurizer.com.au/library/about-urea/.

124 Hannam P (2021) *What is urea and AdBlue, and why does a worldwide shortage threaten Australia's supply chain?*. Viewed 18 Jan 2023, https://www.theguardian.com/australia-news/2021/dec/08/what-is-urea-and-why-does-a-worldwide-shortage-threaten-australias-supply-chain.

125 Milani D, Kiani A, Haque N, Giddey S, Feron P (2022) *Green pathways for urea synthesis: A review from Australia's perspective*. Sustainable Chemistry for Climate Action. https://doi.org/10.1016/j.scca.2022.100008

Hybrid production of urea could increase CO_2 utilisation and lower the emissions intensity of urea production while renewable ammonia and DAC-sourced CO_2 scale.

Domestic production of renewable urea is a long-term opportunity that will require the development of commercial-scale renewable ammonia production and DAC. At present, there are no commercial scale renewable ammonia production facilities operating in Australia, but multiple renewable ammonia projects are being explored for both Western Australia and Queensland. These include:

- ENGIE and Mitsui are developing the first phase of a renewable hydrogen production facility (scheduled for completion in 2024) to provide up to 640 tpa of hydrogen for integration into Yara Pilbara Fertilisers' ammonia production operations near Karratha in Western Australia.[126] The facility is expected to begin production in 2024.[127]
- Fortescue Future Industries is working with Incitec Pivot to explore the conversion of the soon-to-close Gibson Island facility into a renewable ammonia plant using renewable hydrogen. Front End Engineering Design has commenced for the project, which could produce up to 0.4 Mtpa of renewable ammonia. A final investment decision is targeted for 2023.[128]
- Hexagon Energy conducted a pre-feasibility exploring low-emission hydrogen and renewable ammonia production south-east of Alice Springs for export from the NT.[129] However, following the completion of a pre-feasibility study, Hexagon decided to pursue opportunities in Western Australia.[130]

The renewable ammonia required for urea production is also likely to face competing demand as a hydrogen carrier or for direct export or use. In the short term, project proponents may see renewable ammonia production as a lower risk investment due to its diversity of uses.

As such, the NT may be better placed to supply urea with reduced emissions intensity from hybrid production utilising both natural gas and renewable hydrogen in the medium term. Hybrid ammonia production can still produce excess CO_2, so CCS may be required to abate un-utilised CO_2. However, as the ratio of renewable hydrogen to methane feedstock increases, less CO_2 will be produced, and more will be utilised in the production of urea. At high ratios of renewable hydrogen use, methane-derived CO_2 will be fully utilised, and additional sources of CO_2 will be required. As the availability and economics of both renewable hydrogen and DAC-sourced CO_2 improve, non-renewable inputs could be progressively replaced.

Targeting export markets that favor renewable urea production will be critical to capturing market share and enabling commercial-scale production.

At the time of writing, several new conventional urea projects and one hybrid production project are being explored by proponents. If they are developed, the production capacity of these plants is likely to exceed Australia's urea demand. Projects include:

- Derby Fertilizers and Petrochemical Complex have announced the development of a $4.0 billion urea, complex fertiliser and petrochemical plant using natural gas and solar energy near Derby, WA[131]. It will have a urea production capacity of 1.32 Mtpa in Phase 1, the last quarter of 2024.[132]

126 ENGIE (n.d.) *Yuri Renewable Hydrogen to Ammonia Project*. Viewed 23 Jan 2023, https://engie.com.au/yuri.

127 Yara (2022) *Yara at the forefront of clean ammonia in Australia*. Viewed 23 Jan 2023, https://www.yara.com/news-and-media/news/archive/news-2022/yara-at-the-forefront-of-clean-ammonia-in-australia/.

128 Fortescue Future Industries (2022) *Fortescue Future Industries and Incitec Pivot progress green conversion of Gibson Island ammonia facility*. Viewed 23 Jan 2023, https://ffi.com.au/news/fortescue-future-industries-and-incitec-pivot-progress-green-conversion-of-gibson-island-ammonia-facility/.

129 Hexagon Energy Materials (2021) *Pedirka Blue Hydrogen Project Update*. Viewed 23 Jan 2023, https://hxgenergymaterials.com.au/wp-content/uploads/2021/05/2213295.pdf.

130 Hexagon Energy Materials (2022) Hexagon's Pedirka Hydrogen Project Pre-Feasibility Study completed. Study identifies the pursuit of clean Hydrogen opportunities in North Western Australia as most commercially attractive for Hexagon. Viewed 23 Jan 2023, https://hxgenergymaterials.com.au/wp-content/uploads/2022/03/Pedirka-PFS-Completion.pdf.

131 Richardson A (2021) Fertiliser Manufacturing in Australia. IBISWorld.

132 Offshore Technology (2021) *Derby Fertilizer and Petrochemical Derby Complex, Australia*. Viewed 18 Jan 2023, https://www.offshore-technology.com/marketdata/derby-fertilizer-and-petrochemical-derby-complex-australia/.

- Perdaman Industries has plans for a $5.4 billion[133] project in Karratha, WA, producing urea from natural gas supplied by Woodside Energy. Construction is planned to begin in 2023.[134] No carbon abatement plans have been announced for this project. It will have a urea production capacity of 2 Mtpa; however, construction has paused due to concerns of traditional landowners.[135]
- Strike Energy has announced plans for Project Haber. This $2.3 billion low-carbon urea fertiliser plant which will utilise CCS and natural gas from their Greater Erregulla gas resources within the Perth basin project.[136] [137] The plant will also utilise renewable hydrogen input from a 0.01 GW wind-powered hydrogen electrolyser. It will be capable of producing 1.4 Mtpa of urea.[138]

As international and domestic customers increase their commitments to carbon abatement, demand for more sustainable sources of urea is expected to increase. As such, new urea production projects should explore the opportunity to use renewable inputs and other carbon abatement approaches. The EU is implementing the Carbon Border Adjustment Mechanism, which puts a carbon price on imported, carbon-intensive goods, including fertilisers, to support the decarbonisation of EU industry and encourage lower-emission industrial production worldwide.[139] This regulation will make conventional urea producers less competitive and could create export opportunities for renewable urea produced in the NT.

Due to the relatively limited local demand for urea in the NT[140] and competition with new market entrants, export markets will be critical to support scaled urea production in the NT. Establishing offtake agreements with international customers will help to de-risk investment and enable commercial-scale production in the long term.

The global urea market is expected to continue growing at 0.8–2.7% (CAGR) until 2027.[141] [142] [143] Alongside this, the global production capacity of urea is expected to increase by 1.2% by 2030. This growth is attributable to approximately 76 planned and announced new urea plants, based mainly in Asia and the post-Soviet states, that are expected to come online by 2030.[144] Russia is the world's largest supplier of natural gas and a key supplier of downstream products. As described by the International Energy Agency, current geopolitical tensions and punitive trade measures against Russia can be expected to increase demand for alternative suppliers of urea, particularly for the EU, as embargoes come into effect.[145]

133 Perdaman (2022) *$4.2bn US Karratha Urea Project – Revised EPC Contract Signed*. Viewed 18 Jan 2023, https://perdaman.com.au/2022/05/27/revised-epc-contract-signed/.

134 Heavy Vehicle Industry Australia (2022) *Pilbara urea project could deliver 96% of Australia's needs*. Viewed 23 Jan 2023, https://hvia.asn.au/pilbara-urea-project-could-deliver-96-of-australias-needs/.

135 Gorman V (2022) *Perdaman fertiliser plant construction near Karratha paused amid rock art fears*. Viewed 23 Jan 2023, https://www.abc.net.au/news/2022-07-21/perdaman-fertiliser-plant-construction-pause-rock-art-fears/101258864.

136 Richardson A (2021) Fertiliser Manufacturing in Australia. IBISWorld.

137 Milani D, Kiani A, Haque N, Giddey S, Feron P (2022) Green pathways for urea synthesis: A review from Australia's perspective. Sustainable Chemistry for Climate Action. https://doi.org/10.1016/j.scca.2022.100008

138 Bennet M (2022) *Strike Energy pivots urea plant plans into new low-carbon precinct*. Viewed 23 Jan 2023, https://www.afr.com/companies/energy/strike-energy-pivots-urea-plant-plans-into-new-low-carbon-precinct-20220607-p5arrc.

139 European Commission Taxation and Customs Union (n.d.) *Carbon Border Adjustment Mechanism.* Viewed 31 Jan 2023, https://taxation-customs.ec.europa.eu/green-taxation-0/carbon-border-adjustment-mechanism_en.

140 Urea is commonly applied in hay production in the NT. Cameron A (2008) *Fertilisers for Grass Pastures*, Agnote, No. E60, Northern Territory Government.

141 Expert Market Research (n.d.) *Urea Market*. Viewed 23 Jan 2023, https://www.expertmarketresearch.com/reports/urea-market.

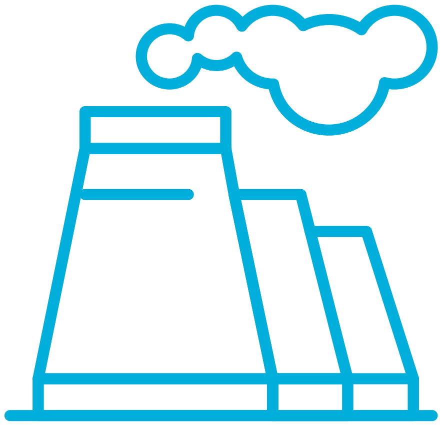
142 Fortune Business Insights (2022) *Urea Market*. Viewed 23 Jan 2023, https://www.fortunebusinessinsights.com/urea-market-106850.

143 IMARC (n.d.) *Urea Market*. Viewed 23 Jan 2023, https://www.imarcgroup.com/urea-market.

144 Fernández L (2022) *Global production capacity of carbamide 2018-2030*. Viewed 23 Jan 2023, https://www.statista.com/statistics/1063689/global-urea-production-capacity/.

145 International Energy Agency (IEA) (2022) *Frequently Asked Questions on Energy Security*. Viewed 23 Jan 2023, https://www.iea.org/articles/frequently-asked-questions-on-energy-security.

2.4 Methane



Key findings

Deployment and scale-up in the NT

CO_2-derived methane production is likely to be less competitive with natural gas. However, customers may be willing to pay a significant premium for methane derived from DAC or recycled carbon where alternative solutions (such as hydrogen, ammonia, or electrification) are economically or technically unsuitable. If this is the case, the NT will be well-placed to meet this demand due to its well-established LNG industry infrastructure, capabilities and export partners.

Considerations

- CO_2-derived methane production costs are not expected to be economically competitive with natural gas.
- International customers' decarbonisation strategies will drive CO_2-derived methane demand.
- DAC-sourced CO_2 or recycled CO_2 inputs are necessary to enable deep abatement, which may constrain the production of CO_2-derived methane.
- The NT's established LNG infrastructure, trade links and gas processing expertise could help to enable the development of a CO_2-derived methane export industry.

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• No significant advancement expected in short term	• Demonstration scale production using renewable hydrogen and blended CO_2 operating at up to 0.05 Mtpa (if appropriate customer can be identified)	• Commercial scale CO_2-derived methane production supply international target markets operating at 0.38 Mtpa
Enablers	• Explore the potential long-term demand for CO_2-derived methane with targeted export markets	• Confirm demand for CO_2-derived methane will continue well beyond the life of NT's natural gas assets	• Secure international offtake agreements willing to pay significant premiums for CO_2-derived methane exports

Levelised cost of production and abatement potential

CO_2 SOURCE	BASE CASE LCOP	BEST CASE LCOP	CARBON STORAGE DURATION	ABATEMENT POTENTIAL
DAC	\$89/t (~12 × conventional sale price)	\$42/t (~5.5 × conventional sale price)		Net zero
Carbon recycling (CO_2 capture at point of use)	\$67/t + CO_2 transport costs (at least ~9 × conventional sale price)	\$33/t + CO_2 transport costs (at least ~4.5 × conventional sale price)	<100 years	Net zero
AGRU emissions	\$62/t (~8.5 × conventional sale price)	\$30/t (~4 × conventional sale price)		Reduced emissions intensity

2.4.1 Overview

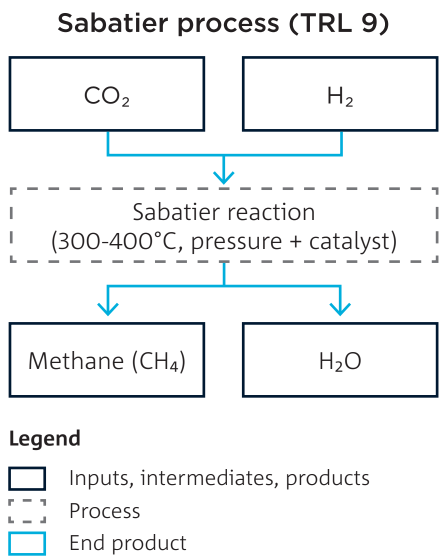
Methane is the primary constituent of natural gas (50–90%), which is used as a heat source for households and industry, and as a feedstock for a variety of manufacturing processes. The global market for natural gas is projected to grow 6.9% (CAGR) between 2023 to 2026.[146] Australia exported over 4,500 PJ (83 Mt) of LNG in 2021–22, making natural gas one of the nation's largest exports (worth $70 billion in 2021–22).[147] The NT is responsible for approximately 15% of Australia's LNG exports.[148]

CO_2 and hydrogen can be upgraded to methane using the Sabatier reaction. CO_2-derived methane can be used as a substitute for most natural gas applications. CO_2-derived methane stores CO_2 for a short time (i.e., fuel). Short-duration storage of CO_2 sourced from industrial emissions can reduce overall emissions through substitution. However, methane produced from renewable hydrogen and DAC-sourced CO_2 would be effectively carbon neutral for these applications.

To justify the high costs of CO_2-derived methane (see Figure 14), it is assumed that customers will expect CO_2-derived methane to enable net zero emissions outcomes. As such, this report focuses on methane derived from sustainable sources of CO_2 (primarily DAC, but also carbon recycling) and renewable hydrogen.

Other sources of CO_2 could also be used, such as emissions from LNG processing activities (e.g., AGRU) that would otherwise be vented or sequestered. This would generate added methane that could be blended with LNG for export. However, the emissions abatement potential of this process is not expected to justify its high cost.

Figure 14: Simplified production process for methane derived from sustainable CO_2 and hydrogen feedstocks



146 The Business Research Company (2023) *Global Natural Gas Market*. Viewed 23 Jan 2023, https://www.thebusinessresearchcompany.com/report/natural-gas-global-market-report.

147 Australian Government Department of Industry, Science and Resources (DISR) (2022) *Resources and Energy Quarterly – September 2022*. Viewed 23 Jan 2023, https://www.industry.gov.au/sites/default/files/minisite/static/ba3c15bd-3747-4346-a328-6b5a43672abf/resources-and-energy-quarterly-september-2022/documents/Resources-and-Energy-Quarterly-September-2022-Gas.pdf.

148 NT Government Department of Industry, Tourism and Trade (2021) *Northern Territory Renewable Hydrogen Master Plan.* Viewed 23 Jan 2023, https://territoryrenewableenergy.nt.gov.au/__data/assets/pdf_file/0018/1057131/nt-renewable-hydrogen-master-plan.pdf.

2.4.2 Deployment and scale-up in the NT

Commercial-scale CO_2-derived methane is not expected in the short term because of its high production costs and dependency on DAC or carbon recycling to offer its full carbon abatement potential. However, in the long term, international customers may be willing to pay a significant premium for carbon-neutral methane if it supports their decarbonisation strategy or is required for specific use cases. Table 6 outlines a pathway to achieving commercial-scale production beyond 2040 and the scale of inputs required to achieve this. Additional detail on the shared, critical requirements for CO_2 utilisation can be found in Section 3.

Table 6: CO_2-derived methane scale-up pathway for the NT

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• No significant advancement expected in the short term	• Demonstration scale production using renewable hydrogen and blended CO_2	• Commercial scale CO_2-derived methane production supply international target markets
Enablers	• Explore the potential long-term demand for synthesised CO_2-derived methane with targeted export markets	• Confirm demand for methane will continue well beyond the life of NT's natural gas assets	• Secure international offtake agreements willing to pay significant premiums for synthesised renewable methane exports
Scale of production	-	0.05 Mtpa / 2.8 PJ/yr	0.38 Mtpa / 20.9 PJ/yr (~3.2% of the NT's current LNG export)
CO_2 utilised	-	0.14 Mtpa	1.06 Mtpa
Hydrogen required	-	0.03 Mtpa	0.19 Mtpa

2.4.3 Considerations for deployment and scale-up in the NT

CO_2-derived methane production costs are not expected to be economically competitive with natural gas

CO_2-derived methane is an expensive alternative to natural gas, with modelling showing a significant premium under all modelled scenarios (see Figure 15). Under the best-case scenario, the levelised cost of production is more than three times the typical price for natural gas. It is \$30–33/GJ using industrial CO_2 emissions and \$42/GJ using DAC. A detailed breakdown of cost reduction drivers between the base and best cases can be seen in Figure 28 in Appendix D.

Natural gas prices are currently much higher than is typical. The average wholesale gas prices on the east coast of Australia exceeded \$20/GJ from July to September 2022,[149] but long-term gas prices are projected to return to \$5–10/GJ.[150] However, the economics of CO_2-derived methane could be improved somewhat if prices do not stabilise or carbon prices further increase the cost of natural gas.

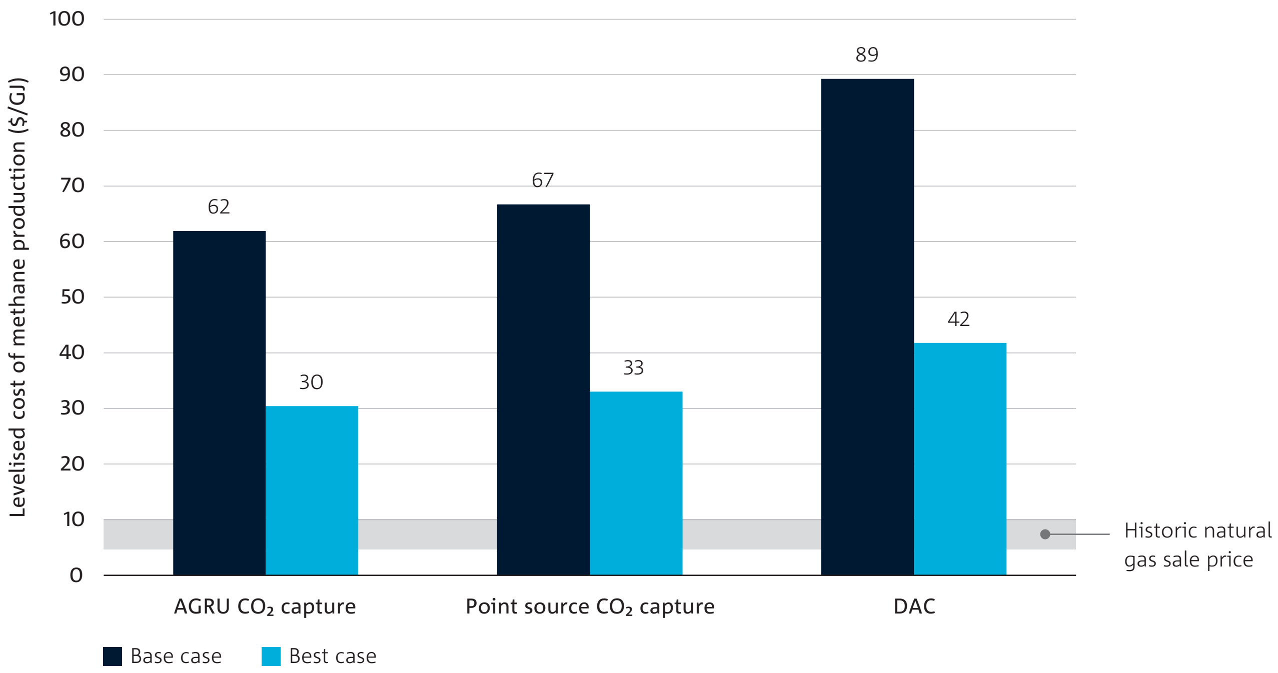
The high cost of CO_2-derived methane is partially driven by the inefficiency of the Sabatier reaction, which produces both methane (CH_4) and water (H_2O) using a nickel catalyst and elevated temperatures (300–400°C). Assuming that the hydrogen input is produced from electrolysis, six hydrogen atoms would need to be produced from water to make a single methane molecule, and two are converted back to water in that process. The cost of hydrogen has the most significant impact on the levelised cost of methane, as shown in Figure 28 in Appendix D, illustrating the primary cost reduction drivers between base and best case.

