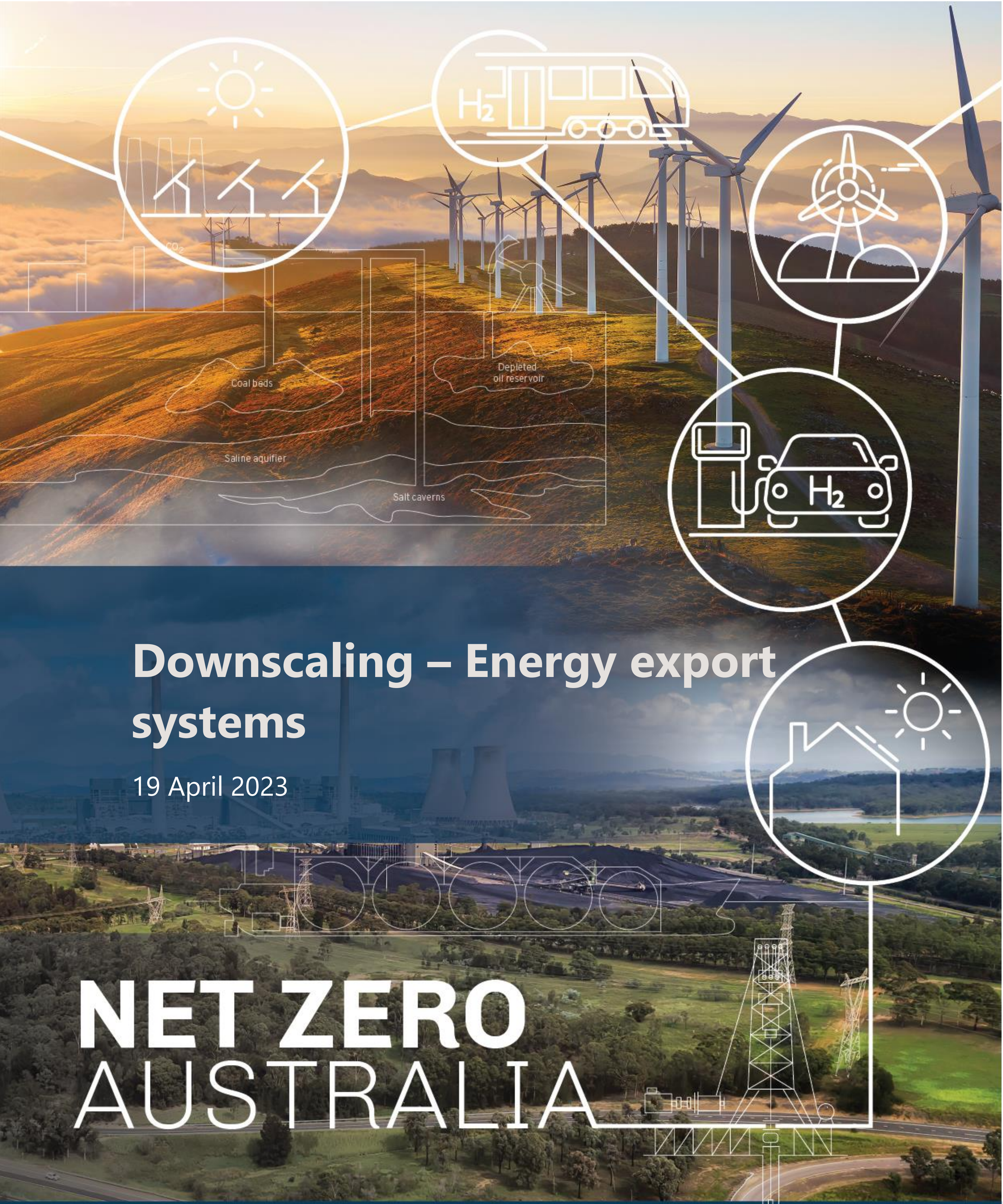

Downscaling – Energy export systems

19 April 2023

NET ZERO AUSTRALIA

The University of Melbourne
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The Net Zero Australia (NZAu) project is a collaborative partnership between the University of Melbourne, The University of Queensland, Princeton University and management consultancy Nous Group. The study identifies plausible pathways and detailed infrastructure requirements by which Australia can transition to net zero emissions, and be a major exporter of low emission energy and products, by 2050.

Net Zero Australia

Downscaling – Energy export systems

19 April 2023

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1 Energy export in NZAu

In the Net Zero Australia study Australia continues exporting energy through 2060 at the 2020 energy export value of ~15EJ, in all scenarios. Figure 1 details the export energy mix for all the modelled NZAu scenarios. See Batterham, Beiraghi [1] for a discussion of the selection of this target along with the methods, assumptions, sensitivities and scenarios (MASS) pursued in NZAu modelling. See Batterham [2] for the Net Zero Australia interim results, which are updated to the latest results in this document.

Figure 1 | Energy export by energy source

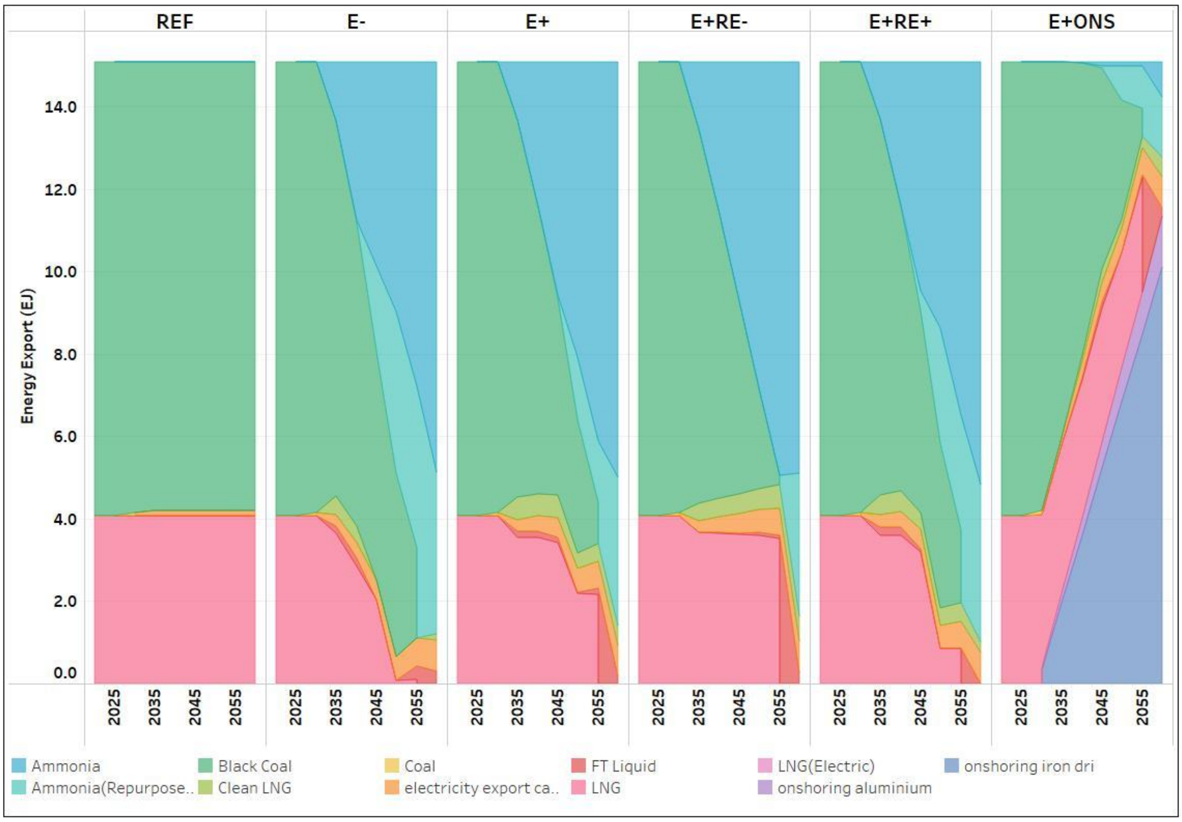


Figure 1 indicates that in the reference scenario (REF), energy exports remain largely unchanged through 2060 as coal and LNG exports are maintained. In all other scenarios, energy exports are gradually replaced by clean energy carriers in the form of ammonia (indicated as "Haber-Bosch" in Figure 1), electricity, LNG from synthetic fuels, and Fischer-Tropsch liquids (FTL); or are kept onshore, along with Australian mining outputs, to produce low-carbon iron and aluminium (indicated as "Onshoring" in Figure 1). In all but the REF and onshoring (ONS) scenarios, the vast majority of energy is exported as ammonia, with much smaller contributions from other clean energy carriers. In the ONS scenario, ~ 85% of the 15 EJ energy export target does not leave Australia's shores. Australia instead invests in its domestic industry to produce an amount of iron and aluminum that is equivalent to the quantity that could have been produced overseas — from Australia minerals also shipped overseas — using the avoided export energy.

The quantity of energy exported by carrier (or onshored replacement) is reported for 2060 in EJ in Table 1.

Table 1 | Energy exports in 2060 for NZAu scenarios (EJ), along with export energy avoided by onshoring iron and aluminium production in the ONS scenario

Scenario	Ammonia	FTL	LNG	Clean LNG	Coal	Electric cable	Onshore DRI (avoided)	Onshore aluminium (avoided)	Total
REF	0	0	4.1	0	10.9	0.1	0.0	0.0	~15
E+	13.7	0.2	0	0.5	0	0.8	0.0	0.0	~15
E+RE+	14	0	0	0.2	0	0.8	0.0	0.0	~15
E+RE–	13.5	0.3	0	0.6	0	0.8	0.0	0.0	~15
E-	13.8	0.3	0	0.2	0	0.8	0.0	0.0	~15
E+ONS	2.4	0.2	0	0.5	0	0.8	10.1	1.2	~15

Given the minor role Fischer Tropsch Liquids (FTL), electric cable, and LNG/clean LNG industries play in NZAu export scenarios in Table 1, this downscaling report only briefly covers them before focusing on ammonia production. A companion report, *Downscaling – Onshoring of industry*, provides more information on the onshoring of iron and aluminium production in the ONS scenario. More information on FTL and the production of H_2 used to produce ammonia can be found in the companion report *Downscaling – Hydrogen and synthetic fuel production, transmission and storage*. This document:

a) Plots LNG and coal exports using historical trends and shows the reduction in fossil fuel export in NZAu scenarios
b) Identifies the geographic location of production and the exporting port for all energy sources currently contributing to Australia's energy exports.
c) Discusses the transition of LNG plants to retrofitted (electrified) LNG (E-LNG Plant) and the reuse/retrofit of existing brownfield LNG sites in producing ammonia from Haber Bosch (R-HB) facilities.
d) Briefly discusses the production of clean (i.e. decarbonised) LNG, FT Liquids and energy export via undersea cable.
e) Tracks the amount of ammonia produced in million tonnes per annum in each scenario.
f) Estimates the number of Haber Bosch plants required to achieve ammonia production in each scenario, with a simplified build schedule.
g) Calculates the land footprint of the ammonia facility and storage at the terminal for export.
h) Provides notional siting for the Haber-Bosch plants used to produce ammonia for export.

2 Results

2.1 Energy export by state

Currently, Queensland (QLD) exports roughly half of all energy exported from Australia. Coal and LNG exports make QLD a fossil fuel exporting hub. Figure 2 highlights that in all NZAu scenarios, exports (and export replacing activity in the ONS scenario) shift away from QLD to the Northern Terrirory (NT) and Western Australia (WA) by 2060, leaving QLD as the third largest producer of energy for export. For example, in the RE– scenario, WA exports 8.6 EJ and the NT and QLD export 2.4 and 2.2 EJ respectively. Notably, the RE– scenario is the only scenario in which a region (Victoria, VIC) other than WA, QLD, or the NT exports more than 1 EJ of energy by 2060. In the E+, RE+, and E- scenarios, the NT is the major energy export hub by 2060, with 5.9 EJ, 6.7 EJ and 6.4 EJ of energy exports respectively by the end of the transition. In the same three scenarios, QLD's total energy exports are only slightly less than energy export from WA.

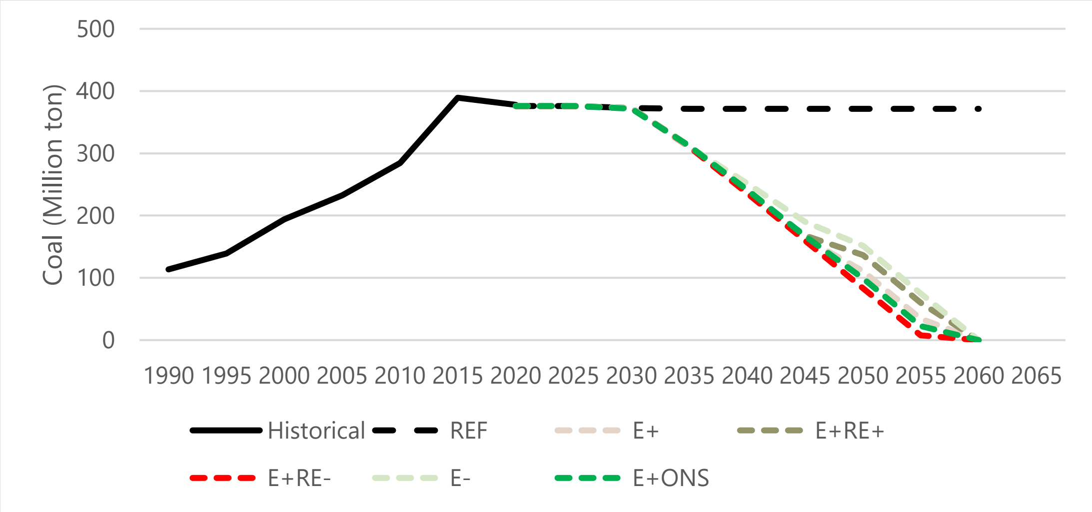
Figure 2 | Energy (EJ) export by location (State). Note the ONS scenario only displays actual energy exported, the embodied or avoided energy of the DRI and aluminium exports is not shown.

2.2 Export of fossil fuel reduces in all scenarios

2.2.1 Coal export

As of 2019, Australia had a coal reserve with a lifespan of 166 years (at 2019 production levels) and contributed to 7% of global coal production in 2019 [insert ref for Australian energy commodity resources]. In 2019 Australia exported 11131 PJ of coal. In all NZAu scenarios but the REF scenario, Australia's coal exports decrease after 2030 and reach zero by 2060 (or before). Figure 3 plots the historical coal export using data from Department of Industry [3] along with the projections of coal exports modelled by NZAu scenarios. For a detailed discussion on coal production and coal mine retirement refer to the *Downscaling – Fossil fuel industries* report.

Figure 3 | Coal export in NZAu scenario plotted with historical coal export data



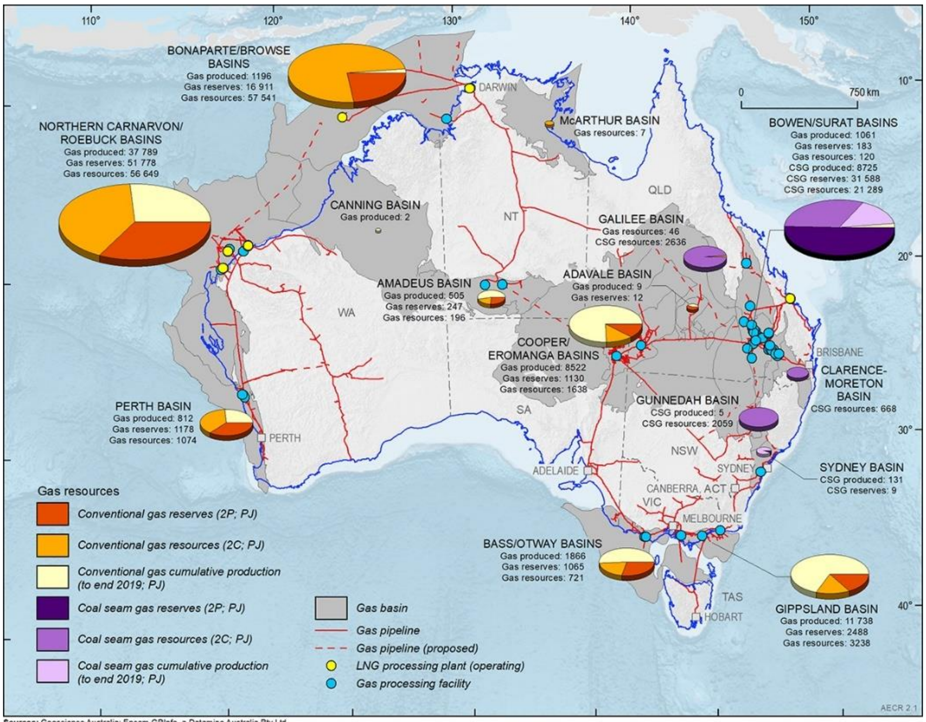
Currently, the vast majority of coal is exported from QLD and NSW. QLD contributed 6.5 EJ out of 11 EJ of coal exports in 2020. In NZAu scenarios, NSW coal reduces almost to zero by 2040, with QLD exports seeing only slight reductions by the same year. As expected from Figure 3 and illustrated by Figure 4, by 2060 none of the states exports coal in NZAu scenarios.

Figure 4 | Coal export by state (EJ)

2.2.2 LNG export

Figure 5 shows the conventional and coal seam gas reserves and cumulative production from each reserve.

Figure 5 | Conventional and coal seam gas reserves in 2019 with demonstrated capacities of basins as assessed by Geoscience Australia [4]

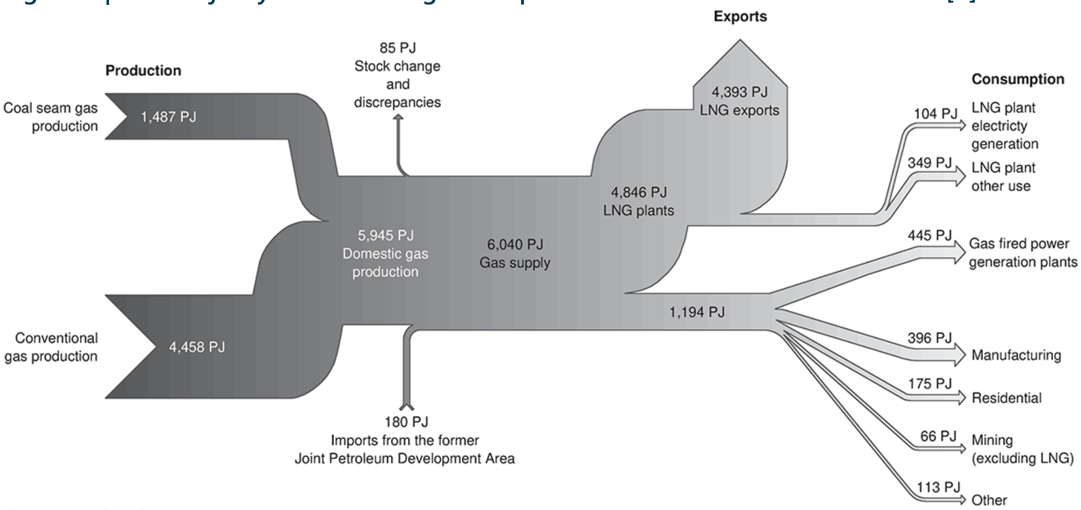


Sources: Geoscience Australia; Encom GPInfo, a Datamine Australia Pty Ltd
Field outlines and pipeline routes from the GPinfo petroleum database.
Note: LNG = liquefied natural gas, PJ = Petajoules.