Figure 16 shows the impact of different hydrogen costs on the levelised cost of methane production. Achieving a stretch target of \$2/kg hydrogen would not make CO_2-derived methane economically viable at typical sale prices for natural gas.

149 Australian Energy Regulator (2022) *Gas market prices*. Viewed 23 Jan 2023, https://www.aer.gov.au/wholesale-markets/wholesale-statistics/gas-market-prices.

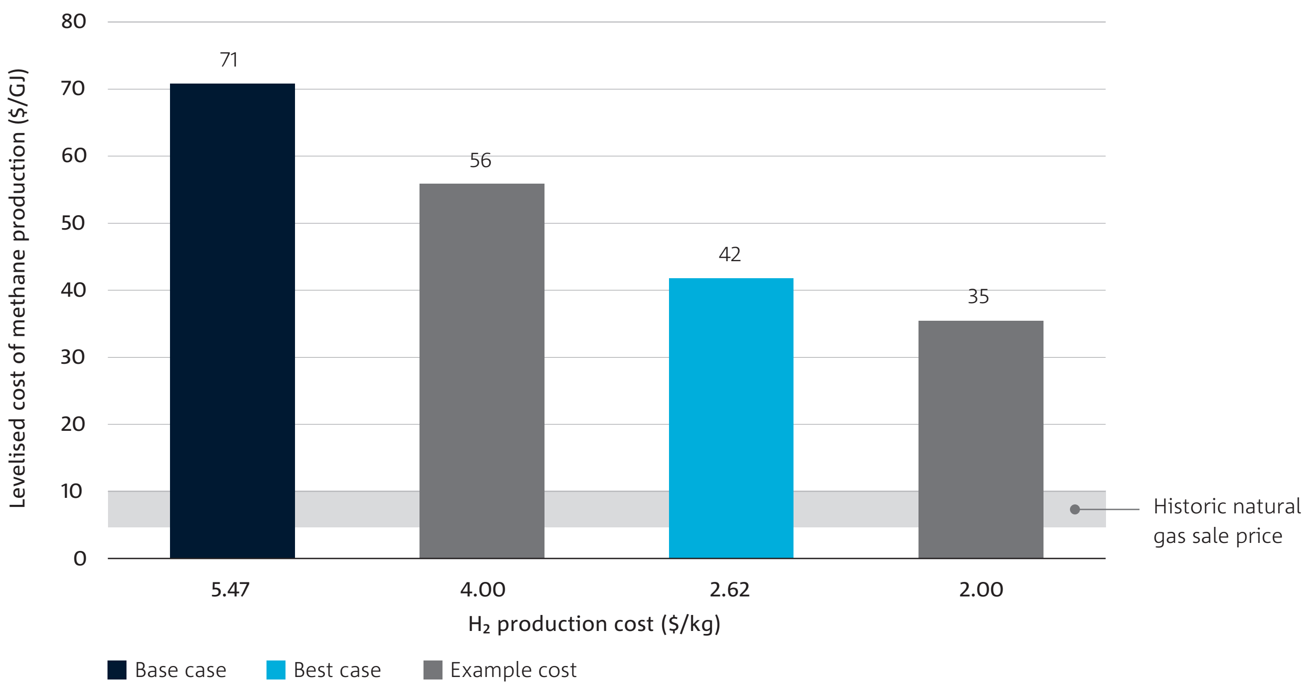
150 Lewis Grey Advisory (2021) *Gas Price Projections for Eastern Australia Gas Market 2022*. Viewed 23 Jan 2023, https://aemo.com.au/-/media/files/major-publications/isp/2022/iasr/lewis-grey-advisory-gas-price-projections-report.pdf.

Figure 15: Levelised cost of CO_2-derived methane production from different CO_2 feedstocks



The modelled CO_2 sources were AGRU capture (assumed zero cost), high partial pressure point source capture ($86/t CO_2 in the base case and $46/t CO_2 in the best case) and direct air capture ($490/t CO_2 in the base case and $200/t CO_2 in the best case). The base case scale assumes utilisation of 1,000 t/d of CO_2 (equivalent to a production scale of 7.2 PJ/yr (0.13 Mtpa) of methane). The best case assumes a five-fold increase in the scale of CO_2 utilisation (and methane production). The natural gas sale price range is based on historic wholesale gas market prices in the Australian market between FY2015–16 and FY2019–20. See Appendix C for all assumptions.

Figure 16: Impact of hydrogen feedstock cost on the levelised cost of methane production utilising DAC CO_2 feedstock and best-case scenario assumptions



Sensitivity analysis shows the effect that the modelled base ($5.47/kg H_2) and best case ($2.62/kg H_2) hydrogen production costs have on the levelised cost of methane production. A midpoint of $4.00/kg and a stretch goal of $2.00/kg were also modelled. This modelling assumes that CO_2 is sourced from DAC and uses the best case scenario for all other variables.

Due to the high production cost of CO_2-derived methane, alternative decarbonisation options (such as hydrogen, ammonia, or electrification) can be expected to be more successful for many typical natural gas applications, particularly where they are more commercially mature. However, CO_2-derived methane can be expected to be deployed where substantial technical or economic barriers exist to transition to other sustainable solutions. Possible use cases include high-temperature industrial processes, areas with significant sunk costs in natural gas infrastructure that cannot be easily repurposed, and as an intermediate solution while transitioning to more affordable alternatives.

International customers' decarbonisation strategies will drive CO_2-derived methane demand.

To support investment in CO_2-derived methane, proponents will require confidence that international demand for methane will extend beyond the life of natural gas assets. This is expected from Australia's existing international LNG customers and the NT's high potential for CCS, renewable electricity, and hydrogen development.

Japan – one of the NT's key LNG customers – has outlined energy policies that support the use and production of synthetic methane to assist in Japan's efforts to achieve carbon neutrality by 2050.[151] [152] In the short-term, Japan has set the goal of providing one per cent of Japan's gas supply with CO_2-derived methane by 2030.[153] INPEX and Osaka Gas are developing a CO_2-methanation project, planned to commence operations in 2025, that will generate up 0.13 PJ of methane per year.[154] Japan has also expressed an intention to import CO_2-derived methane.

Established LNG trade links with China, Korea and Taiwan could also be leveraged to support the export of CO_2-derived methane, dependent on each country's decarbonisation targets and strategies. Combined LNG demand from these markets is expected to grow from 836.8 PJ (200 Mt) in 2020 to 1016.7 PJ (243 Mt) in 2050.[155]

Proponents may also consider exporting to India, Indonesia, Bangladesh, Thailand, Malaysia, Vietnam, and the Philippines, which are expected to grow their LNG demand from 167.3 PJ (40 Mt) in 2020 to 1066.9 PJ (255 Mt) in 2050.[156] Beyond the APAC region, the EU is also reducing reliance on natural gas imported from Russia and exploring the role of CO_2-derived methane and other low-carbon gases as long-term gas supply solutions.[157]

DAC-sourced CO_2 or recycled CO_2 inputs are necessary to enable deep abatement, which may constrain the production of CO_2-derived methane.

Customers are unlikely to pay a premium for CO_2-derived methane that does not offer improved carbon abatement potential than natural gas production combined with CCS. The CO_2 for methane production must be renewably sourced to approach carbon neutrality. DAC is commercially immature and can be expected to constrain the scale-up of CO_2-derived methane production in the short to medium term.

151 NT Government Department of Treasury and Finance (n.d.) *Major trading partners – financial year results*. Viewed 23 Jan 2023, https://nteconomy.nt.gov.au/international-trade/financial-year-results.

152 Agency of Natural Resources and Energy (2021) *Outline of Strategic Energy Plan*. Viewed 23 Jan 2023, https://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/6th_outline.pdf.

153 INPEX, Osaka Gas (2021) Osaka Gas to Commence Technical Development Business on CO_2 Emissions Reduction and Practical Application of Effective CO_2 Use Through One of World's Largest Methanation Operations. Viewed 23 Jan 2023, https://www.inpex.co.jp/english/news/assets/pdf/20211015.pdf.

154 Converted from 400 Nm3/hr, using an energy density of 38 MJ/Nm3 methane. INPEX, Osaka Gas (2021) Osaka Gas to Commence Technical Development Business on CO_2 Emissions Reduction and Practical Application of Effective CO_2 Use Through One of World's Largest Methanation Operations. Viewed 23 Jan 2023, https://www.inpex.co.jp/english/news/assets/pdf/20211015.pdf.

155 Australian Government DISR (2022) *Global Resources Strategy Commodity Report: Liquefied Natural Gas*. Viewed 23 Jan 2023, https://www.industry.gov.au/sites/default/files/2022-09/grs-commodity-report-lng.pdf.

156 Australian Government DISR (2022) *Global Resources Strategy Commodity Report: Liquefied Natural Gas*. Viewed 23 Jan 2023, https://www.industry.gov.au/sites/default/files/2022-09/grs-commodity-report-lng.pdf.

157 IEA (2022) A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas. International Energy Agency.

CO_2 recycling – the capture of CO_2 at the point of production (at a gas-fired thermal power station, for example) and transportation back to the location of production for circular reuse – could present a more cost-effective solution to approaching carbon neutrality in applications that are amenable to point source capture. For example, INPEX's vision for 2030 involves multiple new carbon recycling initiatives, such as constructing a methanation demonstration facility within Australia from which CO_2-derived methane will be shipped to Japan, to be then supplied to customers via gas pipelines.[158]

Significant investments are being made into establishing offshore CCS solutions to address the Scope 1 emissions of natural gas operations in the NT. These projects are currently expected to be more economically feasible than CO_2-derived methane for short-term decarbonisation. However, these projects will only address the emissions associated with using methane (Scope 3 emissions) if the emissions at the point of use are also captured, transported and sequestered.

The NT's established LNG infrastructure, trade links and gas processing expertise could help to enable the development of a CO_2-derived methane export industry.

CO_2-derived methane is a drop-in substitute for most natural gas applications and can be blended with natural gas for export. The ability to utilise existing natural gas processing and export infrastructure with minimal modification could be a critical advantage for CO_2-derived methane production and export in the NT. Current LNG projects in the NT are projected to have an asset life until at least 2050.[159] Should existing LNG infrastructure reach its end of life and be decommissioned before CO_2-derived methane production is established, this advantage will dissipate.

158 INPEX (2022) *Inpex Vision @2022*. Viewed 02 Feb 2023, https://www.inpex.co.jp/english/company/pdf/inpex_vision_2022.pdf.

159 McDermott (n.d.) *Ichthys LNG Project*. Viewed 23 Jan 2023, https://www.mcdermott.com/What-We-Do/Project-Profiles/Ichthys-LNG-Project.

2.5 Mineral carbonates

Key findings

Deployment and scale-up in the NT

CO_2-derived mineral carbonates can produce various products (including aggregates for use in concrete). They can approach cost competitiveness with conventionally produced alternatives. High-level analysis indicates that suitable alkaline mineral feedstocks (such as mafic and ultramafic rock) are present in the NT. However, existing mine waste tailings are not likely to be suitable feedstocks meaning quarrying and crushing costs may increase costs. If new mines in the NT generate suitable waste minerals or low-cost mineral sources are identified in the NT, mineral carbonation could offer a unique opportunity to manufacture negative emission products.

Considerations

- CO_2-derived mineral carbonate production in the NT could become cost competitive in some circumstances if suitable feedstocks can be identified.
- Further analysis is required to identify the presence of suitable mineral feedstocks in the NT.
- Future mining projects in the NT could consider the suitability of CO_2-derived mineral carbonate production as a complementary revenue stream.
- Engagement with potential customers will be critical for project proponents as awareness of CO_2-derived mineral carbonates and their uses are still emerging.

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• No significant advancement in the NT expected in the short term	• Demonstration scale production of CO_2-derived aggregates, operating at 0.1 Mtpa (if appropriate minerals and a customer can be identified)	• Commercial scale CO_2-derived aggregates production facility to supply local markets, operating at 1 Mtpa
Enablers	• Identify suitable geologies for carbonation in the NT (e.g., alkaline minerals, mafic/ ultramafic formations) • Engage with end-users such as local concrete manufacturers to demonstrate the suitability of CO_2-derived aggregates in low-risk concrete and building material applications	• Establish industry standards for CO_2-derived building materials, including the use of aggregates in a wide range of mixes • Identify an appropriate combination of mineral, end-product, and customer	

Levelised cost of production and abatement potential

CO_2 SOURCE	BASE CASE LCOP	BEST CASE LCOP	CARBON STORAGE DURATION	ABATEMENT POTENTIAL
DAC	\$339/t $MgCO_3$ (~2.5 × conventional sale price)	\$188/t $MgCO_3$ (~1.5 × conventional sale price)	>100 years	Negative
Industrial emissions	\$157–189/t $MgCO_3$ (~1.5 × conventional sale price)	\$112–129/t $MgCO_3$ (Comparable to conventional sale price)		Net zero

2.5.1 Overview

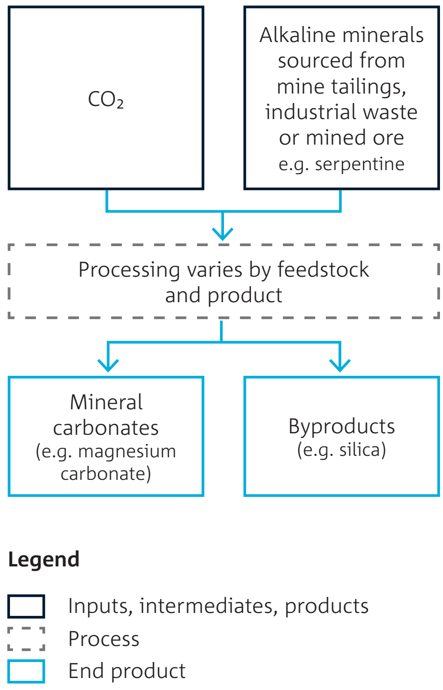
Mineral carbonation describes the reaction of CO_2 with alkaline minerals to produce carbonated products. Mineral carbonation occurs naturally as rock weathering. However, this report focuses on active thermal and chemical engineering processes that can accelerate the rate of reaction to create value-added products. Common products from mineral carbonation include magnesium carbonates ($MgCO_3$) and calcium carbonates ($CaCO_3$). Depending on the feedstock, mineral carbonation can also create valuable by-products like silica (which does not contain carbon) (see Figure 17).

Magnesium and calcium carbonates can be used as aggregates in concrete and building materials like plasterboard. This report focuses on producing carbonated aggregates from DAC-sourced CO_2, that offer a negative emission alternative to conventional quarried rock aggregates.[160] Mineral carbonation can also target higher-value products. A broader discussion of mineral carbonation inputs and products is included in CSIRO's CO_2 Utilisation Roadmap.[161]

Mineral carbonation can use various sources of alkaline minerals as feedstock for reacting with CO_2. Potential feedstocks can be sourced from mined or industrial waste or from quarried mafic/ultramafic rock (silicate minerals rich in magnesium and iron). CO_2 can also be used as a reagent in the production of lithium carbonate. This technology is at low TRL but may present a mineral carbonation opportunity in the long term.

Mineral carbonate products can store CO_2 for the long term. As such, they can be effectively carbon negative when CO_2 is sourced from DAC. Using point source CO_2 can also enable effective abatement of industrial CO_2 emissions.[162] Because of this, products containing CO_2-derived mineral carbonates will have lower net carbon emissions.[163] This compares favourably with the opportunities discussed above, which typically only temporarily store CO_2. This could also enable mineral carbonates to utilise imported CO_2 from neighbouring countries as a carbon abatement strategy.

Figure 17: Simplified production process for mineral carbonates using CO_2 capture and utilisation



160 Imerys (n.d.) *Calcium carbonate*. Viewed 23 Jan 2023, https://www.imerys.com/minerals/calcium-carbonate.

161 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

162 This assumes that renewable electricity is used for any additional mineral processing and low-emission haulage is used for mineral feedstock or product transport. This high-level analysis does not replace a full life cycle analysis of mineral carbonate production and use.

163 This term describes the lower emissions associated with the materials. The material will by design contain an increased amount of carbon.

2.5.2 Deployment and scale-up in the NT

The opportunity to produce aggregates for concrete and building materials from mineral carbonates may be limited in the short term due to a lack of suitable mine tailings and uncertainty on the scale, location and economic viability of mafic/ultramafic rock formations. If appropriate alkaline minerals are identified in the NT, mineral carbonation could offer a unique opportunity to sequester carbon in building materials or other value-added products.

Table 7 outlines a pathway to achieving demonstration-scale production by 2040 and the scale of inputs required to achieve this. The scale-up pathway described assumes a source of alkaline minerals is identified at an appropriate location within the Northern Territory. Additional detail on the shared, critical requirements for CO_2 utilisation can be found in Section 3.

Table 7: CO_2-derived mineral carbonate scale-up pathway for the NT

	SHORT TERM (BY 2030)	MEDIUM TERM (2030-2040)	LONG TERM (BEYOND 2040)
Indicative CO_2 utilisation scale-up pathway	• No significant advancement in the NT expected in the short term	• Demonstration scale production of CO_2-derived aggregates (If appropriate minerals and a customer can be identified)	• Commercial scale CO_2-derived aggregates production facility to supply local markets
Enablers	• Identify suitable mineral feedstocks for carbonation • Engage with end-users such as local concrete manufacturers to demonstrate the suitability of CO_2-derived aggregates in low-risk concrete and building material applications	• Establish industry standards for CO_2-derived building materials, including the use of aggregates in a wide range of mixes • Identify an appropriate combination of mineral, end-product, and customer	
Scale of production	-	0.1 Mtpa	1 Mtpa
CO_2 utilised	-	0.053 Mtpa	0.53 Mtpa

2.5.3 Considerations for deployment and scale-up in the NT

CO_2-derived mineral carbonate production in the NT could become cost competitive in some circumstances if suitable feedstocks can be identified.