Conventional gas and coal seam gas reserves in Australia have assessed life spans of 42 and 36 years respectively in 2019 (at 2019 production levels) [insert reference Australian Energy Commodity Resource]. See the *Downscaling – Fossil fuel industries* report for handling of gas supply in the later years of scenarios that have a greater reliance on natural gas (e.g. RE– scenario which has more autothermal reforming of natural gas for hydrogen production) and exceed projected reserve levels.

Figure 6 illustrates the flow of natural gas in Australia, moving from extraction to the domestic and export sectors. The gas energy flows in Figure 6 indicate that a vast majority of the gas produced in Australia — 4,393 PJ out of 5,945 PJ — is exported. Australia was the world's biggest LNG exporter in 2021

Figure 6 | Vast majority of extracted gas is exported. Source: Geoscience Australia [4]



Source: Australian Energy Statistics 2021.
Note: LNG = liquefied natural gas.

Figure 7 shows the 10 LNG projects under operation in three states of Australia in 2019.

Figure 7 | LNG project with capacity in Australia in 2019. Source: Office of the Chief Economist [5], Resource and Energy Quarterly, March 2019.

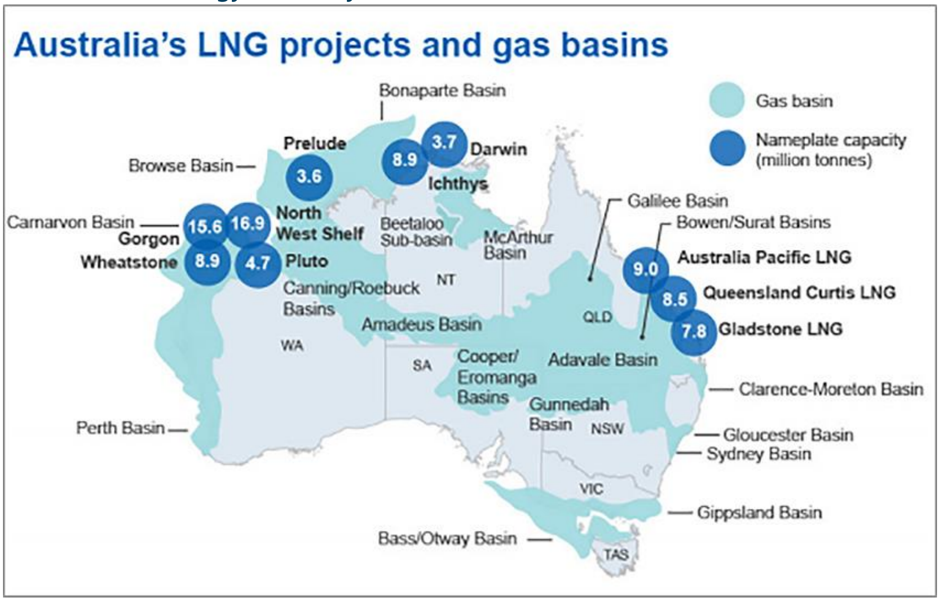
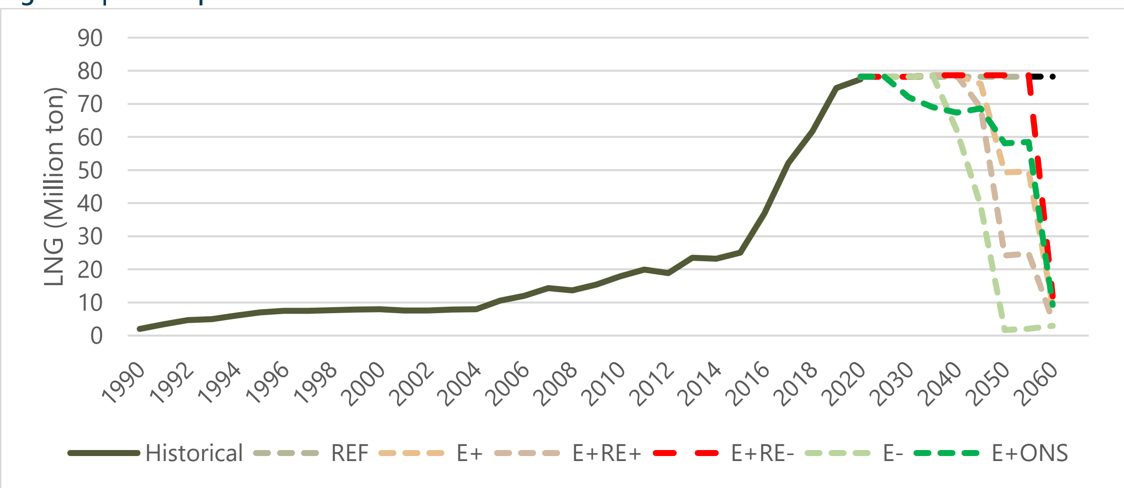


Figure 8 uses historical data on LNG export from the Department of Industry [3] and NZAu modelled data to show how LNG exports change between 1990 and 2060. In all scenarios except REF, the export of LNG reduces almost to zero in 2060. However, the slope of reduction varies by scenario. In E+RE–, LNG export continues until 2055 then sharply reduces, whereas in E+ONS, LNG export starts reducing from 2025.

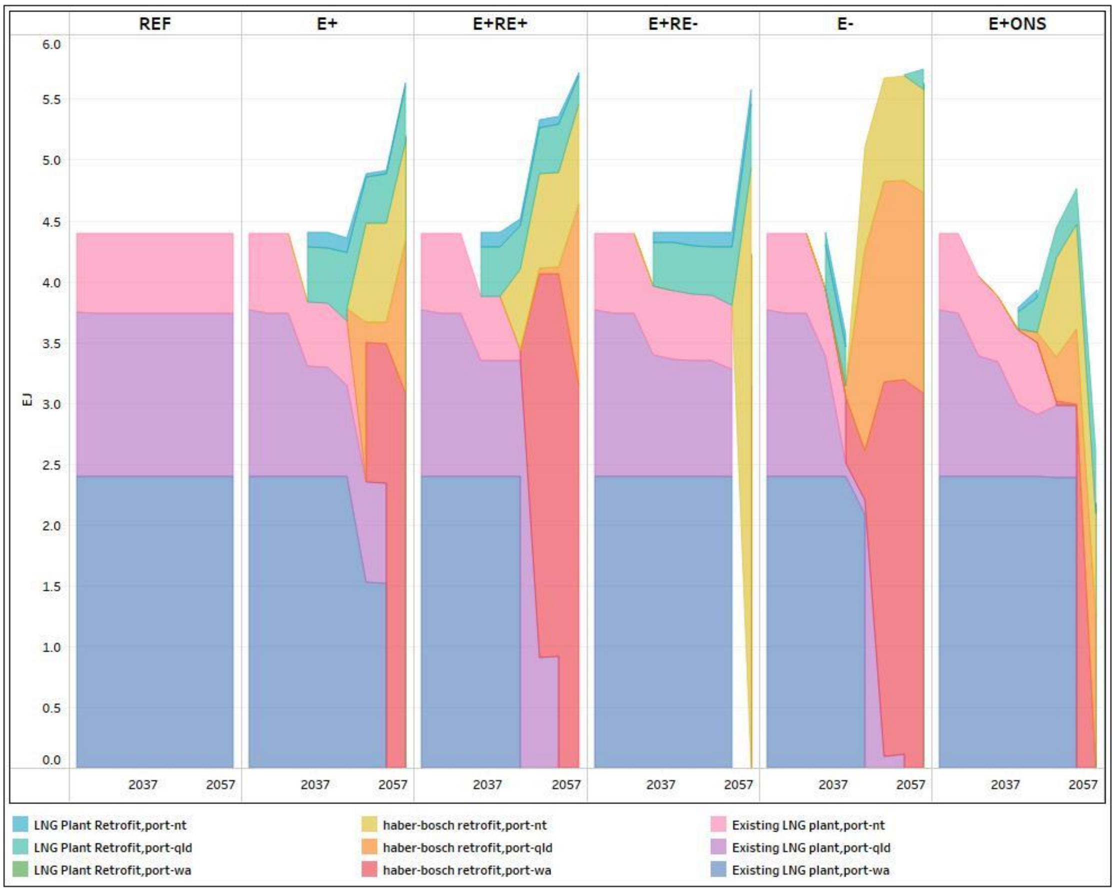
Figure 8 | LNG export in millions of tonnes



2.2.3 The Net Zero transition for LNG: retrofitting existing sites for clean LNG and ammonia production

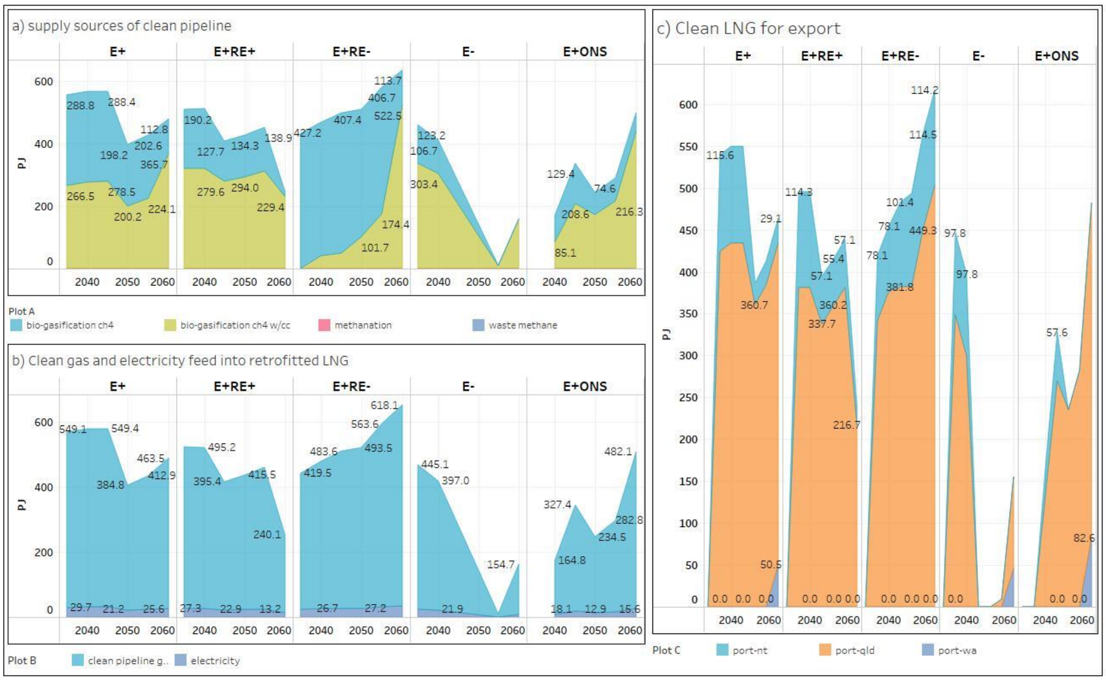
To maximise the use of existing LNG infrastructure and sites under net-zero transitions, NZAu considers two options for reuse of LNG infrastructure at appropriate timeframes, e.g. retirement age. One option for LNG plant infrastructure is the repurposing of the LNG site to produce ammonia using Haber Bosch technology (HB-R hereafter). As stated in the modelling documents, capital costs for the repurposing of the site are expected to benefit from a 20% cost savings when compared to similar sized greenfield Haber Bosch facilities due to the existence of connected utility infrastructure and major hazard facility licences (acknowledging that ammonia has a very different risk profile to LNG). LNG plants, electric LNG plant retrofit, and HB-R exist under the same capacity constraint in the model and are mutually exclusive. Figure 9 shows the energy produced for export as ammonia using repurposed LNG plants. Ammonia production technology will be discussed fully later in this document.

Figure 9 | LNG plant is retrofitted to the Haber Bosch plant. Port-wa covers export ports in WA. Port-NT covers the export port in Darwin. Port-QLD covers export ports in QLD.



The other option for repurposing LNG plants to be retrofitted with low-capital-cost electric compressors, while concurrently only accepting carbon-neutral pipeline gas as a feedstock (clean pipeline gas from biogasification processes – see Plot A of Figure 10 and the *Downscaling – Bioenergy systems* report) and clean electricity (Plot B of Figure 10). Most of the retrofitted LNG plants in NZAu scenarios are located in QLD as shown in Plot C of Figure 10. For example, in 2060 in the E+ scenario, 354 PJ of LNG is produced at retrofitted facilities in QLD, while only 51 PJ and 29 PJ of LNG is produced at retrofitted facilities in WA and the NT respectively. The greatest number of LNG plant retrofits occur in the E+RE– scenario with sees ~617 PJ of clean LNG produced in 2060.

Figure 10 | Supply to clean LNG



Also notable in Figure 10 is that while clean LNG contributes to Australia's clean exports for the remainder of all net-zero transitions, the quantity of clean LNG produced fluctuates (as a result of decreasing solar PV and green hydrogen production costs) in all but the E+RE– scenario. In E+, 539 PJ of clean LNG is produced, which reduces to 386 PJ in 2050 and 464 PJ in 2060. In E+RE–, 419 PJ of clean LNG is produced using an electric LNG plant, which reaches 617 PJ in 2060. Most of the clean LNG is exported from QLD, followed by NT as seen in Figure 10 | Supply to clean LNG.

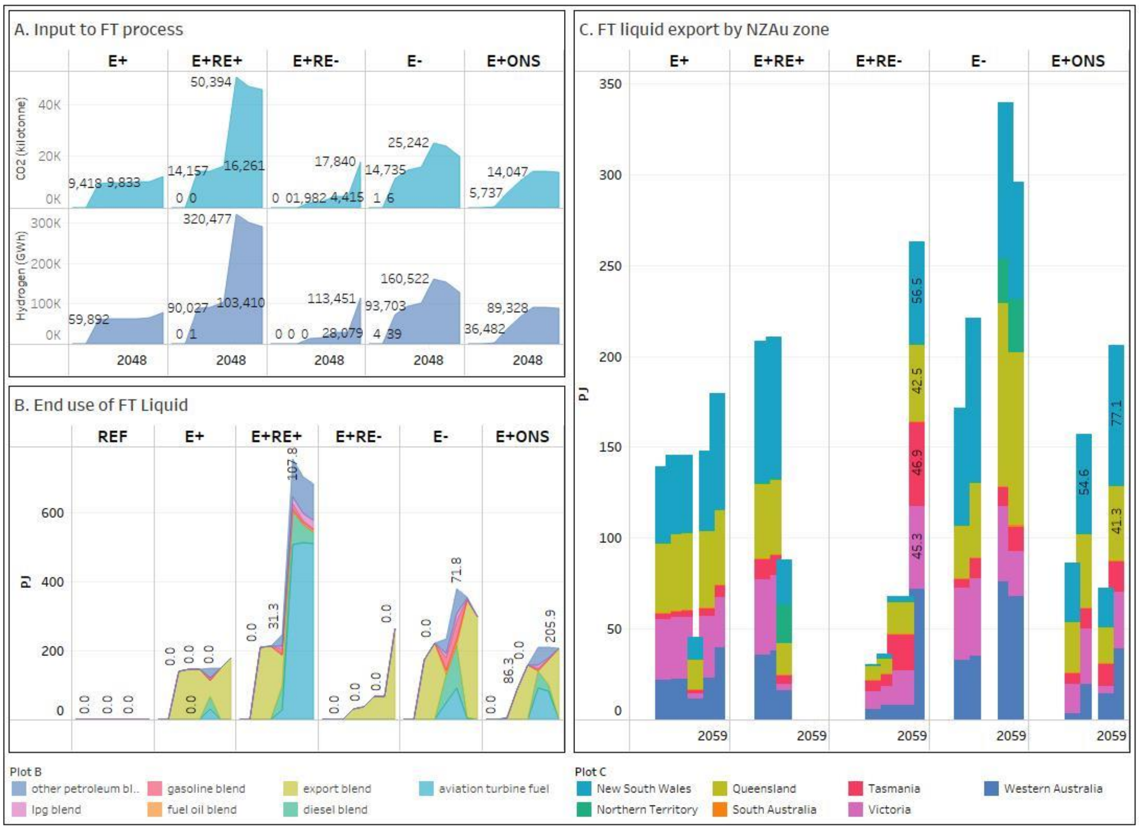
2.2.4 FTL

As discussed in Batterham, Beiraghi [1] and the *Downscaling – Hydrogen and synthetic fuel production, transmission and storage* document, carbon dioxide and hydrogen are fed into the Fischer-Tropsch process to produce synthetic fuels (Figure 11 (A)). The FTL is then supplied to various end-uses depending on the scenario. FTL production varies by scenario and year. In the E+ scenario, only a small quantity of FTLs are supplied for diesel and aviation turbine blend in 2050, while most of the FTL is exported in that same year. However, in the E+RE+ scenario after initial export of most FTL, after 2050, FTL production more than doubles and is supplied to domestic end use such as aviation and LPG fuel blend (Figure 11 (B)). FTL are produced in various states (Figure 11 (C)) depending on the NZAu scenario. The total production of FTL and the proportion of FTL exported in 2040, 2050 and 2060 is reported in Table 2.

Table 2 | Total FTL production and proportion of FTL exported

Scenario	2040		2050		2060	
	Total	% of FTL	Total	% of FTL	Total	% of FTL
REF	0.0	0.0	0.0	0.0	0.0	0.0
E+	145.7	100.0	148.0	30.6	179.8	100.0
E+RE+	210.5	100.0	752.2	0.0	679.7	0.0
E+RE–	30.4	100.0	67.7	100.0	263.3	100.0
E-	221.5	99.9	377.3	0.0	296.1	100.0
E+ONS	86.4	99.9	209.2	0.0	206.0	100.0

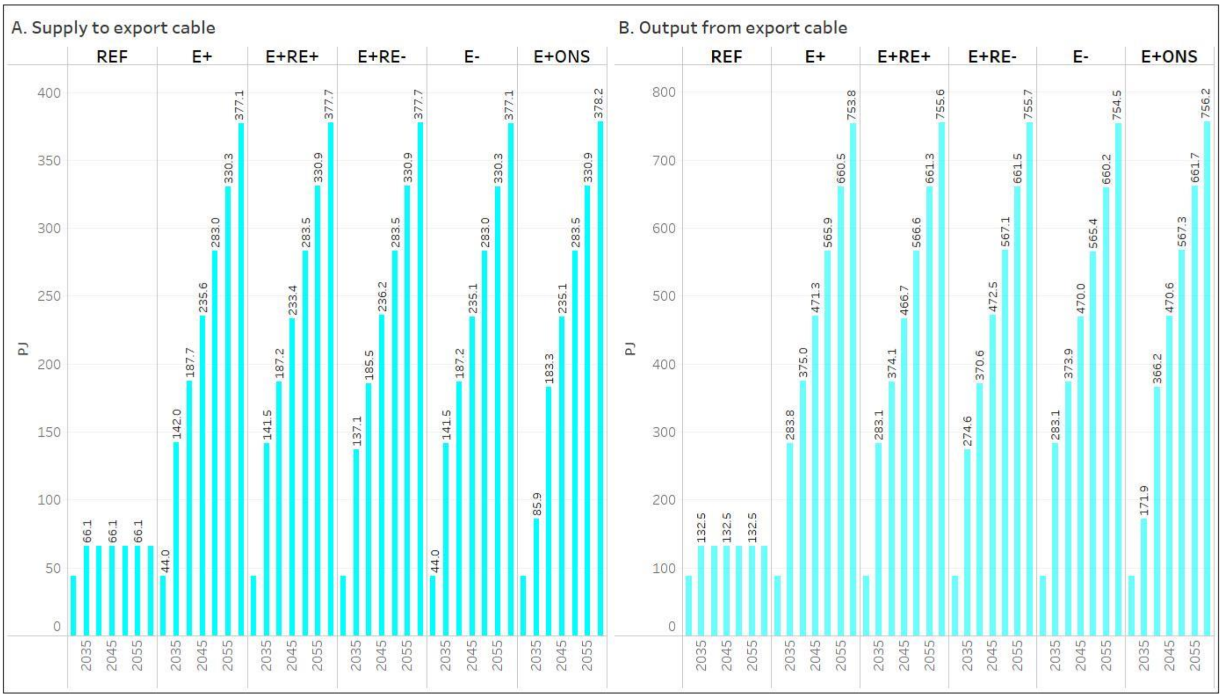
Figure 11 | Input, output and export of Fischer Tropsch liquid (FTL)