Modelling indicates that the levelised cost of magnesium carbonate and silica, produced on-site by carbonation of quarried serpentine rock, is within the sale price of conventional products under the best-case scenario for select CO_2 capture sources (as shown in Figure 18). The sale prices listed are conservative and will be affected by the purity of products, which will vary between different commercial carbonation processes.

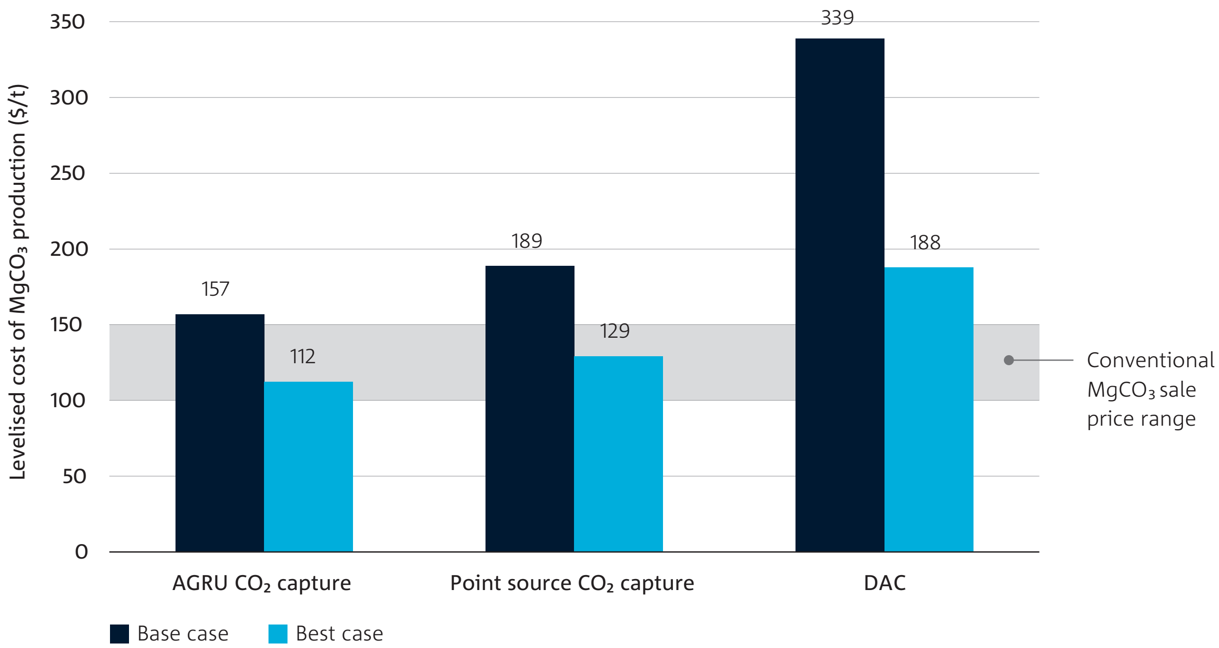
Under the best-case scenario when using AGRU capture and high partial pressure CO_2, the levelised cost of producing magnesium carbonate and silica are within their respective sale price ranges. In the base-case scenario using low-cost AGRU-sourced CO_2, the levelised cost of CO_2-derived silica production reaches $56/t, falling within the price range of conventional production methods. A detailed breakdown of cost reduction drivers between the base and best case scenarios can be seen in Figure 29 in Appendix D.

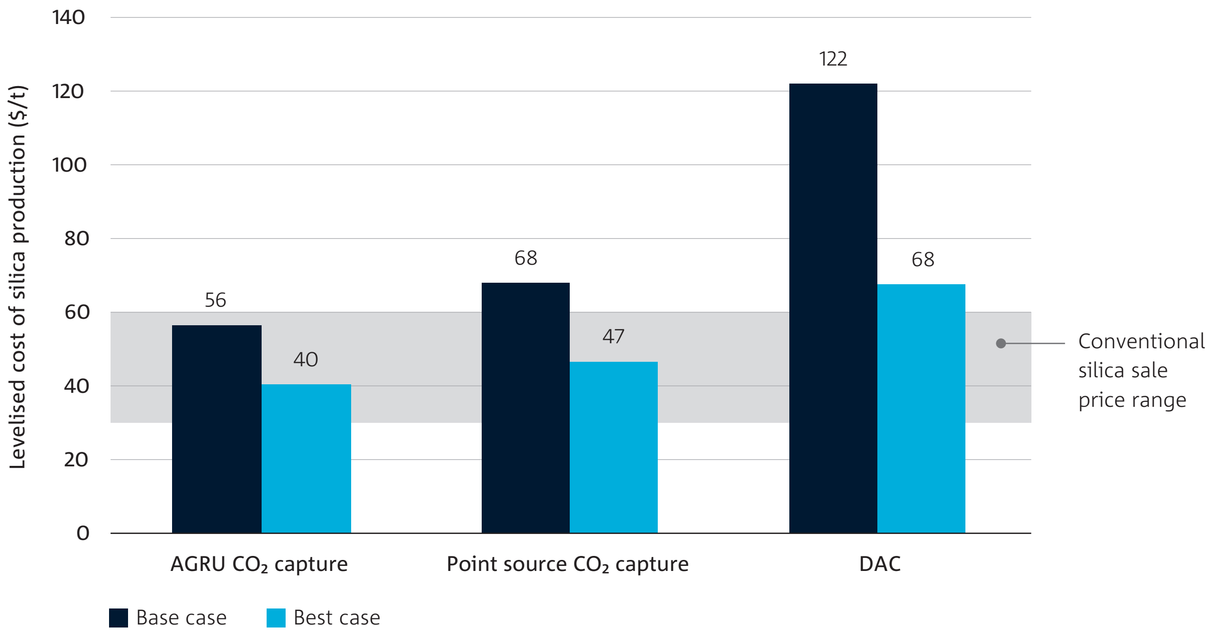
However, the levelised cost of production exceeds the assumed sale price in base and best case scenarios when using DAC-sourced CO_2. Consequently, CO_2 captured from natural gas processing facilities and other industrial processes can be used to prove and scale mineral carbonate production while renewable inputs become available and affordable.

Unlike many other CO_2 utilisation applications, mineral carbonate production is not dependent on low-cost renewable hydrogen production as this is not a direct input. This allows mineral carbonate production to scale independently of commercial-scale hydrogen projects in the NT, creating the opportunity to scale up rapidly should suitable mineral resources be identified.

Modelling excludes the cost of transporting mineral feedstock or carbonated product. The optimised balance of CO_2, mineral and end-products transportation costs will be site-specific. However, opportunities that have co-located CO_2 and mineral feedstocks and access to local customers can be expected to be more economically competitive than sites that are located remotely.

Figure 18: Levelised cost of magnesium carbonate ($MgCO_3$) and silica (by-product) produced from mined serpentine and different CO_2 feedstocks





The modelled CO_2 sources were acid gas removal unit (AGRU) capture (assumed zero cost), high partial pressure point source capture ($86/t CO_2 in the base case and $46/t CO_2 in the best case) and direct air capture ($490/t CO_2 in the base case and $200/t CO_2 in the best case). The base case scale assumes utilisation of 1,000 t/d of CO_2 (equivalent to a production scale of 0.69 Mtpa $MgCO_3$ and 0.82 Mtpa SiO_2). The best case assumes a five-fold increase in the scale of CO_2 utilisation (and mineral carbonates production). See Appendix C for all assumptions.

Further analysis is required to identify the presence of suitable mineral feedstocks in the NT.

High-level analysis of current mining activities in the NT and consultation with mineral carbonation proponents and experts did not identify any likely feedstocks for mineral carbonation in the NT. However, further analysis of historic mines may identify suitable waste feedstocks.

Consideration of particle size, CO_2 reactivity, transport costs, access to CO_2 supply, and project maturity is likely to inform the suitability of a mine site for mineral carbonate production. Projects such as Geoscience Australia's *Atlas of Australian Mine Waste*, which seeks to highlight new opportunities to recover secondary minerals, could support the identification of suitable mine wastes.[164] CSIRO's CarbonLock Future Science Platform is identifying rock formations that may be physically and chemically amenable to storing CO_2 permanently. This analysis targets sequestration rather than carbon utilisation, but it may help mineral carbonation proponents identify suitable feedstocks.[165]

Detailed analysis is also required to determine the suitability of mafic/ultramafic rock formations for long-term mineral carbonation opportunities. Some work has been undertaken to determine the presence of mafic/ultramafic formations, with mafic rock formations located at Pine Creek, approximately 200 kilometres south of Darwin.[166]

Mine tailings or other pre-processed rock are likely the most economically viable feedstock due to the energy costs of grinding mafic/ultramafic rocks into a suitable particle size for carbonation. However, access to low-cost renewable electricity combined with grinding mills able to manage a variable electricity supply could shift the economic viability of this approach in the long term.

Future mining projects in the NT could consider the suitability of CO_2-derived mineral carbonate production as a complementary revenue stream.

The NT is home to eight major operating mines, with another three in care and maintenance mode. However, there are an additional 21 projects in approval processes, which could assess the potential for carbonation of their mining waste streams.[167] [168]

Considering the potential role of mineral carbonates during the planning stage of mining projects may create additional revenue streams and enable emissions abatement. Carbonation and utilisation of mine waste may also reduce risks associated with waste management. For example, decreasing the size of tailings dams could reduce capital and operational costs.

Engagement with potential customers will be critical for project proponents as awareness of CO_2-derived mineral carbonates and their uses are still emerging.

Aggregates are a primary input into the concrete industry which faces a significant decarbonisation challenge. The production and use of carbonated aggregates in concrete manufacturing could present an opportunity to offset emissions from this hard-to-abate industry. The concrete manufacturing industry in Australia is forecast to grow at a CAGR of 1.7% until 2026,[169] which is lower than the global concrete industry's CAGR of 4.6% from 2021 to 2030.[170] Ready-mixed concrete was one of the NT's largest manufacturing industries in 2019-20,[171] but the NT's single cement facility (one of three inputs into concrete) has recently been placed in care and maintenance mode.

Preliminary engagement with the domestic concrete industry suggests limited awareness of CO_2-derived carbonated aggregates and their potential use in concrete manufacturing. For mineral carbonation proponents, partnerships with hard-to-abate industries will be key to deploying commercial-scale technologies.

164 Australian Government GA (2022) *Atlas of Australian Mine Waste puts secondary prospectivity on the map.* Viewed 23 Jan 2023, https://www.ga.gov.au/news-events/news/latest-news/atlas-of-australian-mine-waste-puts-secondary-prospectivity-on-the-map.

165 CSIRO (2022) *Mafic/Ultramafic Carbonation Potential Map of Australia*. Viewed 23 Jan 2023, https://research.csiro.au/carbonlock/mafic-ultramafic-carbonation-potential-map-of-australia/.

166 Glass LM (2011) Palaeoproterozoic island-arc-related mafic rocks of the Litchfield Province, western Pine Creek Orogen, Northern Territory. Northern Territory Geological Survey.

167 NT Government (2022) *Operating* Mines. Viewed 23 Jan 2023, https://resourcingtheterritory.nt.gov.au/minerals/mines-and-projects/operational-mines.

168 NT Government (2022) *Developing* Projects. Viewed 23 Jan 2023, https://resourcingtheterritory.nt.gov.au/minerals/mines-and-projects/developing-projects.

169 Kelly A (2020) Concrete Product Manufacturing in Australia. IBISWorld.

170 Digvijay P (2021) *Concrete Market*. Viewed 23 Jan 2023, https://www.alliedmarketresearch.com/concrete-market-A12420.

171 NT Government (n.d.) *Budget 2021-22: Industry Outlook*. Viewed 23 Jan 2023, https://budget.nt.gov.au/__data/assets/pdf_file/0017/1000385/2021-22-Industry-Outlook-book.pdf.

Targeted mechanisms, such as carbonated aggregate targets in government procurement strategies for the construction sector could further support the integration into concrete and materials production in the NT.

2.6 Summary of CO_2 utilisation opportunities

2.6.1 Deployment plan for scale-up

The deployment plan outlined in Figure 19 draws together the five CO_2 utilisation opportunities discussed above and describes the indicative scale of utilisation opportunities across the short, medium and long term in the NT context. This deployment plan shows how a hub model, integrating different sources of CO_2 alongside CO_2 storage opportunities, can support scale-up of CO_2 utilisation applications. As DAC becomes more available and affordable this can enable CO_2 utilisation to increase in scale and enable greater emissions abatement.

Methanol is expected to have the greatest scale-up potential in the short term, with other opportunities including jet fuel and urea having potential to reach demonstration scale in the medium term. Methane and mineral carbonates may also reach demonstration scale in the medium term, if the right customers and mineral feedstocks are identified, respectively.

Figure 19: Integrated plan for deployment and scale-up in the NT

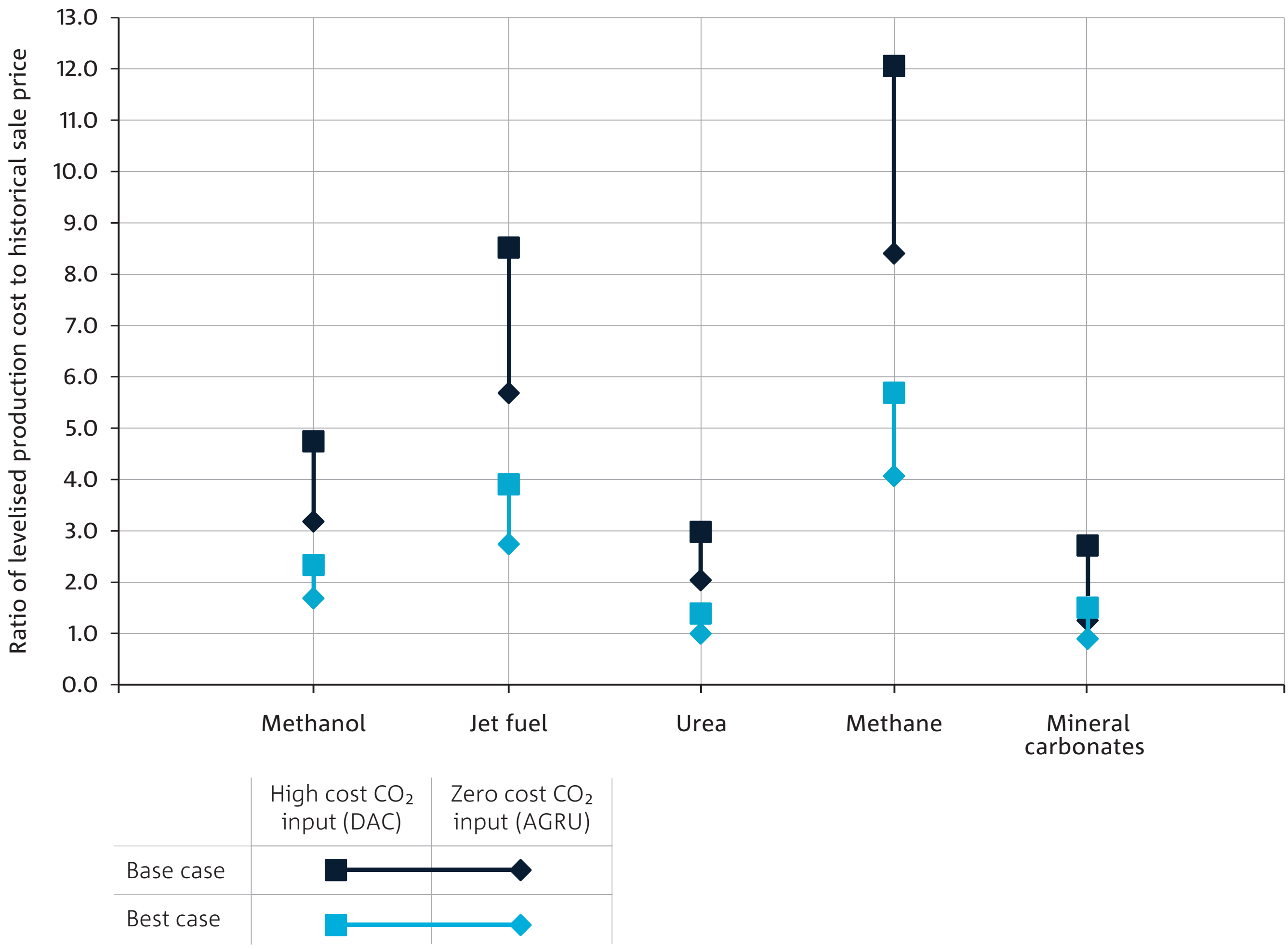
	Short term (by 2030)	Medium term (2030–2040)	Long term (beyond 2040)
CO_2 CAPTURE	Existing industrial emissions (primarily LNG processing)	Existing industrial emissions + Point source + Demonstration scale DAC	Existing industrial emissions + Point source + Commercial scale DAC
CO_2 UTILISATION: **METHANOL**	Demonstration scale	Commercial scale, potential for hybrid production	Commercial scale for local downstream manufacturing and export
JET FUEL	Pilot scale	Demonstration scale for local defence and airport industry	Commercial scale for export
UREA		Demonstration scale, potential for hybrid production	Commercial scale, potential for fully renewable urea
METHANE		Demonstration scale, if suitable customers are identified	Commercial scale for export
MINERAL CARBONATES		Demonstration scale, if appropriate mineral feedstocks are identified	Commercial scale
CO_2 STORAGE	Geological storage	Geological storage	Geological storage

2.6.2 Levelised cost of production

CO_2 utilisation is an emerging technology that will likely face barriers to cost competitiveness with conventional products in the short term. As discussed in Sections 2.1 to 2.5, some opportunities may be more cost competitive than others.

None of the opportunities modelled are expected to be cost competitive with conventional products under the base case scenario. However, some customers may be willing to pay a premium for products with a reduced emissions intensity to support decarbonisation in industries considered hard-to-abate. Modelling shows that the levelised costs of producing mineral carbonates and urea using AGRU-sourced CO_2 approach their conventional sale prices under the best case scenario. However, it should be noted that a profit margin is not included in the levelised cost of production.

Figure 20: Best and base case levelised costs of production for five prioritised opportunities as a ratio of conventional sale price



This figure shows the best and base case levelised costs of production for CO_2-derived products expressed as a ratio to historical sale prices for their conventionally produced equivalents. Two different CO_2 feedstocks are shown, AGRU and DAC, which shows the impact of varying CO_2 costs on levelised cost of production. AGRUs are used for liquefied natural gas (LNG) processes and are a source of near zero-cost CO_2. DAC technologies are emerging and have yet to reach commercial scale globally, producing CO_2 at a higher cost.

3 Requirements for CO_2 utilisation in the Northern Territory

This section provides an overview of the critical inputs and requirements for carbon utilisation, including CO_2, hydrogen, and renewable electricity in the NT.

The development of these inputs and related infrastructure could be a relatively low risk investment for the NT as carbon capture, and renewable electricity and hydrogen are all expected to face increasing demand, even if CO_2 utilisation opportunities do not reach maturity.