2.2.5 Energy export cable

NZAu includes an undersea electricity export cable as a supply-side energy export infrastructure that can expand from a 4,000 MW capacity in 2027 to a maximum capacity of 24,000 MW in 2060. NZAu assumes that every kilowatt hour of energy accessed by the electricity cable's end users will allow those users to avoid importing a solid/gaseous energy carrier from Australia which would then be turned into electricity and transmitted to the end user at the cost of an additional one kWh of embodied energy. In all scenarios, the electricity generated for export in Australia increases from 44 PJ in 2035 to 377 PJ EJ in 2060. This allows Australia to avoid the production of 88 PJ of solid/gaseous fuels for export in 2030, which increases to ~755 PJ in 2060 (see Figure 12).

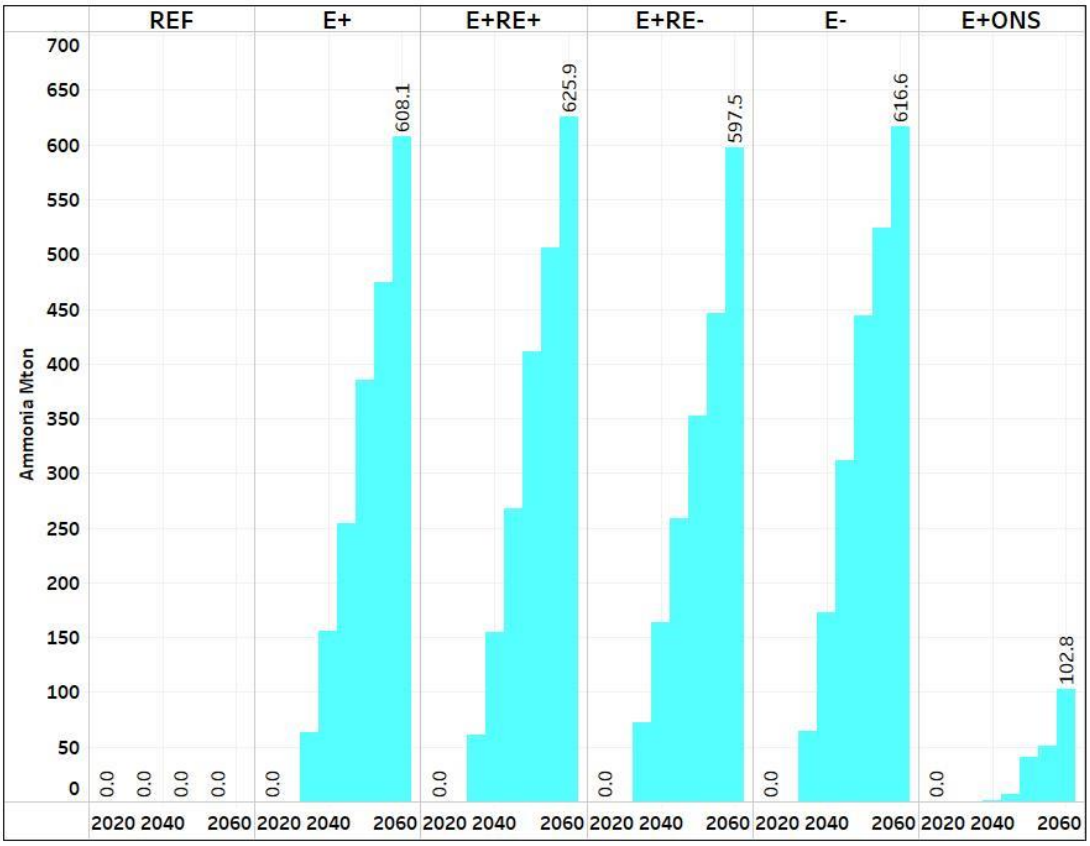
Figure 12 | Energy export using export cable



2.3 Ammonia production

Ammonia production in all NZAu scenarios starts after 2030 (See Figure 13). By 2060, Australia exports roughly the same quantity of Ammonia in four of the five NZAu -scenarios, at ~600 million tonnes (Mt) of ammonia. In the ONS scenario, only 2.31 EJ is produced in 2060. The scale of production varies slightly between 2030 and 2060 across the four common scenarios. For example, 8.66 EJ of Ammonia is produced in 2050 in the E+ scenario while 9.99 EJ of ammonia is produced in the same year in the E– scenario. The highest amount of ammonia is exported in the E+RE+ scenario. In this scenario, Australia exports 625 Mt of ammonia in 2060. In E+RE– Australia exports 597Mt of scenario. In E+ONS, most of the hydrogen is fed into making direct reduced iron (DRI) for use in the domestic iron industry, therefore, ammonia export reduces to 103Mt.

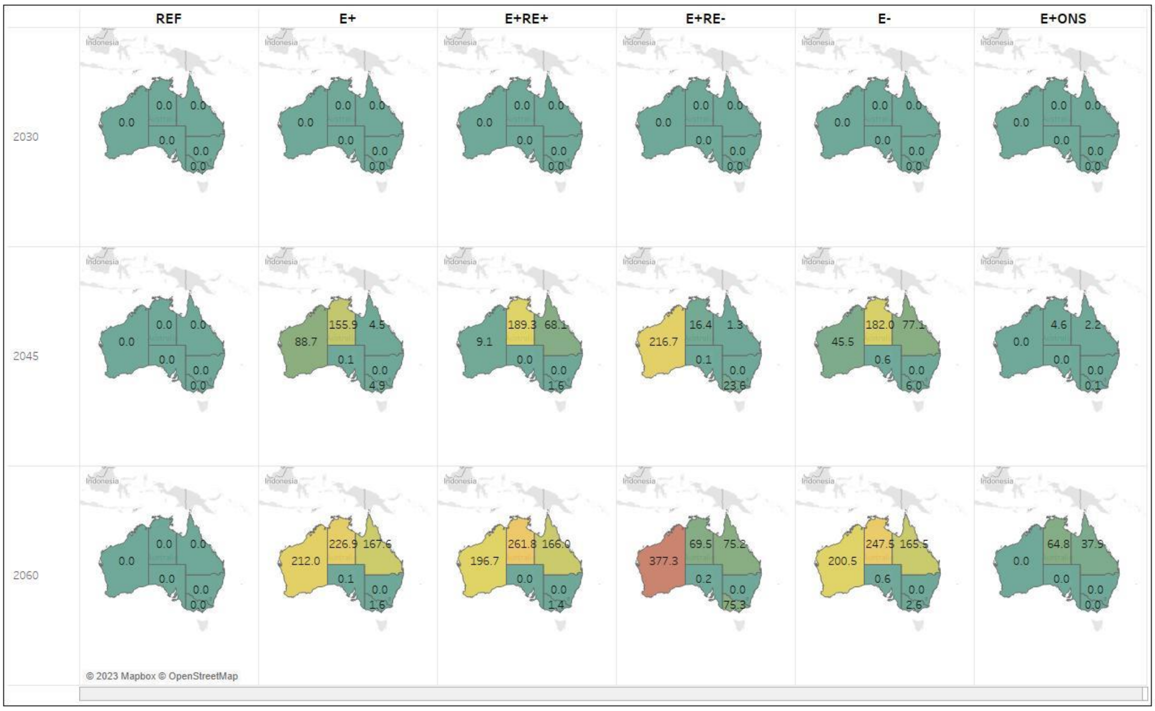
Figure 13 | Ammonia export in million ton



As shown in Figure 14, the vast majority of ammonia is exported through ports in WA, NT, and QLD in all but the ONS scenario. In the E+RE– scenario, 75 Mt of ammonia is exported from VIC east.

Figure 14 shows the quantity of ammonia exported by NZAu port. Ammonia is produced in QLD, NT and WA. But the quantity of ammonia produced in a geographic location depends on the scenario. In E+RE–, out of 597mt of ammonia, 377mt is produced in three ports of WA. VIC and QLD produce ~75mt of ammonia and 69mt is produced in NT. In E+, the highest quantity of ammonia is produced at NT port, followed by 212mt in WA and 167mt in QLD. In E+ONS, ammonia is produced in NT and QLD.

Figure 14 | Ammonia production by state



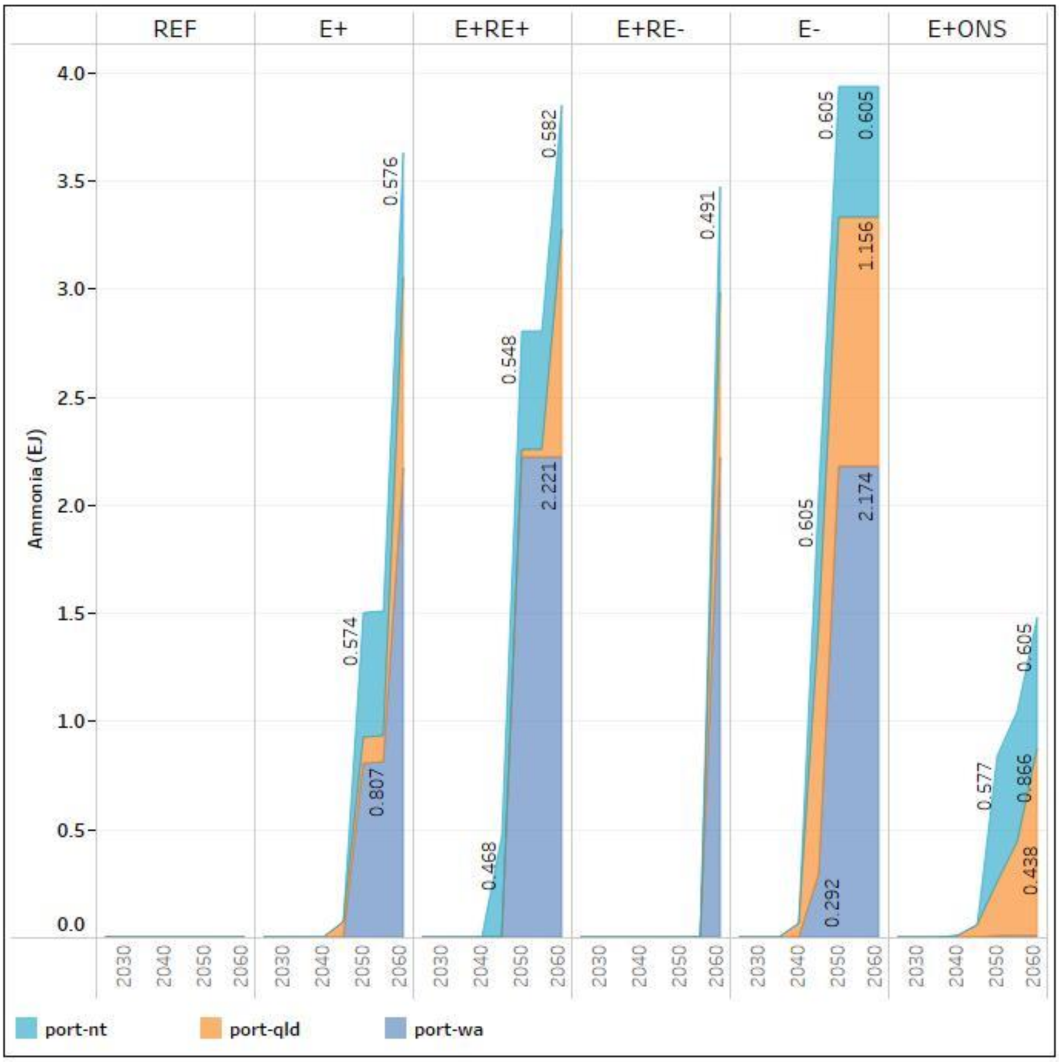
As discussed in Section 2.2.3, some LNG sites are repurposed to Haber Bosch plants to produce green ammonia for export. The model indicates, a substantial amount of ammonia could be produced using Haber Bosch plants sited on the location of former LNG assets (see Table 3) In the E+ scenario, 160 million tons of ammonia are produced using repurposed LNG sites. However, the total contribution of Haber Bosch plants sited on repurposed LNG sites varies by scenario.

Table 3 | Ammonia production (Mt)by type of Haber Bosch plant

Scenario	HB-R	New Haber Bosch	Total	Contribution of HB-R plant (% of total)
REF	0.0	0.0	0.0	18.0
E+	160.6	447.5	608.1	26.4
E+RE+	170.5	455.4	625.9	27.2
E+RE–	153.6	443.9	597.5	25.7
E-	174.4	442.2	616.6	28.3
E+ONS	64.8	37.9	102.8	63.1

Further breakdown of the contribution of ammonia from Haber Bosch plants sited on repurposed LNG sites by exporting port is provided in Figure 15. In the E+RE+ scenario, most of the contribution of ammonia from Haber Bosch plants sited on repurposed LNG sites to exports is found in WA's ports whereas, in the ONS scenario, ammonia produced from the repurposed sites is exported mainly from ports in QLD and the NT.

Figure 15 | Quantity of ammonia (EJ) production from repurposed Haber Bosch plant



2.4 Ammonia production infrastructure

This section analyses the HB plants, HB storage cylinder, ship call and shipping berths for ammonia export.

2.4.1 Haber Bosch plant

NZAu assumes all ammonia exported from Australia will use the Haber Bosch production process. The number of Haber Bosch plants needed to produce the quantity of ammonia for export in NZAu scenarios in 2060 is provided in Table 4. To achieve the ammonia export demanded in E–, 327 Haber Bosch plants (having a capacity of 5000 tonnes per day (tpd)) must be installed by 2060. However, the number of Haber Bosch plants varies by scenario. For example, E+ RE+ requires 342 plants whereas 57 plants are sufficient to produce the exported ammonia in the ONS scenario.

Table 4 | Haber Bosch plant and storage facility for energy export in NZAu

Scenarios	Haber Bosch plant (5000 tpd)	Storage Tanks (50 Kt per tank)
REF	0	0
E+	332	664
E+ RE+	342	684
E+ RE–	327	654
E-	338	676
E+ ONS	57	114

Statewise HB plants are provided in Figure 16. Haber Bosch plants for ammonia production vary by state. WA will have 207 plants in E+RE– and NT will have 143 plants in E+RE–. The concentration of the plants is highest in the WA, NT and QLD ports. As NT has only one port from which all ammonia is exported, and WA and QLD have three potential ports each, NT is likely to have the largest quantity (and density) of plants serving a single export terminal.

Figure 16 | Haber-Bosch plant by state/territory

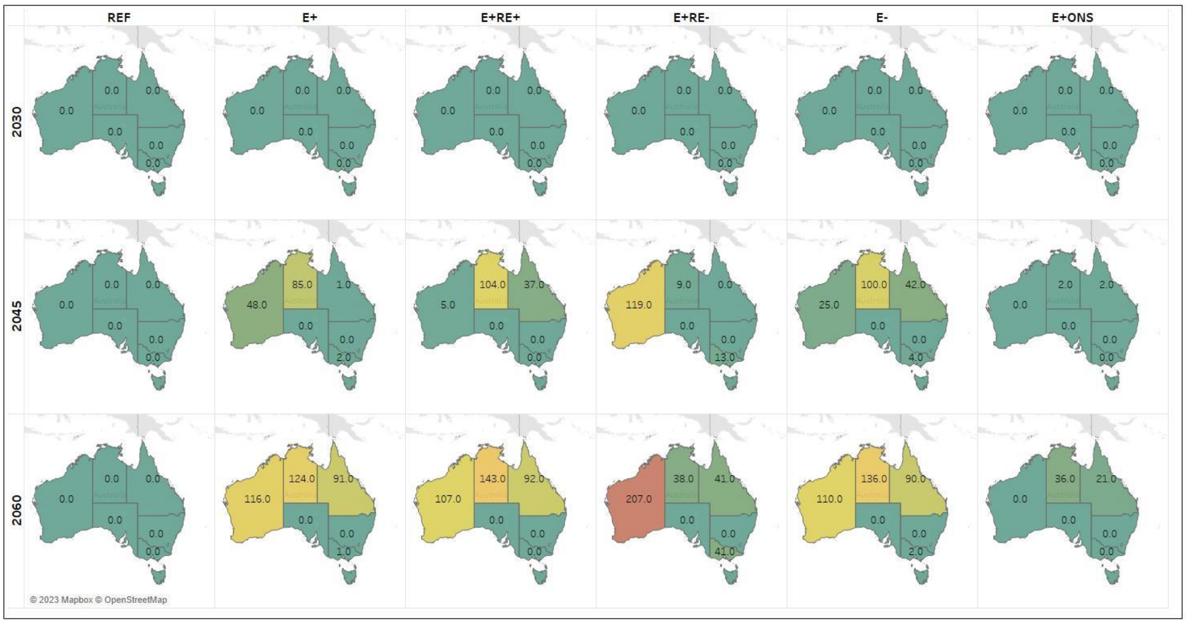
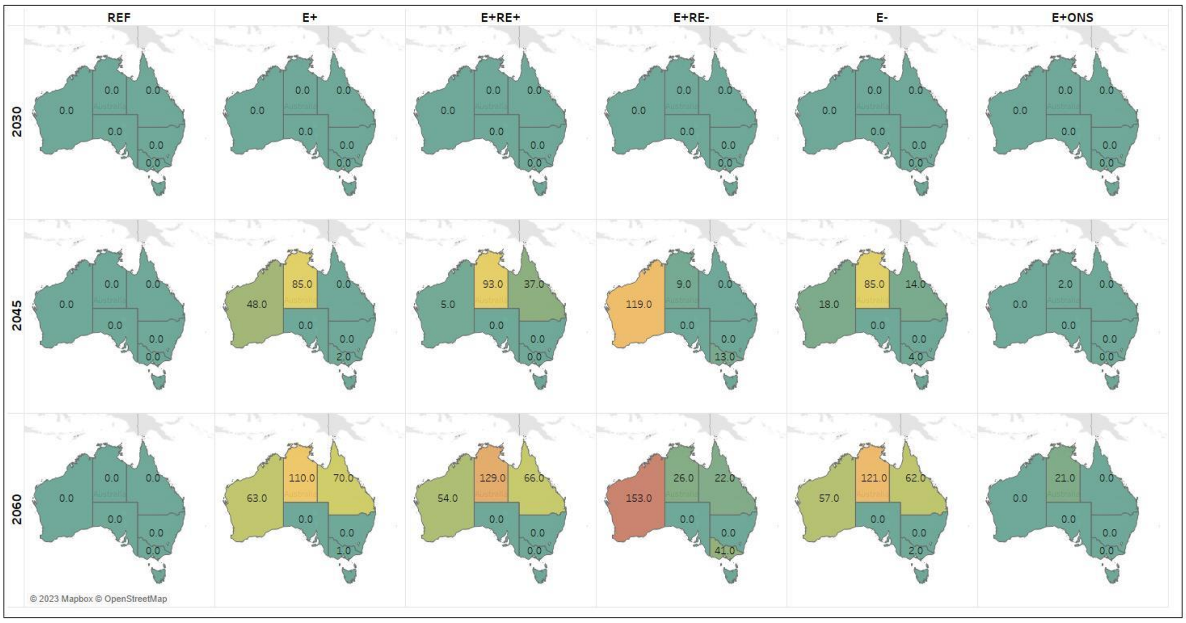


Figure 17 shows the number of new Haber Bosch plants sited on repurposed LNG facility land (HB-R) and indicates that roughly half of all new ammonia facilities are HB-R by 2060.