Figure 21: Cumulative CO_2 and hydrogen demand

CO_2 utilisation scale	Methanol	Jet fuel	Urea	Methane	Mineral carbonates
SHORT TERM (BY 2030)					
2% NTLEH CO_2 emissions (0.15 Mtpa from point sources)	**0.05 Mt** Demonstration scale	**0.01 Mtpa** (0.08m bbl/yr) Pilot scale			
MEDIUM TERM (2030-2040)					
6% NTLEH CO_2 emissions (1.15 Mtpa from point sources and DAC)	**0.35 Mtpa** Commercial scale	**0.1 Mtpa** (0.08m bbl/yr) Demonstration scale	**0.1 Mtpa** Demonstration scale	**0.05 Mtpa** (2.8 PJ/yr) Commercial scale	**0.1 Mtpa** Demonstration scale
LONG TERM (BEYOND 2040)					
20% NTLEH CO_2 emissions (4.84 Mtpa from point sources and DAC)	**1.0 Mtpa** Commercial scale	**0.25 Mtpa** (2m bbl/yr) Commercial scale	**1.0 Mtpa** Commercial scale	**0.38 Mtpa** (20.9 PJ/yr) Commercial scale	**1.0 Mtpa** Commercial scale

Short term (Methanol and Jet fuel): 0.02 Mtpa H_2 (equivalent to 0.7 TWh/yr) Requiring 0.6 – 1 GW of hydrogen electrolysers

Medium term (Methanol, Jet fuel, Urea and Methane): 0.16 Mtpa H_2 (equivalent to 7.2 TWh/yr) Requiring 0.9 – 4.3 GW of hydrogen electrolysers

Medium term (Mineral carbonates): Alkaline mineral feedstock

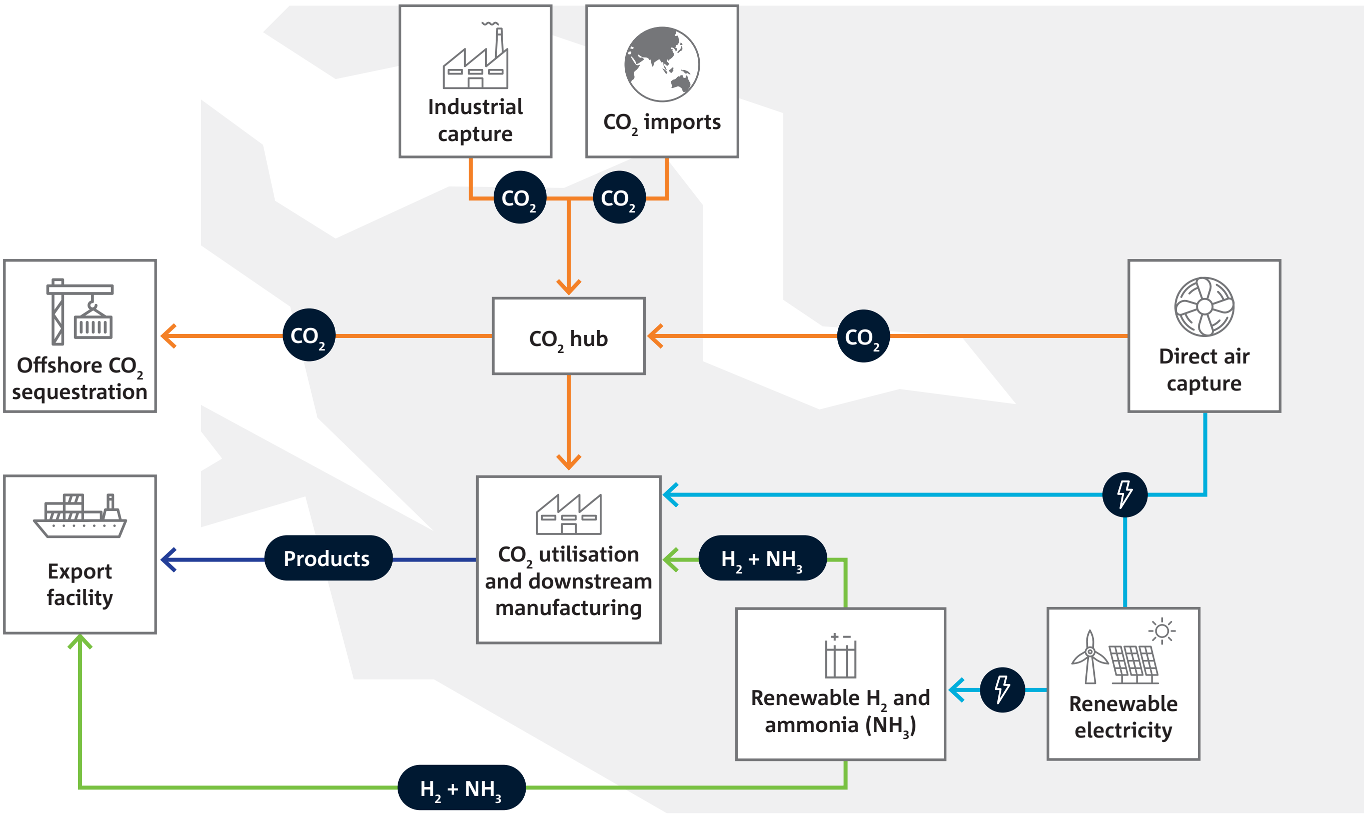
Long term (Methanol, Jet fuel, Urea and Methane): 0.63 Mtpa H_2 (equivalent to 28.3 TWh/yr) Requiring 3.6 – 17 GW of hydrogen electrolysers

Long term (Mineral carbonates): Alkaline mineral feedstock

Figure 22 outlines a long-term hub concept for the NT with a focus on the MASDP. It highlights the relationships between CO_2 sources, renewable hydrogen and ammonia production, renewable electricity generation, CO_2 storage, and export infrastructure. The deployment of CO_2 utilisation opportunities could be stimulated by further developing common use infrastructure associated with the MASDP – for example, the development of precinct-wide CO_2 collection infrastructure system and product export corridors.

To enable commercial-scale production, CO_2 sources (including DAC) and renewable hydrogen, electricity, and ammonia, will require increased production levels by orders of magnitude. In the short to medium term, access to these requirements may constrain scale-up due to competition from other users, such as the exporting of renewable hydrogen for international markets. The interdependencies between the required inputs for CO_2 utilisation can be used to de-risk investment across decarbonisation projects in the NT and support commercial scale-up.

Figure 22: Long-term concept for incorporating CO_2 utilisation into a CCS and low emissions manufacturing hub in the NT



3.1 CO_2

Suppose all five carbon utilisation opportunities scale up as described in Section 2.6. In that case, they will consume almost 20% of the carbon emissions that could be processed through an NTLEH. This could buffer geological storage capacity requirements and increase a low-emission hub's overall CO_2 capacity (storage and utilisation).

In the short and medium term, CO_2 demand will likely be met by point-source industrial carbon emissions, such as AGRU. However, industrial emissions are expected to be progressively abated by new technologies, new processes, and CO_2 storage. Over time, it is likely that sustainable sources of carbon such as DAC (and biomass) will become more competitive and in demand. Long-term investments in manufacturing and infrastructure will need to consider and plan for these anticipated shifts in carbon sources.

Table 8: Cumulative CO_2 demand

	NEAR FUTURE (2030)	**FAR FUTURE (2040)**	**VERY FAR FUTURE (BEYOND 2040)**
CO_2 sources	• Industrial emissions	• Industrial emissions • DAC • Imports[172]	• Industrial emissions • Increasing volumes of DAC • Imports[183]
Projected industrial CO_2 emissions amenable to capture in the NT	10 Mtpa	20 Mtpa +	
Cumulative CO_2 utilisation	0.15 Mtpa	1.15 Mtpa	4.84 Mtpa
(Consumption of projected CO_2 emissions)	(1%)	(5%)	(19%)

172 CO_2 imports are not a focus of this analysis. However, there are two scenarios in which CO_2 imports might be utilised in CO_2-derived products. The first is CO_2 utilisation in products that sequester CO_2 for extended periods (e.g., mineral carbonates, and plastics). The second is carbon recycling (e.g., capturing the CO_2 released when burning CO_2-derived methane to make more methane).

CO_2 sources in the NT

The NT's total CO_2 emissions for 2020 were 17.3 Mt CO_2-equivalent. Almost 80% (13.6 Mt CO_2-equivalent) of these emissions were from the energy sector.[173] This report considers two sources of CO_2: point source capture (industrial emissions) and direct air capture of atmospheric emissions. The modelled cost assumptions for these two CO_2 sources are described in Table 9.

The impact of carbon capture costs on the production costs of each product is explored in Section 2. For products containing hydrogen, sensitivity to cost of CO_2 is less than hydrogen.

A high-level overview of point source, DAC, and CO_2 distribution requirements is included below. A detailed investigation of CO_2 capture opportunities and related infrastructure is beyond the scope of this report. Other work streams associated with the NTLEH studies explore these topics in more detail.

Point source capture (industrial emissions)

Point source capture technologies can extract CO_2 from industrial process waste streams in diverse industries, including oil and gas extraction, power generation, and manufacturing. These technologies have been deployed at commercial scale around the world, including at natural gas processing facilities and manufacturing facilities for fertiliser and ethanol.

CSIRO analysis of CO_2 sources in the NT that are amenable to carbon capture suggests that captured emissions could reach 10 Mtpa by 2030 and over 20 Mtpa by 2040. These sources are expected to include LNG processing, gas-powered thermal power generation, and gas-derived manufacturing (such as blue hydrogen, ammonia, methane, and urea).

The NT's natural gas processing facilities are a significant source of CO_2 emissions. Current CO_2 emissions from the onshore LNG facilities at Middle Arm are approximately 7–8 Mtpa. The carbon emissions from the AGRUs is 2–3 Mtpa.

AGRUs offer a unique value proposition for CO_2 utilisation projects, as they are a near zero-cost source of CO_2 (excluding compression and transport costs). AGRUs strip acidic gases, such as CO_2 and hydrogen sulphide, from natural gas before liquefaction, transport and sale. This separation process produces significant volumes of CO_2 which are currently vented into the atmosphere. This presents an effectively free source of captured CO_2, for utilisation. As such, they can support the development and demonstration of CO_2 utilisation opportunities by lowering the initial cost of CO_2-derived products while sustainable sources of CO_2 become available and affordable.

Table 9: Modelled CO_2 capture costs (excluding compression and transport)

TECHNOLOGY	DESCRIPTION	SOURCE	CAPTURE COST ($/TCO₂) BASE CASE	BEST CASE
Point source carbon capture	CO_2 captured from industrial processes including but not limited to oil and gas extraction, power generation, and manufacturing.	AGRU emissions (LNG processing)	Assumed zero cost	
		Point source emissions (High partial pressure)	86	46
Direct air capture (DAC)	Removal of CO_2 directly from the atmosphere using	Atmospheric CO_2	490	200

173 Australian Government DCCEEW (n.d.) *Emissions by State and Territory, Australia's National Greenhouse Gas Accoun*ts, https://www.greenhouseaccounts.climatechange.gov.au/.

Direct air capture (DAC)

DAC is critical to unlocking the long-term potential of CO_2 utilisation to enable net zero (and even negative) life cycle emissions from CO_2-derived products. For example, if CO_2 captured through DAC is used to create fuel, CO_2 would be released back into the atmosphere once used, potentially resulting in a net zero emission product. If the CO_2 is used to create a mineral carbonate or plastic, the carbon could be stored for extended periods, effectively creating a negative emission product.

DAC technologies use a variety of approaches to capture CO_2 from the atmosphere. They typically need a significant amount of thermal (which can be provided by natural gas) or electrical energy.[174] A list of mature DAC technologies is presented in Table 10.

DAC technologies have been deployed at pilot and demonstration scales internationally. There are around 18 plants in operation worldwide, capturing almost 0.01 Mtpa CO_2.[175] The world's first 1 Mtpa CO_2 plant is being developed in the United States with plans to commence operations in 2024.[176]

To drive the development of sustainable CO_2 utilisation opportunities, it will be necessary to reduce the cost of DAC. IEA modelling suggests that the average levelised cost of capture for DAC was $210–420/t$CO_2$ in 2020. This modelling suggests that this can be reduced to $70–211/t$CO_2$ through a combination of R&D, learning by doing, and economies of scale.[177] The modelled costs of DAC used in this report are listed in Table 9 and Appendix C.

Table 10: Direct air capture technologies[178]

TECHNOLOGY	DESCRIPTION	TRL	COMMENTS
Solid-based absorption and desorption (low temp)	Two variations are commercially available: Climeworks and Global Thermostat. Climeworks' technology draws ambient air over amine compounds bound to dry porous granules as a filter. Once enriched with CO_2, CO_2 is removed by applying a combination of pressure and temperature (approx. 100°C). Global Thermostat has a different structure of amines and regenerates these materials using low-temperature steam.	6–9	Active: Climeworks, Global Thermostat The low thermal requirements can be met by waste heat.
Solution-based absorption and calcination (high temp)	CO_2 is absorbed using a sodium or potassium hydroxide (NaOH or KOH) aqueous solution. If KOH, CO_2 is absorbed to form potassium carbonate (K_2CO_3). Then, K_2CO_3 is precipitated into calcium carbonate ($CaCO_3$) in a pellet reactor. $CaCO_3$ is then calcinated at 850°C, decomposing into CO_2 and CaO to be collected.	6–8	Active: Carbon Engineering
Solution-based absorption and electrodialysis (no heat)	Air is drawn in and CO_2 is absorbed using a sodium hydroxide (NaOH) solution. The resulting sodium carbonate (Na_2CO_3) solution is then acidified using sulfuric acid (H_2SO_4), releasing almost pure CO_2. The NaOH and H_2SO_4 are then regenerated through electrodialysis to be used again.	5	Requires only electricity. No thermal energy needed.

174 IEA (2022) *Direct Air Capture*. Viewed 23 Jan 2023, https://www.iea.org/reports/direct-air-capture.

175 IEA (2022) *Direct Air Capture*. Viewed 23 Jan 2023, https://www.iea.org/reports/direct-air-capture.

176 IEA (2021) *DAC 1*. Viewed 31 Jan 2023, https://www.iea.org/reports/ccus-around-the-world/dac-1.

177 Converted from US$0.15-0.3/kg CO_2 in 2020 and US$50-150/t$CO_2$ in future. IEA (2022) *Direct Air Capture 2022*. International Energy Agency.

CO_2 transportation and infrastructure

CO_2 can be transported by pipeline, ship, rail, truck, or a combination of transport modes (see Table 11). CO_2 pipelines are typically the most cost-effective transportation option, as they can transport (and store) large volumes of CO_2 and benefit from economies of scale. Their installation is expensive, so existing infrastructure should be repurposed as a priority where possible. Natural gas pipelines could be repurposed for the transport of CO_2, though not without some structural integrity and operation challenges.[179]

Further techno-economic and cost-benefit analyses assessing the suitability of existing infrastructure to meet anticipated demand will need to be conducted to determine the best transport options for the NT. CSIRO's national CO_2 Utilisation Roadmap[180] discusses this topic, and other work streams in the NTLEH project are exploring this topic in more detail.

Table 11: CO_2 distribution technologies[181]

TRANSPORT METHOD	INDICATIVE DISTANCES	DESCRIPTIONS AND USE
Truck	Short-medium	CO_2 is liquefied for transport in pressurised vessels aboard freight trucks.[182]
Rail	Medium-long	CO_2 is transported on freight trains in the same way as truck transport.
Pipeline	Medium-long	CO_2 is compressed until it reaches a supercritical or 'dense' phase.[183] Impurities of concern for pipeline transport include water, which leads to corrosion of pipe steels, non-condensable gases (such as N_2, O_2, H_2 and Ar)[184] and other contaminants (such as H_2S and CH_4).
Ship	Long	CO_2 is compressed and often refrigerated to reach a liquid state, stored in pressurised vessels.

178 Adapted from Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

179 NASEM (2022) Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report. The National Academies Press.

180 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

181 Reproduced from Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

182 Linde Engineering (2021) CO_2 purification and liquefaction plants. Viewed 3 May 2021, https://www.linde-engineering.com/en/process-plants/co2-plants/co2-purification-and-liquefaction/index.html

183 Bui M et al. (2018) Carbon capture and storage (CCS): the way forward. Energy & Environmental Science

184 Bui M et al. (2018) Carbon capture and storage (CCS): the way forward. Energy & Environmental Science

3.2 Hydrogen

Renewable hydrogen is a critical input for the fuel and chemical manufacturing opportunities discussed in this report (including methanol, jet fuel, urea and methane). If all CO_2 utilisation opportunities considered above scale-up as described, they would consume over 0.63 Mtpa of hydrogen (see Table 12) in the long term. This is almost 1000 times the expected production from Australia's largest planned electrolyser.[185]

Renewable hydrogen production in the NT

The Northern Territory Renewable Hydrogen Master Plan suggests that the NT could produce up to 3 Mtpa of renewable hydrogen by 2050 (15% of Australia's hydrogen production).[187] There are multiple renewable or low-emission hydrogen projects proposed for development in the NT. These include Desert Bloom, TIWI H_2 Project, Darwin H_2 Hub, and the Lattice Technology Joint Development Project. These hydrogen projects have a planned production capacity of approximately 0.6 Mtpa (see Table 13). Hydrogen production from some of these projects is expected to commence as early as 2027.[188]

In addition to these proposed projects, the MASDP strategic assessment has stated that it aims to support renewable hydrogen related land use.[189] INPEX has also been awarded up to $1 million via the Australian Government's Regional Hydrogen Hubs Program to conduct a Market Development Study for a Darwin Clean Hydrogen Hub in the MASDP.[190]

Table 13: Cumulative capacity of proposed hydrogen production projects in the NT

PROJECT	CAPACITY
Darwin H_2 Hub (Total Eren)	0.08 Mtpa
Tiwi H_2 Project (Provaris Energy)	(Up to) 0.1 Mtpa
Lattice Technology Joint Development Project	0.042 Mtpa
Desert Bloom (Aqua Aerem)	(Up to) 0.41 Mtpa
TOTAL	**0.6 Mtpa (rounded)**

CSIRO's modelling of renewable hydrogen prices suggests that the most competitive levelised cost in the Darwin region will be achieved using off-grid renewables without storage. This results in a best case levelised cost of production approaching $2.68/kg beyond 2040. See Appendix C for all modelling assumptions.

Low-emission hydrogen, produced using natural gas coupled with CCS, is not considered in this project. However, further work should consider the environmental and economic trade-offs between renewable and natural gas-derived hydrogen. Natural gas-derived hydrogen may also be used as a cheaper source of hydrogen to demonstrate emerging CO_2-derived fuel and chemical manufacturing opportunities while renewable hydrogen availability and affordability improves. A detailed discussion of hydrogen production and transport infrastructure requirements is not within the scope of this report.

Table 12: Indicative hydrogen demand from CO_2 utilisation scale-up

TIMELINE	ASSUMED RENEWABLE HYDROGEN PRODUCTION IN THE NT[186] Mtpa	CUMULATIVE HYDROGEN DEMAND Mtpa	PERCENTAGE OF NT HYDROGEN PRODUCTION %
Short term (By 2030)	0.6	0.02	3%
Medium term (2040)	1.05	0.16	15%
Long term (Beyond 2040)	3	0.6	20%

185 ENGIE's 10MW electrolyser due to be constructed in 2024 is expected to provide 640tpa of renewable hydrogen to the Yara Pilbara Fertiliser ammonia production facility. ARENA (2022) *Australia's first large scale renewable hydrogen plant to be built in Pilbara*. Viewed 23 Jan 2023, https://arena.gov.au/blog/australias-first-large-scale-renewable-hydrogen-plant-to-be-built-in-pilbara.