Figure 17 | New Haber Bosch plants sited on repurposed LNG facility land by state/territory

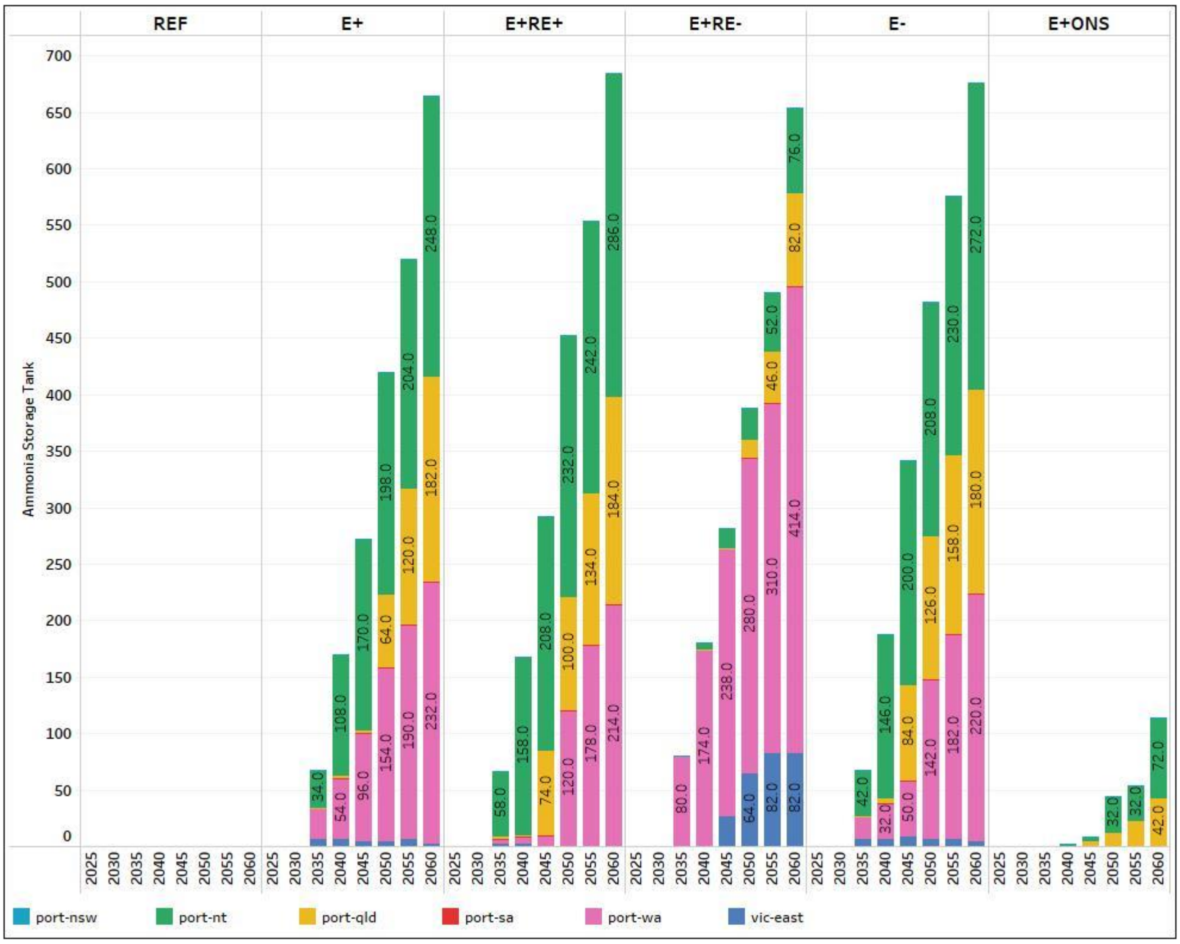


2.4.2 Ammonia storage

NZAu uses 20 days of storage for ammonia storage cost calculations (See Batterham, Beiraghi [1]). Therefore, we assume ammonia will be stored for a maximum of 20 days before it is shipped. This provision allows continuous production of ammonia and intermittent shipping. We use a 50 kt capacity ammonia storage tank in downscaling. We have required a Haber Bosch plant of 5000 tpd to have two ammonia storage tanks which allow for 20 days storage of ammonia produced to accommodate process fluctuations and planned outages and still maintain the shipping schedule.

Figure 18 shows the number of storage tanks required to meet ammonia export in NZAu. 674 and 682 ammonia storage tanks are required in E-and E+ in 2060. In 2060, 692 storage tanks are required scenario to store ammonia produced in E+RE+. NT has the highest number of storage tanks in E+, E- and E+RE+. More than half of the storage cylinders are located in WA ports in E+RE– scenario. Note, the very large number of co-located Haber Bosch plants suggests that it should be possible to reduce the size and/or number of storage tanks and still maintain the shipping schedule. That is, co-located plants may ramp up or down to accommodate maintenance schedules and unplanned outages, rather than having lots of storage to ensure continuity of supply. However, the NZAu study has taken a conservative view on what is operationally possible and included traditional storage volumes in our analysis.

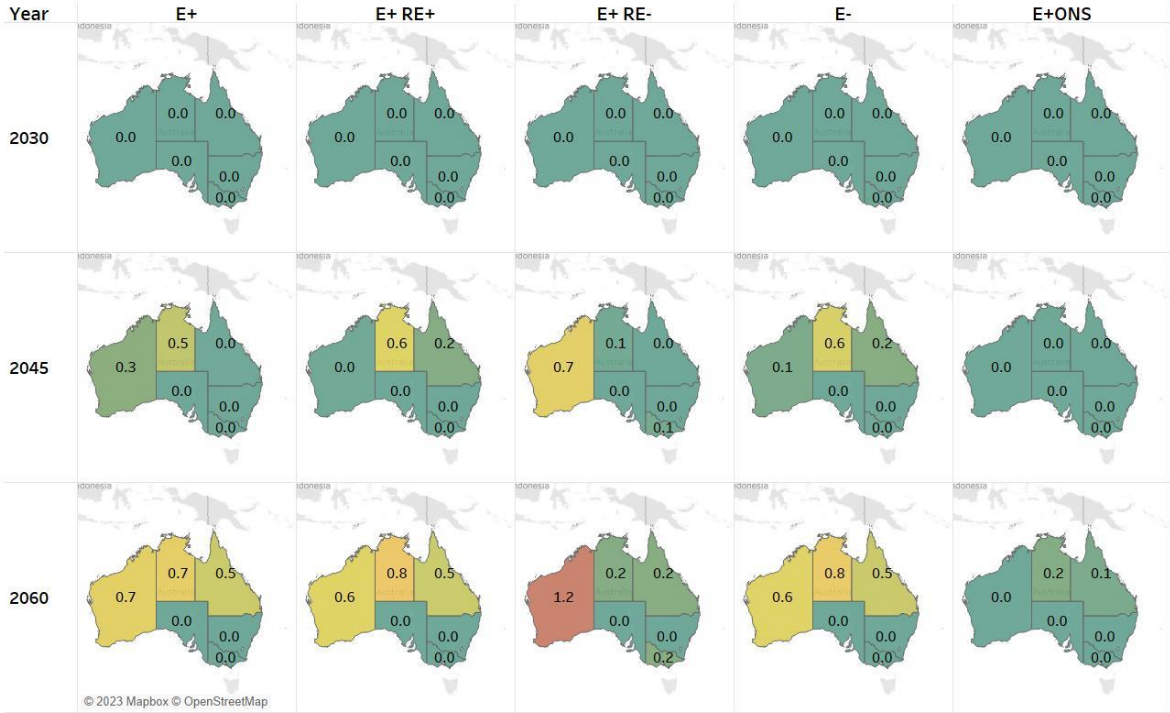
Figure 18 | Ammonia storage tank by scenario



2.4.3 Desalination plant for ammonia production

NZAu assumes the use of the wet or evaporative cooling for ammonia production, requiring treated or fresh water supply. In NZAu we have taken the view to reduce water stress through desalination of seawater. Water demand for ammonia in NZAu is discussed in more detail in the Downscaling – *Water use and transmission* report. Figure 19 below provides the proportion of 1000 megalitres per day (MLD) desalination plants required for ammonia production in different states. There is also a likelihood that future ammonia production could use a once-through cooling systems with seawater as currently seen in many seawater cooled coastal thermal (i.e. nuclear, coal or gas) power plants [6]. In this case, a desalination plant may not be needed. NZAu has taken a conservative approach here to detail the necessary additional infrastructure that may be required.

Figure 19 | Number of desalination plants needed for ammonia production.



2.4.4 Ship call demand for ammonia export

Figure 20 presents the number of ship calls required to transport the exported ammonia. Ship calls are where a vessel docks at port to load or unload cargo. Ammonia starts being shipped after 2030 and sharply increase after 2050. E+RE+ requires the highest number of ship calls. By 2060, E+RE+ requires 8920 ship calls whereas E+ONS requires 1488 ship calls and E+RE– requires 8516 ship calls.