186 See Table 13: Cumulative capacity of proposed hydrogen production projects in the NT. Medium- and long-term assumptions are 15% of projected Australian hydrogen production under Scenario 1, in 2040 and 2050 respectively in: Deloitte (2019) *Australian and Global Hydrogen Demand Growth Scenario Analysis.* Viewed 02 Feb 2023, https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf.

187 Northern Territory Government Department of Industry, Tourism and Trade (2021) *Northern Territory Renewable Hydrogen Master Plan.* Viewed 23 Jan 2023, https://territoryrenewableenergy.nt.gov.au/__data/assets/pdf_file/0018/1057131/nt-renewable-hydrogen-master-plan.pdf.

188 Northern Territory Government (n.d.) *Hydrogen*. Viewed 23 Jan 2023, https://territoryrenewableenergy.nt.gov.au/strategies-and-plans/hydrogen.

189 Australian Government DCCEEW (n.d.) *Middle Arm Sustainable Development Precinct Strategic Assessment*. Viewed 31 Jan 2023, https://www.dcceew.gov.au/environment/epbc/strategic-assessments/middle-arm.

190 CSIRO (2022) *Regional Hydrogen Hubs Program*. Viewed 02 Feb 2023, https://research.csiro.au/hyresource/regional-hydrogen-hubs-program/.

3.3 Electricity

Electricity is a critical input into most aspects of CO_2 utilisation. It can be used in carbon capture and in CO_2 utilisation facilities to manufacture CO_2-derived products. For most of the opportunities explored in this report, renewable hydrogen production is the primary cost driver and the biggest consumer of electricity. As such, this section focuses on the electricity demand for hydrogen production as a proxy for the scale of electricity demand associated with CO_2 utilisation.

Over 28,000 GWh of renewable energy is required to produce the indicative long-term hydrogen demand. Assuming no energy storage is used, this would require 17 GW of solar power and electrolysers operating at a 19% capacity. This capacity factor was selected as modelling showed this produced the lowest hydrogen cost. However, this may not be commercially appealing for project proponents, given the significant downtime for capital-intensive electrolysers. The scale of electrolysers can be reduced to 3.6 GW if the electrolysers operate at high (90%) capacity factor (see Table 15). This would require significant investments in energy storage, network upgrades, and/or a source of firm renewable electricity.

Renewable electricity production in the NT

Thermal power plants currently supply most of the NT's power needs. In 2021, only 12% (approximately 200 GWh) of electricity demand in the NT was supplied by renewables (a combination of large-scale and small-scale solar farms). The NT Government has set a 50% renewable energy target for 2030 (equivalent to 905 GWh).[193] An estimated 0.32 GW of solar and 0.11 GW (0.6 GWh capacity) of batteries for energy storage will be required to achieve the target.[194]

Deployment of CO_2 utilisation technologies will further increase demand for renewable electricity, and this will place additional pressure on the power system. To meet the indicative short-term demand for renewable hydrogen alone, the NT's demand for renewable energy would increase by 55% of the NT's total electricity demand in 2021.

Meeting the long-term demand will require a renewable electricity capacity that is orders of magnitude greater than Australia's largest solar farm.[195] This would require a supply of almost 17 times the NT's total electricity demand in 2021 for hydrogen production alone. The NT has excellent potential for solar development,[196] and proponents are already exploring multi-GW solar farms for renewable hydrogen production and electricity exports in the Northern Territory.

Table 15: Indicative renewable energy requirements for hydrogen production

	HYDROGEN DEMAND	REQUIRED RENEWABLE ENERGY[191]		REQUIRED SCALE OF DEDICATED RENEWABLE ENERGY GENERATION CAPACITY[192]
TIMELINE	Mtpa	GWh/yr	% of NT's 2021 electrical energy consumption	GW
Short term (By 2030)	0.02	922	55	0.1–0.6
Medium term (2040)	0.16	7155	426	0.9–4.3
Long term (Beyond 2040)	0.63	28,296	1686	3.6–17

191 Assuming a 45kWh/kg electrolyser efficiency.

192 Assuming a 19% to 90% capacity factor.

193 50% of projected demand of 1810GWh. The NT Government has set a 50% renewable energy target for 2030. NT Government (2021) *Our renewable energy target*. Viewed 23 Jan 2023, https://territoryrenewableenergy.nt.gov.au/about/our-renewable-energy-target.

194 Northern Territory Government Department of Industry, Tourism and Trade (2022) *Darwin-Katherine Electricity System Plan*. Viewed 23 Jan 2023, https://territoryrenewableenergy.nt.gov.au/__data/assets/pdf_file/0011/1056782/darwin-katherine-electricity-system-plan-web.pdf?v=0.1.1

195 For comparison, Australia's largest solar farm at the time of writing (currently under construction as part of Neon Australia's Western Downs Green Power Hub in Queensland) will have 460MW of solar panels when complete. Neoen (n.d.) *Western Downs Green Power Hub*. Viewed 31 Jan 2023, https://westerndownsgreenpowerhub.com.au/.

196 The NT has the best solar resource of all Australian states and territories with an average annual solar radiation of 22-24 MJ per square metre. NT Government (2022) *Renewable energy*. Viewed 31 Jan 2023, https://invest.nt.gov.au/infrastructure-and-key-sectors/key-sectors/renewable-energy.

The base case electricity prices were based on typical grid electricity prices in the NT. This is a firm power supply that is primarily generated from gas. Best case electricity prices for general electricity demand used optimised long-term projections for renewable electricity with storage in the Darwin region.[197] Best case electricity prices for hydrogen production assume off-grid dedicated renewables (primarily solar) operating at a 19% capacity factor (see Table 16 and Appendix C.

Table 16: Electricity cost assumptions

	BASE CASE	BEST CASE	
	Grid electricity	Renewables and storage (90% capacity factor)	Renewables only (19% capacity factor)
Electricity price (c/kWh)	8	6.3	2.1

197 Originally modelled by CSIRO for the Climate Works AusIndustry Energy Transitions Initiative.

3.4 Other requirements

Other critical requirements to enable the deployment and scale-up of CO_2-derived products in the NT include (but are not limited to):

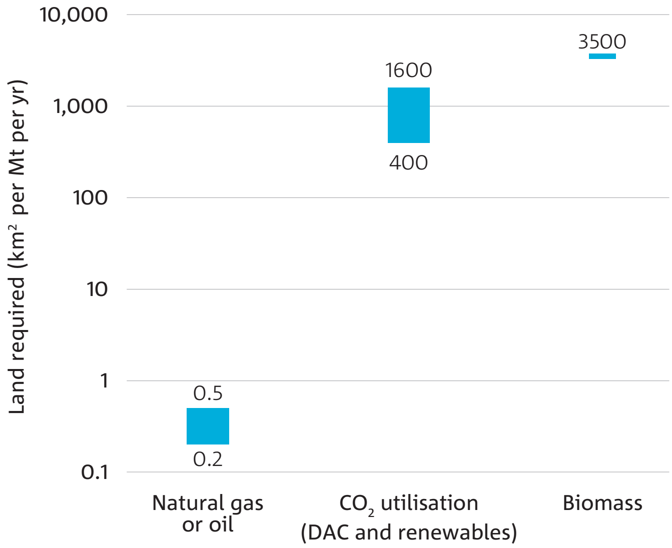
- Land
- Water
- Natural gas
- Export infrastructure

While a detailed exploration of these inputs is beyond the scope of this report, some high-level context and insights related to each of these requirements are included below.

Land

The production of CO_2-derived fuels and chemicals (utilising DAC and renewables) requires significantly more land than those derived from oil or natural gas. However, it is typically less land intensive than biomass-derived products.[198] The National Academies of Sciences, Engineering, and Medicine estimated land-use requirements for every million tonnes per year of synthetic fuel or ethylene production and shows that biomass derived products require greater land mass than CO_2-derived products (as shown in Figure 23). The same analysis suggests that using DAC and CCS to offset the emissions from natural gas or oil-derived products is significantly less land intensive than CO_2 utilisation. Life cycle assessments comparing the impacts of alternative low-carbon manufacturing processes will be critical to optimise environmental and economic outcomes.

Figure 23: Typical land-use footprint for hydrocarbon fuel production[199]



Water

Water is a critical input in the production of all products, as well as hydrogen and electricity, and its availability and proximity to CO_2 utilisation facilities should be considered.[200] Water is also used in many CO_2 capture technologies.[201] CO_2-derived manufacturing processes may use water as a feedstock or in a variety of processes (e.g., dilution, distillation, rinsing, and waste mineralisation). Many of which have specific water quality requirements.[202] For example, high pressure or temperature processes have salt content requirements to manage scale formation, while electrolytic processes may have higher requirements for purity.[203]

The water demands of DAC systems vary significantly (from zero up to 15.2 tonnes of water per tonne of CO_2 captured), as they may consume or co-produce water.[204]

198 NASEM (2022) Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report. The National Academies Press.
199 Adapted from NASEM (2022) Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report. The National Academies Press.
200 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.
201 Meckling J, Biber E (2021) A policy roadmap for negative emissions using direct air capture. Nature Communications.
202 NASEM (2022) Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report. The National Academies Press.
203 NASEM (2022) Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report. The National Academies Press.
204 NASEM (2022) Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report. The National Academies Press.

Renewable hydrogen production is particularly water intensive, and so water sources need to be located with hydrogen production facilities.[205] Globally, it is predicted that water levels required for hydrogen production can be met. IRENA estimated that equivalent to <0.25% of current annual global freshwater consumption will be needed to meet required hydrogen levels by 2050 (409 Mtpa hydrogen), as per the 1.5°C pathway specified in the Paris Agreement.[206] [207] The challenge however will be in ensuring sufficient, accessible water in areas of hydrogen and renewable electricity production, as these tend to be the driest.[208]

Sustainable sources of water are critical to the development of CO_2 utilisation and hydrogen production industries. There is likely to be growing competition for water resources in the NT, particularly fresh and brackish sources, including from the carbon offset market. Recognising this, the NT Government has committed to incorporating the emerging hydrogen industry's demand in its water strategies and plans.[209]

Natural gas

Consumption of natural gas, which can be used to produce electricity and low-emission hydrogen, is predicted to decline as the global economy transitions towards net zero emissions. The speed of this transition, however, is dependent on the economic viability of its replacements (renewable hydrogen and electricity), which in large part will be influenced by energy prices, and the extent to which industry can offset and abate its emissions through CCS and other solutions.

In the long term, there may still be critical roles for natural gas in CO_2 capture and utilisation. As an example, liquid solvent DAC systems require high grade heat (in the order of 900°C) which is typically provided by natural gas.

Natural gas combined with CCS may also be used in combination with energy storage systems to improve the reliability of renewable electricity systems. If the NT does transition away from the extraction and use of natural gas, this may present an opportunity to repurpose infrastructure for the transportation of alternative products such as CO_2-derived fuels (e.g., methane), hydrogen, or CO_2.

Export infrastructure

Export will be critical to enabling scale-up of most of the opportunities discussed in this report, especially methanol, urea and methane. The NT Government is currently developing plans for the MASDP. If the precinct is developed it plans to include marine infrastructure (e.g. import and export jetties), a shipping channel and a module offloading facility. If the five CO_2 utilisation opportunities scale up as described in this report, they could generate up to 131 shiploads of export traffic for the NT.

Table 17: Indicative scale-up of export shipments for each CO_2 utilisation opportunity[210]

APPLICATION	ASSUMED SHIP CAPACITY (t)	EXPORT SHIPMENTS PER YEAR		
		Short term	Medium term	Long term
Methanol	50,000	1	7	20
Jet fuel	80,000	0.1	1.3	3.1
Urea	20,000	0	5	50
Methane	50,000	0	1	7.6
Mineral carbonates	20,000	0	5	50
Total (rounded)	**-**	**1**	**19**	**131**

205 Council of Australian Governments Energy Council (2019) *Australia's National Hydrogen Strategy.* Department of Climate Change, Energy, the Environment and Water

206 IRENA (2022) Geopolitics of the Energy Transformation: The Hydrogen Factor. International Renewable Energy Agency.

207 United Nations (2015) *Paris Agreement.* United Nations Framework Convention on Climate Change.

208 NASEM (2022) Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report. The National Academies Press.

209 NT Government (2020) *Northern Territory Renewable Hydrogen Strategy.* Viewed 1 Feb 2023, https://industry.nt.gov.au/__data/assets/pdf_file/0014/905000/nt-renewable-hydrogen-strategy.pdf.

210 High level calculations. Shipment numbers assumed that 100% of each CO_2-derived product is exported.

4 Enabling CO_2 utilisation in the Northern Territory

CO_2 utilisation is an emerging technology which is unlikely to be cost-competitive with conventional products in the short term. As such, its uptake will primarily be driven by decarbonisation targets in hard-to-abate industries. To enable the deployment of CO_2 utilisation applications in the NT, targeted actions will be necessary to reduce costs, overcome barriers to scale-up, and incentivise production of lower emission products.

The following actions are designed to support a wide range of decarbonisation opportunities and lay the foundations for deployment and scale-up of CO_2 utilisation applications in the NT.

Access to large-scale and affordable CO_2 sources, and renewable hydrogen and electricity

As outlined in Section 3, CO_2 utilisation requires access to captured CO_2, renewable hydrogen, and renewable electricity generation. This is likely to require orders of magnitude increase in the scale of these inputs to produce CO_2-derived products at commercial scale.[211] Balancing the sustainability and affordability input requirements will be critical to attracting customers for CO_2-derived products. Specific enablers include:

- **Investment in large-scale renewable electricity generation**, with a focus on capitalising on the NT's high solar irradiance, coupled with appropriate storage technologies to support firm electricity supply for manufacturing and chemicals processing. Investment should consider where transmission and distribution infrastructure will be required to transport electricity from high solar radiance regions to Darwin and support the stabilisation of the electricity grid for applications requiring firm power.
- **Increasing the supply of sustainable sources of CO_2** is essential to enabling the net zero or negative emission CO_2-derived products. In most cases, this will require investment in maturing and scaling the deployment of DAC technologies to improve the cost and availability. Further work to explore the sustainable and cost-effective sources of carbon (including biological sources of carbon and carbon recycling) will be valuable.
- **Improving the availability and affordability of renewable hydrogen** is also critical for most of the opportunities explored in this project. Hydrogen is a key cost driver for methanol, jet fuel, urea and methane. Encouraging the development of commercial-scale renewable hydrogen production and related infrastructure (i.e., storage and transportation) in the NT will be critical to achieving economies of scale and reducing costs.
- **Undertaking life cycle assessments** will be critical to evaluating and managing the intersection of CO_2 capture, hydrogen, land, water, natural gas, and export infrastructure requirements associated with CO_2 utilisation and competing low-emission manufacturing opportunities.

Strategic planning for the efficient deployment of CO_2 utilisation and related low emissions manufacturing opportunities

Strategic planning to identify synergies and efficiencies between CCUS, renewable hydrogen, low-emissions manufacturing, and other industrial developments in the NT will be essential to optimise benefits and minimise negative impacts. Specific enablers include:

- **Exploring the interaction of potential CO_2 utilisation and storage in the NT** to identify opportunities (such as shared infrastructure) and challenges. This should include exploring the economic and environmental trade-offs between CO_2 utilisation and other low-emission manufacturing opportunities, such as biomass-derived products and CCS. The NTLEH business case begins this work by defining the requirements and benefits of a CCUS hub designed to enable shared use and new market entrants.

211 NASEM (2022) Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report. The National Academies Press.

- **Future-proofing investments in new manufacturing facilities** by identifying and supporting opportunities to integrate CO_2 utilisation technologies and renewable feedstocks as they become more available and affordable. For example, building plants that can incorporate CO_2 and hydrogen from multiple sources and transition from conventional to CO_2 utilisation processes.
- **Identifying opportunities to co-locate feedstock production, CO_2 utilisation and end-user facilities** to improve the economics of CO_2 utilisation projects. For example, co-locating DAC and renewable hydrogen production with a CO_2-derived jet fuel plant near an airport.

Maturing the technologies that support CO_2 utilisation to reduce production costs and enable emerging opportunities

Research, development, and demonstration (RD&D) is critical to increasing the maturity of the range of technologies that support sustainable CO_2 utilisation and emerging utilisation technologies. Specific enablers include:

- **Supporting RD&D into CO_2 utilisation technologies**, including novel technologies with the potential to improve efficiency and economic performance.
- **Identifying opportunities to support CO_2 utilisation RD&D in the NT**. This could target research into emerging CO_2 utilisation applications and enable cost reductions, manufacturing new high-value products and creating valuable IP.
- **Investing in developing and demonstrating DAC and hydrogen electrolysis** technologies to improve the cost competitiveness of sustainable feedstocks.

5 Appendices

Appendix A – Stakeholder consultation list

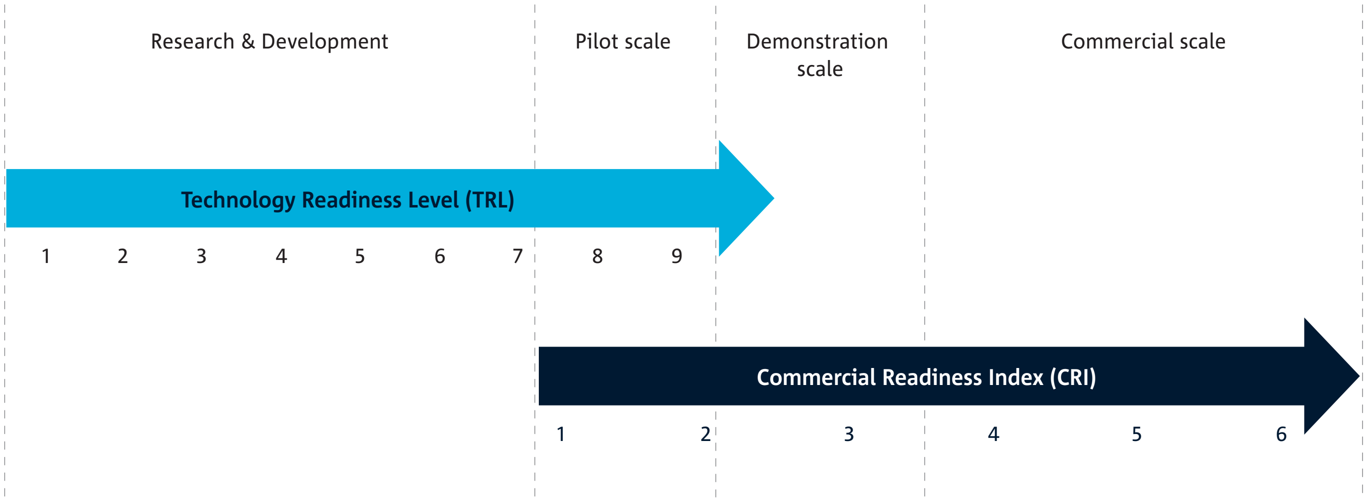
ORGANISATIONS	CSIRO
Adbri	Sandra Occhipinti
BHP Australia	Dia Milani
CO_2 Value Australia	Chaoen Li
Department of Chief Minister and Cabinet (NT)	Yonggang Jin
Department of Climate Change, Energy, the Environment and Water	Jim Austin
Department of Environment and Natural Resources (NT)	Nawshad Haque
Department of Local Government, Housing and Community Development (NT)	Tara Hosseini
ENI	Graeme Puxty
INPEX	Andrew Lenton
Invest NT	Phillip Fawell
MCi Carbon	Doki Yamaguchi
Middle Arm Petrochemicals	Giovanni Spampinato
Santos	Paul Feron
Woodside Energy	Jim Patel
Xodus Group	Hai Yu
	Chris Vernon

Appendix B – Prioritisation of CO_2 utilisation opportunities

Eleven CO_2 utilisation opportunities were assessed against three high-level prioritisation criteria to identify applications with high potential for deployment in the NT (see Table 18 and Table 19). These criteria include the availability of prerequisites (including inputs and relevant industry activity), technology maturity, and market readiness. Technology maturity was assessed according to the Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) framework (as shown in Figure 24). The criteria were developed in consultation with the project's Advisory Group and selected external stakeholders.

Following desktop research and targeted stakeholder consultations, five opportunities were selected for detailed consideration. These opportunities include methanol, jet fuel, urea, methane and mineral carbonates, and are discussed in further detail in Section 2. This appendix includes a high-level analysis of excluded CO_2 utilisation opportunities. Importantly, this prioritisation does not imply that other opportunities do not have potential in the NT. This prioritisation is simply to focus the scope of the report.

Figure 24: Technology Readiness Level and Commercial Readiness Index framework[212]



212 Australian Government Australian Renewable Energy Agency (ARENA) (2014) *Technology Readiness Levels for Renewable Energy Sectors*. Australian Renewable Energy Agency.

Table 18: Prioritisation criteria

RANKING	PREREQUISITES (INPUTS AND INDUSTRY)	CO_2 UTILISATION TECHNOLOGY MATURITY	MARKET READINESS
● High	Prerequisites likely to be met within five years (by 2028)	Commercial scale demonstration or above (CRI 3+)	Strong demand growth and reasonable prospect of NT supply
◐ Medium	Prerequisites could be met within 10 years if other projects scale effectively (by 2033)	Pilot scale demonstration (TRL 7-9 / CRI 1-2)	Strong demand growth but limited prospect of NT supply OR Low demand growth but reasonable prospect of NT supply
○ Low	Prerequisites are not expected to be met within 10 years	Research and development (TRL <6)	Low demand growth and limited prospect of NT supply

Table 19: Summary of CO_2 utilisation opportunity assessment[213]

APPLICATION	PREREQUISITES	MATURITY	MARKET
Methanol	●	●	●
Jet fuel	◐	◐	●
Urea	◐	●	◐
Methane	●	◐	◐
Mineral carbonates	◐	◐	●
Olefins (Polymer precursors)	◐	◐	◐
Ethanol	◐	◐	◐
Food and beverage manufacturing	○	●	◐
High-value algae products	◐	◐	◐
Animal feed proteins	◐	◐	◐
Carbon-based materials	◐	○	◐

213 Highlighted applications were selected for further consideration in this report.

Methanol

Methanol is an alcohol used to synthesise a wide variety of chemicals and fuels, such as plastics, textiles, medical equipment, insulation and paints, and is also used as solvent, fuel and fuel additive.[214] CO_2-derived methanol can be produced using syngas as an intermediary or by direct hydrogenation of CO_2. The duration of CO_2 storage in methanol is dependent on downstream use cases.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	●	• The primary input to CO_2-derived methanol production is hydrogen.[215] Local hydrogen production is expected in the NT from 2027 (see Section 3.2). There will likely be competing offtakes for renewable hydrogen while production increases.
Maturity	●	• Up to CRI 4 (commercial scale) via syngas: First commercial scale production facility launched in late 2022 (Carbon Recycling International's Shunli plant, China), with others in construction (Carbon Recycling International's Sailboat project, China). [216] • Up to TRL 7 (late research and development) via direct hydrogenation. [217]
Market	●	• Australian demand was 4.9 Mtpa in 2020 and is projected to grow at a compound annual growth rate (CAGR) of 4.60% until 2030.[218] • Global demand was 85 Mtpa in 2021 and is projected to grow at a CAGR of 4.24% until 2032. Much of this demand is from the Asia-Pacific (APAC) region.[219] • The renewable methanol market demand is projected to grow faster than the broader market, at a CAGR of 5.8%, reaching a total market value of $5.3 billion by 2027.[220]

214 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

215 Borisut P, Nuchitprasittichai A (2019) Methanol Production via CO_2 Hydrogenation: Sensitivity Analysis and Simulation—Based Optimization. Frontiers in Energy Research.

216 CRI (n.d.) *Projects*. Viewed 17 Jan 2023, https://www.carbonrecycling.is/projects.

217 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

218 ChemAnalyst (2021) *Australia Methanol Market Analysis*. Viewed 23 Jan 2023, https://www.chemanalyst.com/industry-report/australia-methanol-market-201

219 ChemAnalyst (2022) *Methanol Market Analysis*. Viewed 23 Jan 2023, https://www.chemanalyst.com/industry-report/methanol-market-219.

220 Ayushi C (2020) *Renewable Methanol Market*. Viewed 16 Jan 2023, https://www.alliedmarketresearch.com/renewable-methanol-market.

Jet fuel

CO_2-derived jet fuel is a refined, kerosene-based electrofuel that can be produced via the Fischer-Tropsch process. It can be produced using syngas as an intermediary, or via the upgrading of methanol. The abatement potential of CO_2-derived jet fuel is short duration.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	◑	• Both the Fischer Tropsch and methanol processes require hydrogen,[221] with renewable hydrogen plants to come online in the NT in 2027. For this report, a demonstration of methanol production using CO_2 is considered a prerequisite and the potential for methanol production is discussed above. • There is a growing military industry in Darwin, with the United States building a 300 ML capacity storage facility for military jet fuel.
Maturity	◑	• Up to CRI 3 (demonstration scale) via Fischer-Tropsch process: World-first industrial scale demonstration facility planned (Norsk e-Fuel, Norway, to launch in 2024 with 0.16 million bbl or 25 ML per year by 2026).[222] • Up to TRL 9 (pilot scale) via methanol process: Green Fuels (Denmark) aims to produce 0.275 Mtpa of combined SAF, CO_2-derived methanol and renewable hydrogen by 2030;[223] ExxonMobil announced in 2022 that they are developing SAF production capabilities using the methanol-process, expanding on their existing biofuel production capabilities.[224]
Market	●	• The pre-COVID Australian demand for jet fuel was approximately 59 million bbl (9380 ML) per annum.[225] • The global commercial jet fuel market is expected to grow from 2.52 billion bbl (400 BL) in 2019 to over 5.48 billion bbl (871 BL) by 2050. • Global SAF production in 2022 is estimated at 1.89 million bbl (300 ML).[226]

221 Bruce S, Temminghoff M, Hayward J, Palfreyman D, Munnings C, Burke N, Creasey S (2020) *Opportunities for hydrogen in aviation*. CSIRO.

222 Norsk e-Fuel (n.d.) *Our Technology*. Viewed 17 Jan 2023, https://www.norsk-e-fuel.com/technology.

223 Orsted (2022) *Green Fuels for Denmark receives IPCEI status*. Viewed 17 Jan 2023, https://orsted.com/en/media/newsroom/news/2022/07/20220715544411.

224 6 ExxonMobil (2022) *ExxonMobil methanol to jet technology to provide new route for sustainable aviation fuel production*. Viewed 17 Jan 2023, https://www.exxonmobilchemical.com/en/resources/library/library-detail/101116/exxonmobil_sustainable_aviation_fuel_production_en.

225 2019 data. TheGlobalEconomy.com (2021) *Australia: Jet fuel consumption*. Viewed 17 Jan 2023, https://www.theglobaleconomy.com/Australia/jet_fuel_consumption/.

226 IATA (2022) *2022 SAF Production Increases 200% - More Incentives Needed to Reach Net Zero*. Viewed 17 Jan 2023, https://www.iata.org/en/pressroom/2022-releases/2022-12-07-01/.

Urea

Urea is the most widely used synthetic nitrogen fertiliser, accounting for more than 70% of worldwide fertiliser usage. Conventional urea production is a mature application of CO_2 utilisation but a significant contributor to global CO_2 emissions. Commercial-scale production of renewable hydrogen and ammonia can reduce emissions from urea production.[227] The abatement potential of urea is short duration.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	◑	• Low-emission ammonia (produced from low carbon hydrogen and nitrogen derived from air separation) and DAC are required for CO_2-derived urea production. It is not typically considered to be a new CO_2 utilisation opportunity because CO_2 is already captured and used in conventional urea production, however, if low-emission ammonia production reaches scale in the NT, urea production will require a new source of CO_2.[228]
Maturity	●	• Up to CRI 1–2 / TRL 9 (pilot scale): Strike Energy's Project Haber (Australia) is planned, using CCS and natural gas from the Perth basin project.[229] [230] [231] It will be capable of producing 1.4 Mtpa urea.[232] Strike Energy aims to complete engineering studies and agreements in 2023.
Market	◑	• The global market for urea was approximately 166 Mtpa in 2021[233] and is expected to continue growing at 0.8–2.7% (CAGR) until 2027.[234] [235] [236] • Australia imported 2.4 Mtpa of urea in 2021 for use in the agriculture industry.[237] Australia's demand for urea-based fertilisers is forecasted to continue to rise, [238] [239] but this may be disrupted in the long-term by a high global market price and unprecedented weather conditions.[240] • Australia exports a very small amount of urea. The majority is used domestically in the agriculture industry, with global demand for fertilisers expected to continue to grow.[241] This may change in the longer-term, however, as low-emission ammonia reaches scale.[242] • There is potential for conventional ammonia processes coupled with CCS (i.e., blue ammonia) to compete in the short to medium term.

227 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO

228 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

229 Richardson A (2021) Fertiliser Manufacturing in Australia. IBISWorld.

230 Milani D, Kiani A, Haque N, Giddey S, Feron P (2022) *Green pathways for urea synthesis: A review from Australia's perspective*. Sustainable Chemistry for Climate Action. https://doi.org/10.1016/j.scca.2022.100008

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235 Fortune Business Insights (2022) *Urea Market*. Viewed 23 Jan 2023, https://www.fortunebusinessinsights.com/urea-market-106850.

236 IMARC (n.d.) *Urea Market*. Viewed 23 Jan 2023, https://www.imarcgroup.com/urea-market.

237 Grain Central (2022) *Green light for WA plant to shore up Australia's urea supply*. Viewed 18 Jan 2023, https://www.graincentral.com/logistics/green-light-for-wa-plant-to-shore-up-australias-urea-supply/.

238 Cameron A (n.d.) *Agricultural overview: December 2022*. Viewed 18 Jan 2023, https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/agriculture-overview.

239 Mordor Intelligence (n.d.) *Urea Market – Growth, Trends, COVID-19 Impact, and Forecasts (2023 – 2028)*. Viewed 18 Jan 2023, https://www.mordorintelligence.com/industry-reports/urea-market.

240 Fonseca B (2022) *Fertilizer Outlook – Is History Repeating Itself?*. Viewed 18 Jan 2023, https://research.rabobank.com/far/en/documents/894300_Rabobank_Fertilizer-Outlook_Fonseca_Nov2022.pdf.

241 Mordor Intelligence (n.d.) *Urea Market – Growth, Trends, COVID-19 Impact, and Forecasts (2023 – 2028)*. Viewed 18 Jan 2023, https://www.mordorintelligence.com/industry-reports/urea-market.

242 IRENA, Ammonia Energy Association (AEA) (2022) *Innovation Outlook: Renewable Ammonia*. International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn.

Methane

CO_2-derived methane is produced from DAC-sourced CO_2 and renewable hydrogen using the Sabatier reaction. CO_2-derived methane can act as a replacement for natural gas – currently one of Australia's largest exports. The abatement period of CO_2-derived methane is short duration.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	●	• Hydrogen can be reacted with captured CO_2 to produce methane.[243] Local hydrogen production is expected in the NT from 2027 (see Section 3.2). The gas processing expertise and LNG export infrastructure present in the NT can support this opportunity.
Maturity	◑	• Up to CRI 1–2 / TRL 9 (pilot scale): INPEX and Osaka Gas (Japan) will begin operating the largest CO_2-methanation facility in 2025, expected to generate 0.13 PJ/yr.[244]
Market	◑	• The global market for natural gas is projected to grow at 6.9% (CAGR) from 2023 to 2026.[245] However, in the context of the NT's substantial LNG industry, market demand is expected to be met mainly through existing natural gas production (likely coupled with CCS) for the foreseeable future. • Australia exported over 4,500 PJ (83 Mt) of LNG in 2021–22, making natural gas one of the nation's largest exports (worth $70 billion in 2021–22).[246] The NT is responsible for approximately 15% of Australia's LNG exports.[247] • India, Indonesia, Bangladesh, Thailand, Malaysia, Vietnam, and the Philippines are expected to grow their LNG demand from 167.3 PJ (40 Mt) in 2020 to 1066.9 PJ (255 Mt) in 2050.[248] • Combined LNG demand from China, Korea and Taiwan, with whom Australia has established trade links, is expected to grow from 836.8 PJ (200 Mt) in 2020 to 1016.7 PJ (243 Mt) in 2050.[249] • Some countries (e.g., Japan) have identified synthesised methane as part of their decarbonisation strategy.[250] [251]

243 Becker WL, Penev M, Braun RJ (2019) Production of Synthetic Natural Gas From Carbon Dioxide and Renewably Generated Hydrogen: A Techno-Economic Analysis of a Power-to-Gas Strategy. Journal of Energy Resources Technology.

244 Converted from 400 Nm3/hr, using an energy density of 38 MJ/Nm3 methane. INPEX, Osaka Gas (2021) Osaka Gas to Commence Technical Development Business on CO_2 Emissions Reduction and Practical Application of Effective CO_2 Use Through One of World's Largest Methanation Operations. Viewed 23 Jan 2023, https://www.inpex.co.jp/english/news/assets/pdf/20211015.pdf.

245 The Business Research Company (2023) *Global Natural Gas Market.* Viewed 23 Jan 2023, https://www.thebusinessresearchcompany.com/report/natural-gas-global-market-report.

246 Australian Government Department of Industry, Science and Resources (2022) *Resources and Energy Quarterly – September 2022*. Viewed 23 Jan 2023, https://www.industry.gov.au/sites/default/files/minisite/static/ba3c15bd-3747-4346-a328-6b5a43672abf/resources-and-energy-quarterlyseptember-2022/documents/Resources-and-Energy-Quarterly-September-2022-Gas.pdf.

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248 Australian Government DISR (2022) *Global Resources Strategy Commodity Report: Liquefied Natural Gas*. Viewed 23 Jan 2023, https://www.industry.gov.au/sites/default/files/2022-09/grs-commodity-report-lng.pdf.

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250 NT Government Department of Treasury and Finance (n.d.) *Major trading partners – financial year results*. Viewed 23 Jan 2023, https://nteconomy.nt.gov.au/international-trade/financial-year-results.

251 Agency of Natural Resources and Energy (2021) *Outline of Strategic Energy Plan*. Viewed 23 Jan 2023, https://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/6th_outline.pdf.

Mineral carbonates

Aggregates include a broad range of raw materials (e.g., crushed stone and sand). These are typically sourced from mines and quarries.[252] As an alternative to existing aggregate production, mineral carbonation can produce bulk products for concrete and building materials. The abatement potential of mineral carbonation is long duration CO_2 storage.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	◑	• The availability of suitable minerals for mineral carbonation in the NT has not been explored. The suitability of mine wastes will depend on various factors, including particle size, reactivity, and proximity to CO_2. High-level analysis suggests there are unlikely to be suitable mine wastes in the NT at present. Mafic/ultramafic rock formations are present in the NT, however the scale and suitability for carbonation require additional analysis. • The NT's growing number of mining projects could consider suitability for CO_2-derived mineral carbonation as a complementary revenue stream. • Sodium in waste from bauxite processed via the Bayer process is an area of growing interest. The bauxite refinery at Rio Tinto's Gove operations is currently closed, with the mine site planned to cease operations in 2030.[253] Should this change, CO_2 may be used to treat sodium-based waste from refining processes.
Maturity	◑	• Up to CRI 2 / TRL 8 (pilot scale) for carbonated aggregates:[254] MCi (Australia) and CarbMin (Canada) have developed technologies for treating minerals, tailings and other industrial waste.[255] [256]
Market	●	• The concrete manufacturing industry in Australia is forecast to grow at a CAGR of 1.7% until 2026.[257] This is lower than the global concrete industry's CAGR of 4.6% from 2021 to 2030.[258] • Ready-mixed concrete is one of the NT's largest manufacturing exports.[259] However, the NT's single cement facility (one of three inputs into concrete) has recently been placed in care and maintenance mode.

252 Imerys (n.d.) *Calcium carbonate*. Viewed 23 Jan 2023, https://www.imerys.com/minerals/calcium-carbonate.

253 RioTinto (n.d.) *Gove*. Viewed 23 Jan 2023, https://www.riotinto.com/en/operations/australia/gove.

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255 MCi Carbon (n.d.) *Carbon Platform*. Viewed 16 Jan 2023, https://www.mineralcarbonation.com/carbon-platform.

256 CarbMin Lab (n.d.) *About*. Viewed 23 Jan 2023, https://carbmin.ca/about/.

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258 Digvijay P (2021) *Concrete Market*. Viewed 23 Jan 2023, https://www.alliedmarketresearch.com/concrete-market-A12420.

259 Northern Territory Government Department of Treasury and Finance (2022) *Northern Territory Economy: Mining and manufacturing*. Viewed 16 Jan 2023, https://nteconomy.nt.gov.au/industry-analysis/mining-and-manufacturing.

Olefins (polymer precursors)

Olefins are unsaturated compounds that feature at least one double bond between carbon atoms. Some examples include propylene, ethylene and butylene, which are typically used as raw materials to produce polymers (i.e., plastics). The abatement potential of olefins is long duration storage of CO_2.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites		• The primary input to olefin production is either methanol or syngas. The demonstration of methanol production using CO_2 is a prerequisite and the potential for methanol production is discussed above. Local downstream manufacturing is limited, with only small-scale plastics manufacturing identified in the NT.[260] • Australia's polymer production has been declining in favour of imports, with 60% of plastics imported in 2018–19.[261]
Maturity		• Maturity varies across use cases. • Up to CRI 2 / TRL 9 (pilot scale) for polyol plastic: Covestro (Germany) are producing end-user products such as mattresses from a polyol plastic, the basis of polyurethane.[262] • Up to TRL 5 (lab scale) for ethylene: LanzaTech (New Zealand) announced in October 2022 that they had engineered specialised biocatalysts to directly produce ethylene from CO_2.[263]
Market		• The global olefins market is anticipated to grow at a CAGR of 4.0% from 2022–27, reaching US$322.12 billion by 2027.[264] • Olefins produced from CO_2 are predicted to mature as an industry and achieve cost competitivity from 2050 onwards.[265]

260 Discover Darwin (n.d.) *Qingdao Tianfule* Plastic. Viewed 23 Jan 2023, https://discover.darwin.nt.gov.au/international-directory/qingdao-tianfule-plastic.

261 Australian Government Department of Agriculture, Water and the Environment (DAWE) (2021) *National Plastics Plan 2021*. DAWE.

262 Cormier Z (n.d.) *Turning carbon emissions into plastic*. Viewed 23 Jan 2023, https://www.bbcearth.com/blog/?article=turning-carbon-emissions-into-plastic.

263 LanzeTech (2022) *LanzaTech Produces Ethylene from CO_2, Changing the Way We Make Products Today*. Viewed 23 Jan 2023, https://lanzatech.com/lanzatech-produces-ethylene-from-co2-changing-the-way-we-make-products-today/.

264 Market Data Forecast (2022) *Olefins Market*. Viewed 23 Jan 2023, https://www.marketdataforecast.com/market-reports/olefins-market.

265 Ministry of Economy, Trade and Industry (METI) (2019) *Roadmap for Carbon Recycling Technologies*. METI.

Ethanol

Ethanol is a primary liquid alcohol that is commonly used as a transport fuel additive or in production of pharmaceuticals, detergents, disinfectants, polymers, polishes and cosmetics. Current production of ethanol is from cellulose feedstock (fermentation of sugars) or hydration of ethylene (derived from fossil-fuels). Ethanol's abatement potential is short duration storage of CO_2.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	◑	• Direct conversion of CO_2 requires hydrogenation with hydrogen, producing both ethanol and ethylene.[266] Local hydrogen production is expected in the NT from 2027 (see Section 3.2). There will likely be competing offtakes for renewable hydrogen while production increases. • Chemical manufacturing in the NT is small scale.
Maturity	◑	• Up to CRI 2 (pilot scale) for direct conversion of CO_2:[267] Air Company (USA and Canada) has launched two commercial pilot plants utilising point source CO_2 for direct conversion into ethanol. [268] • Up to CRI 2 (pilot scale) via syngas: Woodside (Australia) has launched a pilot project to produce ethanol from syngas with point source CO_2.[269] [270]
Market	◑	• As fossil-fuel production decreases and cellulose feedstock faces increasing pressure from the agricultural sector, the demand for ethanol synthesis from CO_2 may grow.[271] • Ethanol production in Australia has recently increased to support hand sanitiser production. The use of ethanol for fuel in Australia is limited. • Manildra Milling Pty Ltd supplies 60% of Australia's ethanol market, using wheat by-products to produce ethanol. Their current capacity is 300 ML,[272] none of which is made in the NT.[273]

266 Borisut P, Nuchitprasittichai A (2019) Methanol Production via CO_2 Hydrogenation: Sensitivity Analysis and Simulation—Based Optimization. Frontiers in Energy Research.

267 Pace G, Sheehan SW (2021) Scaling CO_2 Capture With Downstream Flow CO_2 Conversion to Ethanol. Frontiers in Climate.

268 Pace G, Sheehan SW (2021) Scaling CO_2 Capture With Downstream Flow CO_2 Conversion to Ethanol. Frontiers in Climate.

269 Battersby A (2022) *Woodside eyes carbon capture and utilisation pilot*. Viewed 23 Jan 2023, https://www.upstreamonline.com/energy-transition/woodside-eyes-carbon-capture-and-utilisation-pilot/2-1-1215918.

270 ReCarbon (2022) *ReCarbon developing innovative Carbon to Products project with Woodside Energy*. Viewed 23 Jan 2023, https://www.recarboninc.com/news/carbon-to-products-project.

271 Wang Y, Wang K, Zhang B, Peng X, Gao X, Yang G, Hu H, Wu M, Tsubaki N (2021) *Direct Conversion of CO_2 to Ethanol Boosted by Intimacy-Sensitive Multifunctional Catalysts*. ACS Catalysis.

272 Kelly A (2023) *Ethanol Fuel Production in Australia.* Viewed 9 Feb 2023, https://my.ibisworld.com/au/en/industry-specialized/od5088/major-companies.

273 Manildra Group (n.d.) *Our Facilities*. Viewed 23 Jan 2023, https://www.manildra.com.au/manildra-facilities/.

Food and beverage manufacturing

The food and beverage industry offers an opportunity for the early demonstration of DAC and adoption of new point source capture technologies, as CO_2 is used directly rather than converted into new products.[274] Typical use cases include beverage carbonation, decaffeination, refrigeration and food processing, each of which offer short duration CO_2 storage.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	○	• There is limited or small-scale food and beverage production in the NT, with local agriculture focused on products that do not require CO_2 processing (such as cotton, sorghum, and soybean).[275 276]
Maturity	●	• Over CRI 4 (commercial scale)[277]: Coca-Cola HBC and Climeworks (Switzerland) launched DAC if CO_2 for beverage carbonation in 2018, aiming to reduce cost per tonne CO_2 significantly by 2030 (~$780/t to ~$130/t).[278]
Market	◑	• Over 65% of the Australian CO_2 market is used for food processing and beverage carbonation, however the volume of CO_2 used remains small comparative to emerging applications[279] • The annual growth in direct use applications within Australia is expected to be 1.4% to 2025,[280] however local demand and production is unlikely to grow significantly given the NT's population size and the low likelihood of direct use of CO_2 as an export opportunity.

274 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

275 Northern Territory Government (2022) *Agribusiness*. Viewed 23 Jan 2023, https://invest.nt.gov.au/infrastructure-and-key-sectors/key-sectors/agribusiness.

276 Dun & Bradstreet (n.d.) *Beverage Manufacturing Companies In Northern Territory, Australia*. Viewed 23 Jan 2023, https://www.dnb.com/business-directory/company-information.beverage_manufacturing.au.northern_territory.html.

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278 Jasi A (2018) *Climeworks pioneering air-captured CO_2 for drinks carbonation*. Viewed 23 Jan 2023, https://www.thechemicalengineer.com/news/climeworks-pioneering-air-captured-co2-for-drinks-carbonation/.

279 IEA (2019) *Putting CO_2 to Use*. International Energy Agency.

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High-value algae products

The emergence of synthetic biological conversion pathways presents an opportunity for high-value, niche products, such as algae. High-value algae are produced using microorganisms to convert CO_2 and creating products such as bio-oils, nutraceuticals, flavours, pharmaceuticals and feed supplements. High-value algae products offer short duration CO_2 storage.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	◑	• The main requirements for algae production are microalgae strains that can efficiently uptake CO_2 via photosynthesis[281] and produce high concentrations of the target product. Scaled production requires large areas of land (can be non-arable), so will not compete with the agricultural sector, but could constrain deployment at scale in the NT.[282]
Maturity	◑	• Up to CRI 2 / TRL 9 (pilot scale)[283]: Eni (Italy) has developed a pilot plant to produce 500 tonnes of biomass (namely bio-oils) annually[284], while Provectus Algae and BondiBio (Australia) are in design and development of commercial facilities for high-value algae products across aquaculture feed, nutraceuticals, pharmaceuticals, agriculture, cosmetics, flavours, fragrances, and other speciality chemical industries.[285] [286]
Market	◑	• There is growing demand for some value-added products that could be produced via algae (e.g., intracellular compounds and metabolites). However, global markets are likely to be small and use case specific.[287] • The global market for high-value algae products is expected to grow at a CAGR of 6.3% between 2021 and 2026.[288]

281 Office of Energy Efficiency & Renewable Energy (2017) *Algae Cultivation for Carbon Capture and Utilization Workshop Summary Report*. U.S. Department of Energy.

282 Office of Energy Efficiency & Renewable Energy (2017) *Algae Cultivation for Carbon Capture and Utilization Workshop Summary Report*. U.S. Department of Energy.

283 Pace G, Sheehan SW (2021) Scaling CO_2 Capture With Downstream Flow CO_2 Conversion to Ethanol. Frontiers in Climate.

284 Eni (n.d.) *Biofixation of CO_2: bio-oil and valuable products from microalgae*. Viewed 23 Jan 2023, https://www.eni.com/en-IT/operations/carbon-dioxide-biofixation.html.

285 CSIRO Futures (2022) On-farm applications of advanced bioengineering. CSIRO, Canberra.

286 Bondi Bio (n.d.) *Carbon Capture & Utilization.* Viewed 23 Jan 2023, https://www.bondi.bio/carbon-capture-utilization.

287 Singh J, Dhar DW (2019) Overview of Carbon Capture Technology: Microalgal Biorefinery Concept and State-of-the-Art. Frontiers in Marine Science.

288 Markets and Markets (2021) *Algae Products Market.* Viewed 9 Feb 2023, https://www.marketsandmarkets.com/Market-Reports/algae-product-market-250538721.html.

Animal feed proteins

Growing population and income, urbanisation, and lifestyle and food preference changes have led to a 'livestock revolution', for which alternative protein sources for animal feed are being demanded.[289] Today's animal feed (or aquaculture and poultry feed) proteins are many and varied; however include sources such as legumes, soybeans and other oil meal crops. Alongside replacement, animal feed protein can reduce the use of arable land and fertiliser.[290] Animal feed proteins offer short duration CO_2 storage.

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	◑	• Animal feed proteins produced via bacterial fermentation pathways are being explored. This requires the cultivation of microorganisms for efficient and selective conversion of CO_2 and hydrogen to targeted proteins.[291]
Maturity	◑	• The production of food from CO_2 is at an early stage of development. Microorganism CO_2 utilisation pathways are currently not cost-effective due to high downstream processing costs, and scale-up constraints.[292] • Up to CRI 2 / TRL 9 (pilot scale):[293] Deep Branch (UK) produces single-cell proteins for fish and poultry feed through the gas fermentation of hydrogen and CO_2;[294] Air Protein (US) creates proteins from hydrogen and CO_2, which is sold as flour;[295] Solar Foods (Finland) produces edible single-cell proteins through the conversion of hydrogen, oxygen and CO_2 (consumed from the atmosphere by microorganisms).[296]
Market	◑	• The global market size of animal feed products (global animal feed, global feed additives and global animal feed ingredients) was $603.8 billion in 2021, with a CAGR between 4.4% and 5.5% until 2026.[297] Australia's market is expected to grow at a CAGR of 3.28% reaching a market size of $7 billion in 2025.[298] However, there is limited intensive farmed aquaculture and no sizeable commercial poultry farms in the NT.[299]

289 Food and Agriculture Organization (FAO) *Protein Sources for the Animal Feed Industry.* FAO.

290 Aiking H (2011) Future protein supply, Trends in Food Science & Technology, Viewed 9 Feb 2023, https://doi.org/10.1016/j.tifs.2010.04.005.

291 Office of Energy Efficiency & Renewable Energy (2017) *Algae Cultivation for Carbon Capture and Utilization Workshop Summary Report*. U.S. Department of Energy.

292 Global CO_2 Initiative, CO_2 Sciences (2019) *Global Roadmap for Implementing CO2 Utilization*. Global CO_2 Initiative

293 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

294 Deep Branch (2022) *Deep Branch and BioMar agree strategic partnership to enhance the aquaculture industry*. Viewed 23 Jan 2023, https://deepbranch.com/2022/05/03/deep-branch-and-biomar-agree-strategic-partnership-to-enhance-the-aquaculture-industry/

295 Air Protein (n.d.) *Science.* Viewed 23 Jan 2023, https://www.airprotein.com/science.

296 Solein (n.d.) *What is Solein?.* Viewed 23 Jan 2023, https://www.solein.com/what-is-solein.

297 Technavio (2022) *Animal Feed Market*. Viewed 23 Jan 2023, https://www.technavio.com/report/animal-feed-market-industry-analysis; Technavio (2022) *Animal Feed Additives Market*. Viewed 23 Jan 2023, https://www.technavio.com/report/animal-feed-additives-market-industry-analysis; Frost & Sullivan (2021) *Global Animal Feed Ingredient Market Powered by Antibiotic Alternatives and Vertical Integration.* Viewed 23 Jan 2023, https://store.frost.com/global-animal-feed-ingredient-market-powered-by-antibiotic-alternatives-and-vertical-integration.html.

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299 Northern Territory Government (n.d.) *Keeping poultry and pigeons.* Viewed 23 Jan 2023, https://nt.gov.au/industry/agriculture/livestock/keeping-poultry-and-pigeons.

Carbon-based materials

Carbon-based materials (such as carbon black, carbon fibre, graphite, graphene, carbon nanotubes and nanodiamonds) are in the early stages of technology maturity. They broadly fit into one of two categories: use of CO_2 as an input into existing manufacturing processes (e.g., carbon black, carbon fibre and graphite) or use of CO_2-based methods to enable a new process or synthesise a currently difficult-to-make product.[300]

CRITERIA	ASSESSMENT	DESCRIPTION
Prerequisites	◑	• While the inputs vary across use case, the NT does not have a local advanced manufacturing industry that can support most use applications.
Maturity	○	• Maturity varies across use cases; however, most applications are low TRL. • Up to TRL 7 (lab scale) for carbon black: Karlsruhe Institute of Technology and Climeworks (Germany) are building a test facility for active reduction of atmospheric CO_2 over three years.[301]
Market	◑	• The markets for carbon-based materials vary. However, most products are high-value which could offset the costs associated with low maturity CO_2 utilisation.[302] For example, the carbon fibre market is expected to grow from \$3.2 billion in 2019 to \$9.2 billion by 2029.[303]

300 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

301 Climeworks (2020) *Turning CO_2 into a high-tech resource: Carbon black*. Viewed 10 February, 2023, https://climeworks.com/news/turning-co2-to-a-high-tech-resource-carbon-black.

302 Ministry of Economy, Trade and Industry (METI) (2019) *Roadmap for Carbon Recycling Technologies*. METI.

303 Markets and Markets (2022) *Carbon Fiber Market*. Viewed 23 Jan 2023, https://www.marketsandmarkets.com/Market-Reports/carbon-fiber-396.html.

Appendix C – Techno-economic analysis assumptions

Overarching assumptions

The tables below provide a summary of the key financial and model parameters used for the analysis of all CO_2 utilisation applications. It is assumed that each project would run for 30 years, and that these projects were funded by 100% debt financing.

Cost assumptions used in this report were informed by desktop analysis and project consultations undertaken for the CSIRO CO_2 Utilisation Roadmap, CSIRO National Hydrogen Roadmap and CSIRO Opportunities for Hydrogen in Commercial Aviation report. They are designed to reflect estimates of the costs that could be achieved for different scale projects at the time of writing. All assumptions are in real terms for 2022, and these costs can be expected to reduce as the industry grows in scale.

The base case and best case CO_2 utilisation scales were set at 1,000 t/day and 5,000t/day, respectively. Further information on the assumptions derived from the CO_2 Utilisation Roadmap can be found in Appendix C of the Roadmap.[304]

Technology assumptions

To model levelised cost of production, specific technologies were selected based on commercial maturity, process efficiency, and end-product market. Further information on the technology selection process is available in Appendix C of CSIRO's CO_2 Utilisation Roadmap.[305]

CO_2 UTILISATION OPPORTUNITY	MODELLED TECHNOLOGY PATHWAY
Methanol	Direct hydrogenation of CO_2 over a catalyst, with an H_2:CO_2 ratio of 3:1.
Jet Fuel	Methanol to olefin pathway via the Mobil olefins-to-gasoline/distillate process.
Urea	Ammonia produced via the Haber-Bosch process is reacted with CO_2.
Methane	Hydrogenation of CO_2 by hydrogen, with an H_2:CO_2 ratio of 4:1. Conversion efficiency of 99%.
Mineral carbonates	Mined raw serpentinite is transported to cement plant, with the cost of mining included.

304 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

Financial assumptions

VARIABLES	UNIT	BASE CASE	BEST CASE	REFERENCE
Discount rate	%	6		Assumption.
Interest rate (real)	%	6		Assumption. Kept stable and consistent with discount rate.
Debt financing ratio	%	100		Consistent with CSIRO CO_2 Utilisation Roadmap[306]
Length of loan	Years	20		Consistent with CSIRO CO_2 Utilisation Roadmap[307]
Plant life	Years	30		Consistent with CSIRO CO_2 Utilisation Roadmap[308]
AUD: USD Exchange Rate	USD	0.78		Based on the 20-year average from Reserve Bank of Australia.
AUD: EUR Exchange Rate	EUR	0.64		Based on the 20-year average from Reserve Bank of Australia.
AUD: CNY Exchange Rate	CNY	5.56		Based on the 20-year average from Reserve Bank of Australia.

Modelling input assumptions

VARIABLES	UNITS	BASE	BEST	SOURCE
CO_2 utilised (Scale of operations)	t/d	1,000	5,000	CSIRO CO_2 Utilisation Roadmap[309]
Cost of captured CO_2: High partial pressure industrial emissions	$/t	86	46	Aligned to base (8 c/kWh) and best (6.3 c/kWh) case electricity price. These costs exclude compression and transport.
Cost of captured CO_2: DAC	$/t	490	200	Aligned to base (8 c/kWh) and best (6.3 c/kWh) case electricity price. The model uses high-temperature DAC, where CO_2 absorption occurs with potassium hydroxide aqueous solution, and these costs exclude compression and transport. Additional information on DAC technologies can be found in the CSIRO CO_2 Utilisation Roadmap.[310]
Electricity price	¢/kWh	8	6.3	Base case: NT-specific price assumptions provided by CSIRO Energy aligned with current grid electricity prices. Best case: Long-term Darwin-specific electricity price projections conducted by CSIRO Energy from Climate Works AusIndustry Energy Transitions Initiative. Combined solar + wind with storage: 90% capacity factor.
Hydrogen price	$/kg	5.47	2 .68	Base case: Cost of hydrogen produced using PEM electrolysis and base case electricity price assumptions (8 c/kW and 90% capacity factor) Best case: Based on off-grid renewables with a 19% capacity factor (2.1c/kWh)
Electricity requirements for hydrogen production	Kwh/kg (H_2)	45		CSIRO CO_2 Utilisation Roadmap[311]

305 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.
306 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.
307 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.
308 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.
309 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.
310 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.
311 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

Historical sale price range for cost comparisons

VARIABLES	UNITS	LOWER BOUND	MIDPOINT	UPPER BOUND	SOURCE
Conventional methanol sale price	$/t	280	495	709	Lower bound: Lowest market price over a 5-year period, ending December 2019[312] Upper bound: Highest market price over a 5-year period, ending December 2019[313]
Conventional jet fuel (A1) sale price	$/bbl	48	85	123	Lower bound: Lowest market price over a 5-year period, ending December 2020[314] Upper bound: Highest market price over a 5-year period, ending December 2020[315]
Conventional urea sale price	$/t	250	383	515	Lower & upper bound: Typical market prices between Jan 2015 and Jan 2020. Peaks have been excluded [316]
Conventional natural gas sale price	$/GJ	4.66	7.38	10.10	Lower & upper bound: Based on average Australian Energy Regulator Wholesale gas market prices between FY2015–16 and FY19–20[317]
Conventional $MgCO_3$ sale price	$/t	100	125	150	Lower & upper bound: CSIRO CO_2 Utilisation Roadmap[318]
Conventional SiO_2 sale price	$/t	30	45	60	Lower & upper bound: CSIRO CO_2 Utilisation Roadmap[319]

312 Trading Economics (2022) *Methanol*. Viewed 24 Jan 2023, https://tradingeconomics.com/commodity/methanol.

313 Trading Economics (2022) *Methanol*. Viewed 24 Jan 2023, https://tradingeconomics.com/commodity/methanol.

314 IATA (2022) *Jet Fuel Price Monitor*. Viewed 24 Jan 2023, https://www.iata.org/en/publications/economics/fuel-monitor/.

315 IATA (2022) *Jet Fuel Price Monitor*. Viewed 24 Jan 2023, https://www.iata.org/en/publications/economics/fuel-monitor/.

316 Fertilizer Australia (2021) *The Australian Fertilizer Industry Review 2021*. Viewed 24 Jan 2023, https://fertilizer.org.au/Portals/0/Documents/Publications/Information%20and%20Education%20Paper%20-%20The%20Australian%20Fertilizer%20Industry%20review%202021.pdf?ver=2021-11-29-005345-453.

317 Australian Energy Regulator (2022) *Gas market prices*. Viewed 23 Jan 2023, https://www.aer.gov.au/wholesale-markets/wholesale-statistics/gas-market-prices.

318 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

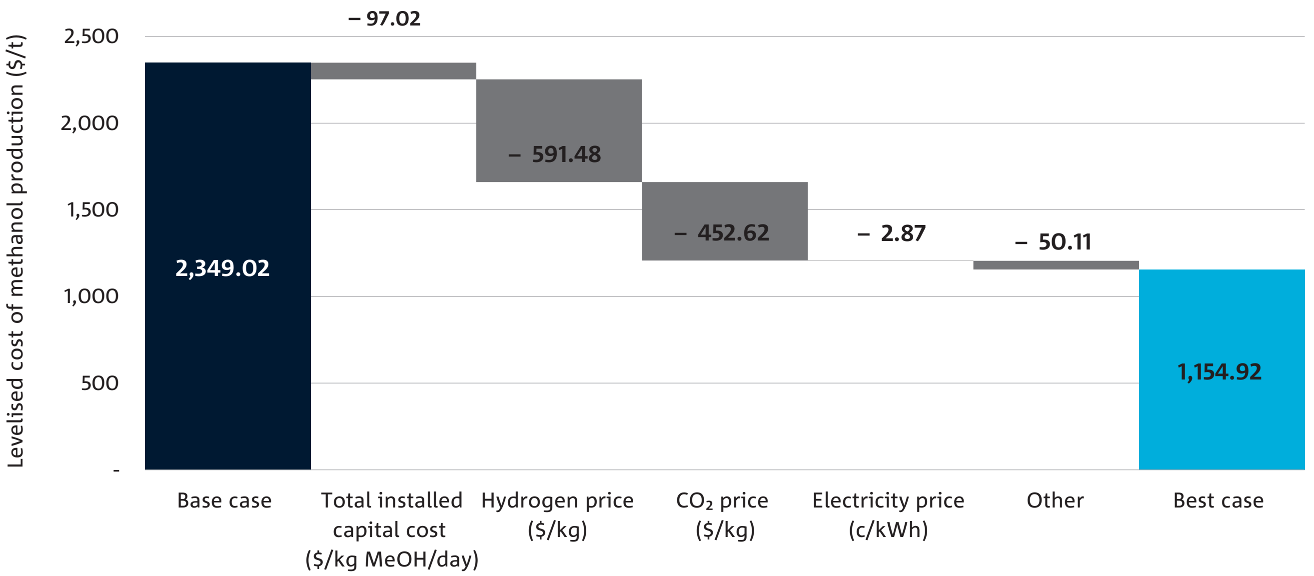
319 Srinivasan V, Temminghoff M, Charnock S, Moisi A, Palfreyman D, Patel J, Hornung C, Hortle A (2021) *CO_2 Utilisation Roadmap*. CSIRO.

Appendix D – Techno-economic analysis results

Waterfall charts have been developed to show the key cost drivers and potential for reduction between the base and best case scenarios. This analysis assumes the utilisation of DAC-sourced CO_2 which has the largest potential for a price reduction and the greatest emissions abatement impact. The 'Other' category on the waterfall charts captures the remaining factors that change from the base to the best cases. These variations can include the capacity factor (or utilisation), the size of the plant, and various financial factors.

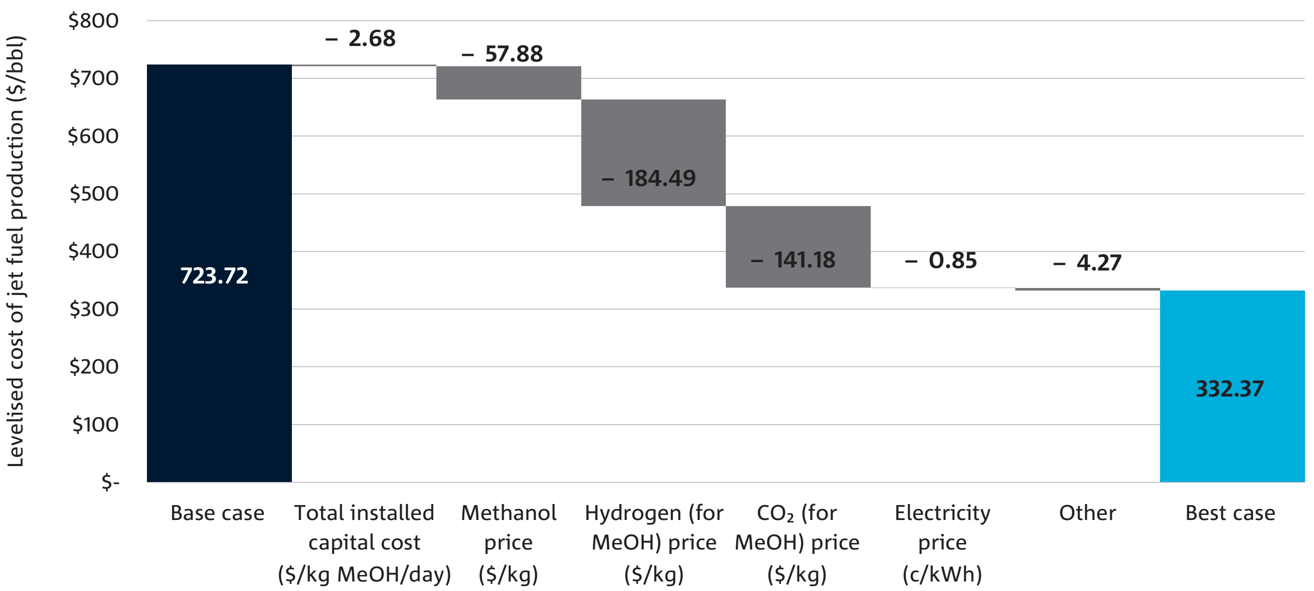
Methanol

Figure 25: Waterfall chart showing cost reduction drivers between the base and best case for methanol produced from renewable hydrogen and DAC-sourced CO_2



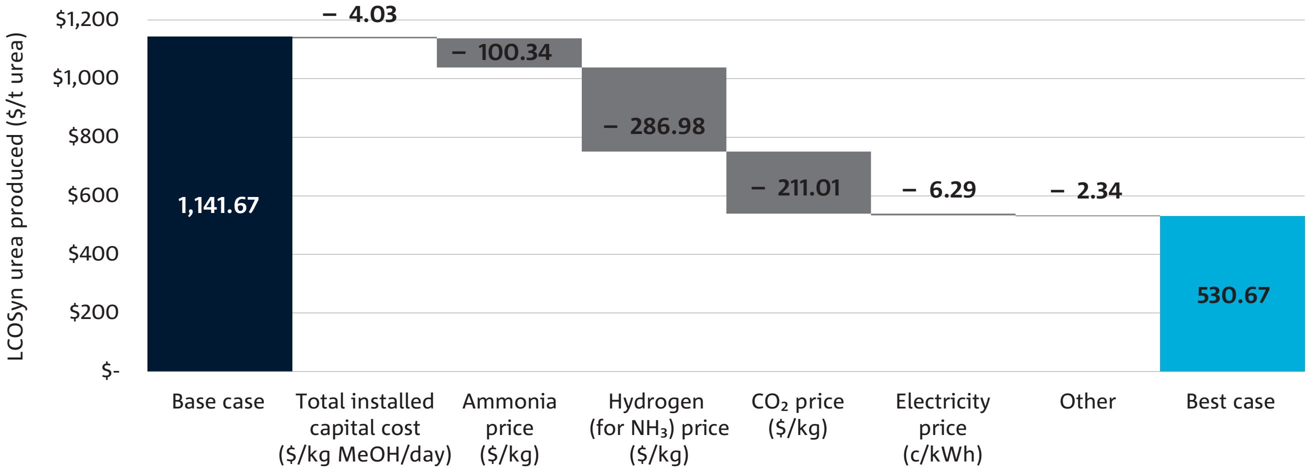
Jet fuel

Figure 26: Waterfall chart showing cost reduction drivers between the base and best case for jet fuel produced from renewable hydrogen and DAC-sourced CO_2



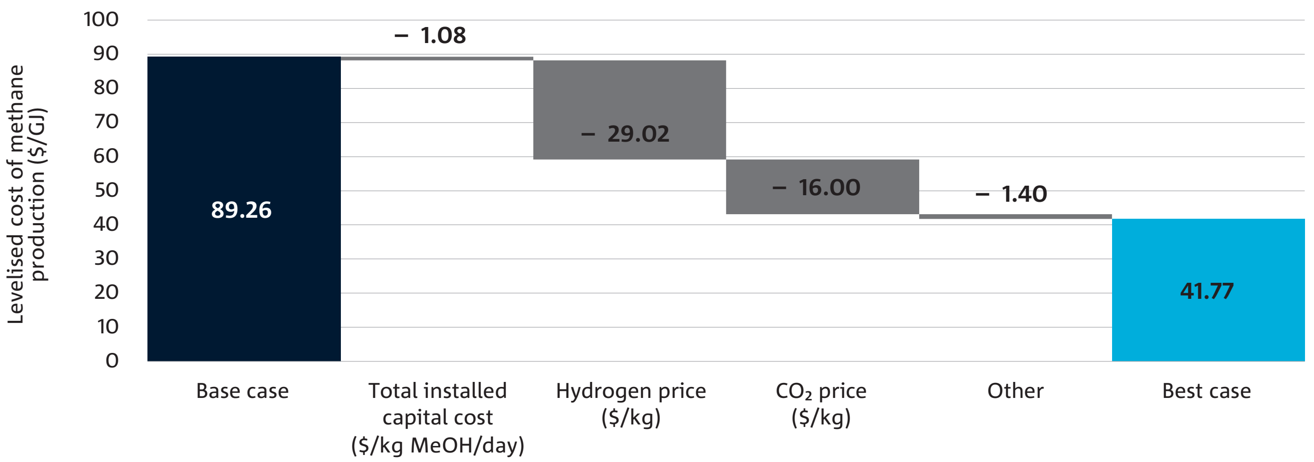
Urea

Figure 27: Waterfall chart showing cost reduction drivers between the base and best case for urea produced from renewable hydrogen and DAC-sourced CO_2



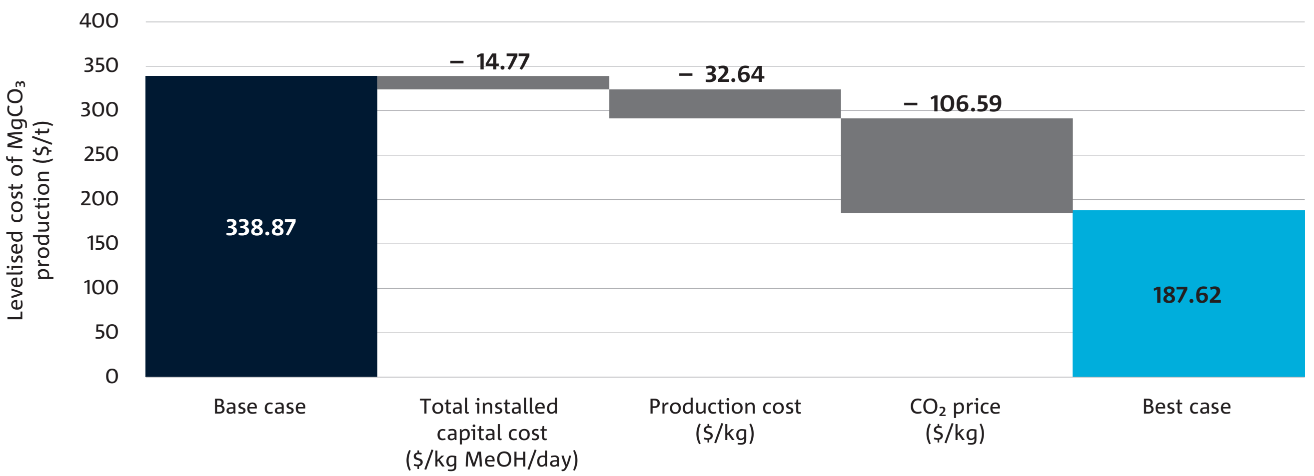
Methane

Figure 28: Waterfall chart showing cost reduction drivers between the base and best case for methane produced from renewable hydrogen and DAC-sourced CO_2



Mineral carbonates

Figure 29: Waterfall chart showing cost reduction drivers between the base and best case for magnesium carbonate produced from DAC-sourced CO_2



Appendix E – Glossary

TERM	DESCRIPTION
Aggregates	Granular filling materials such as sand, ground rock and gravel comprise 60–80% of a concrete's volume.
APAC	Asia-Pacific.
Bbl	Barrels are a common measurement for jet fuel that equals 42 gallons or 159 litres.
Biofuel	Liquid, solid, or gaseous fuel is produced by the conversion of biomass such as bioethanol from sugar cane or corn, charcoal or woodchips, and biogas from anaerobic decomposition of wastes.[320]
Carbon price	A price on carbon that is emitted.
CAGR	Compound annual growth rate: the annualised average growth rate of an investment over a specified period longer than one year.
CCS	Carbon capture and storage: CO_2 is captured from emissions sources or the atmosphere and stored permanently in underground geological formations.
CCUS	Carbon capture, utilisation, and storage: an umbrella term including CCS, CO_2 capture and CO_2 utilisation.
CO_2	Carbon dioxide: a greenhouse gas released through human activities.
Commercial scale project	Large-scale production of a commodity may involve large-sized firms, huge investments and a large and expanding market.
CRI	Commercial readiness index.
DAC	Direct air capture: Technologies that extract CO_2 from the atmosphere.
Demonstration scale project	A project designed to demonstrate the performance of technology at a small scale in its intended environment and conditions.
Fischer-Tropsch (FT) process	A collection of chemical reactions that converts a mixture of carbon monoxide and hydrogen, known as syngas, into liquid hydrocarbons.[321]
GJ	Gigajoule (10^9 joules).
GW	Gigawatt (10^9 watts).
GWh	Gigawatt-hour (10^9 watt-hours).
Haber-Bosch process	The method of directly synthesising ammonia from hydrogen and nitrogen.[322]
Hard-to-abate industries	Heavy industry (cement, steel, chemicals and aluminium) and heavy-duty transport (shipping, trucking and aviation) where emissions are difficult or unavoidable with efficiency improvements and implementation of renewable technology alone.
Hybrid production	The approach of producing a target chemical using a combination of both conventional (fossil fuel-derived) and CO_2-derived methods.
Hydrogen	Hydrogen is produced from renewable electricity.
Hydrogenation	A chemical reaction between molecular hydrogen and another compound or element, usually in the presence of a catalyst such as nickel, palladium or platinum.[323]
kw	Kilowatt (1,000 watts).
kwh	Kilowatt-hour (1,000 watt-hours).

320 ScienceDirect (n.d.) *Biofuel*. Viewed 1 Jan 2023, https://www.sciencedirect.com/topics/earth-and-planetary-sciences/biofuel.

321 ScienceDirect (n.d.) *Fischer-Tropsch Process*. Viewed 1 Jan 2023, https://www.sciencedirect.com/topics/engineering/fischer-tropsch-process.

322 ScienceDirect (n.d.) *Haber-Bosch Process.* Viewed 1 Feb 2023, https://www.sciencedirect.com/topics/engineering/haber-bosch-process.

323 Rafiee A, Khalilpour KR, Milani D (2019) *CO_2 Conversion and Utilization Pathways*. Polygeneration with Polystorage for Chemical and Energy Hubs, Academic Press.

TERM	DESCRIPTION
Aggregates	Granular filling materials such as sand, ground rock and gravel comprise 60–80% of a concrete's volume.
LNG	Liquified natural gas.
Long-term project	A project is becoming operational after 2040.
Mafic/ultramafic rock	An igneous rock composed mostly of pyroxene, calcium-rich plagioclase, and minor amounts of olivine. Ultramafic rock also contains low silica and gas contents.[324]
MASDP	Middle Arm Sustainable Development Precinct.
Medium-term project	A project is becoming operational between 2030 and 2040.
MJ	Metajoules (10^6 joules)
Mt	Million tonnes (10^6 tonnes).
Mtpa	Million tonnes per annum.
NTLEH	Northern Territory Low Emission Hub.
Partial pressure	The product of total pressure and concentration of a gas stream.
Pilot scale project	Small-scale tests to understand how technology may perform at full-scale.
PJ	Petajoule (10^{15} joules).
Point source	Stationary locations where CO_2 is emitted.
RD&D	Research, development & demonstration.
RWGS	Reverse water gas shift: The reduction of CO_2 using H_2 to form CO and H_2O. The RWGS is an important rection in CO_2 conversion processes as it can be used to produce syngas.[325]
Sabatier reaction	The process of producing methane and water from a reaction of hydrogen with carbon dioxide at elevated temperatures and pressures in the presence of a nickel catalyst.[326]
Short-term project	A project is beginning operations before 2030.
Syngas (synthesis gas)	A valuable flammable gas mixture of hydrogen and carbon monoxide (CO) and smaller quantities of methane, carbon dioxide and hydrocarbons, principally used for producing ammonia or methanol or as a fuel. [327]
Tailings	A liquid slurry of fine mineral particles from the processing and extracting valuable minerals and metals from mined ore.
t	Metric tonne.
Tpa	Tonne per annum.
TRL	Technological readiness level.

324 GeologyIn (2014) *How to Classify Igneous Rocks Into (Ultramafic, Mafic, Intermediate and Felsic)?*. Viewed 1 Feb 2023, https://www.geologyin.com/2014/12/how-to-classify-igneous-rocks-into.html.

325 Zhu M, Ge Q, Zhu X (2020) Catalytic Reduction of CO_2 to CO via Reverse Water Gas Shift Reaction: Recent Advances in the Design of Active and Selective Supported Metal Catalysts. Transactions of Tianjin University.

326 ScienceDirect (n.d.) *Sabatier Reaction*. Viewed 1 Feb 2023, https://www.sciencedirect.com/topics/earth-and-planetary-sciences/sabatier-reaction.

327 Ragaert K, Delva L, Geem KV (2017) Mechanical and chemical recycling of solid plastic waste. Waste Management.

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