Figure 20 | Ship calls by year and scenario using MASS pack ship capacity

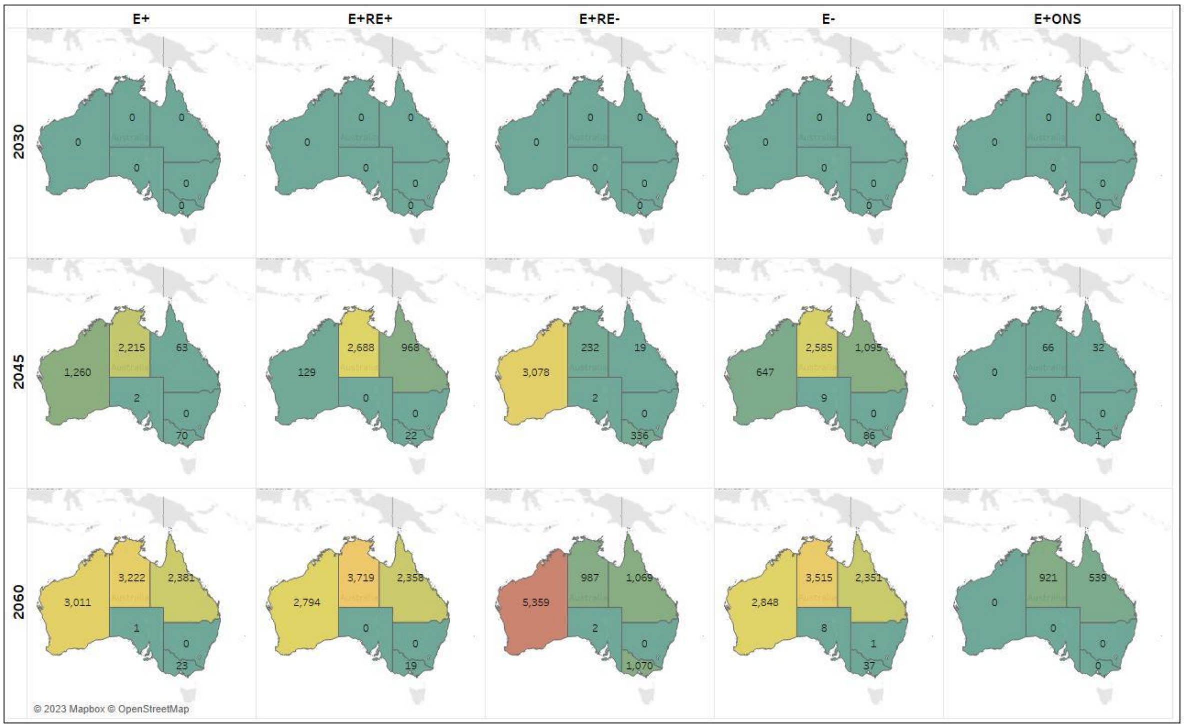


Table 5 | Ship call for ammonia export in 2060 compares the ship calls for ammonia against the 2020-21 ship call at the state/territory level to explore what the energy export shipping arrangement might look like in future. In 2020-21, NT received 1078 ship calls. In E+, E- and E+RE+, NT ammonia export requires three times the 2020-21 ship calls.

Table 5 | Ship call for ammonia export in 2060

Zone	E+	E+RE+	E+RE-	E-	E+ONS
Total number of ship call in 2060					
Port-NT	3222	3720	987	3515	921
Port-WA	3022	2805	5370	2856	11
Port-QLD	2388	2366	1077	2357	547
VIS-east	27	24	1074	40	4
Port-SA	2	0	2	8	0
Port-NSW	5	5	5	5	5
NZAu ship call as % of total ship call in the state in 2020-21					
Port-NT	299	345	92	326	85
Port-WA	32	30	57	30	0
Port-QLD	30	29	13	29	7
VIC-east	1	1	27	1	0
Port-SA	0	0	0	0	0
Port-NSW	0	0	0	0	0

2.4.5 Number of ship berths required for energy export

We assume one ship requires 16 hours to fill ammonia and the berth operates 90% of the days in a year. A berth serves ~492 ship calls a year. The berth requirement by NZAu port is reported in Table 6 (Panel A). Roughly 18 berths are required in ports of QLD, NT and WA in all scenarios except E+ONS. WA ports require 11 berths in E+RE– a scenario which is 4 berths in each WA port. NT port requires 7 berths in E+, E_ and E+RE+.

Table 6 Panel B compares the berth required against berth available in selected NZAu ports these days (See Table 8 for berth facilities in ports). In E+RE+, berth demand in NT is 200% of existing berth whereas NZAu energy export requires 12% and 22% of total berth available in three ports of WA in E+ and E+RE-. Note, the berth number used for comparison varies in capacity and purpose. For example, Port Hedland and Dampier port are heavily used for iron ore export [7, 8] and may need upgrading for energy exports, or may conflict with the existing iron ore industry. In E+ONS, the ship call for iron could fall by one third due to reduced volume of exported commodity (DRI compared to iron ore; see *Downscaling – Onshoring of industry* document) and existing berths could be repurposed for energy export.

Table 6 | Number of berths required to ship ammonia (Rounded figure)

Zone	E+	E+RE+	E+RE-	E-	E+ONS
Panel A: Total number of berth in 2060					
Port-NT	7	8	2	7	2
Port-WA	6	6	11	6	0
Port-QLD	5	5	2	5	1
VIC-east	0	0	2	0	0
Port-SA	0	0	0	0	0
Port-NSW	0	0	0	0	0
Panel B: Total number of ship call in 2060					
Port-NT	175	200	50	175	50
Port-WA	12	12	22	12	0
Port-QLD	19	19	7	19	4
VIC-east	0	0	29	0	0
Port-SA	0	0	0	0	0
Port-NSW	0	0	0	0	0

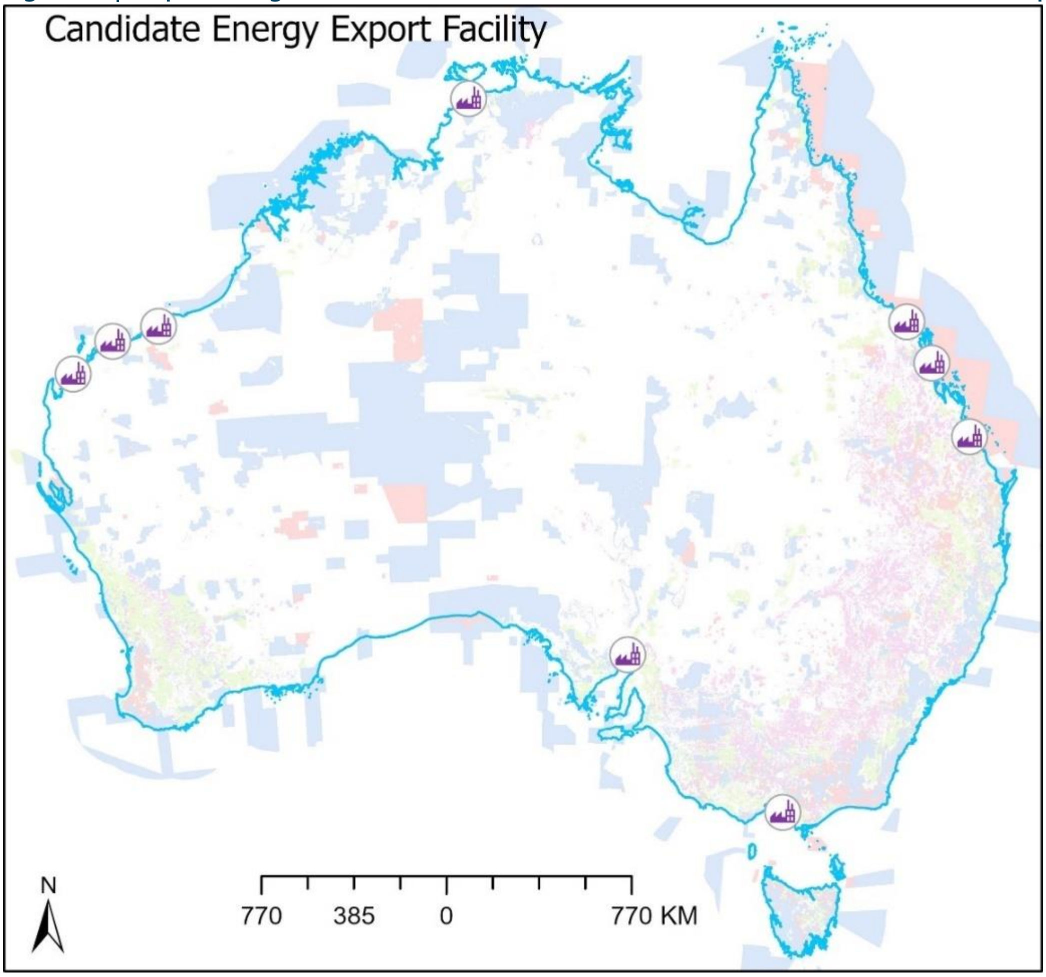
3 Candidate Energy Export Facility (CEEF)

NZAu assumes energy will be exported from the selected 10 ports. Therefore, we locate candidate energy export facilities (CEEF) near the port. Based on the CEEF selection method described in the method section 5.3, we locate the CEEF sites near the port as shown in Figure 21.

Each port will have a CEEF where energy export activities are conducted. CEEF in WA were selected using the exclusion criteria discussed in the method section. These CEEFs are near the port and have enough space to conduct all activities together. CEEF for QLD port uses brownfield sites. Due to the limited footprint of existing brownfield sites, we may have to find additional space. CEEF in NT requires roughly 56 km^2 of land in the E+ scenario. The CEEF in South Australia uses an area near the port that is not currently being used for residential purposes. CEEF in Hasting port and VIC-East is difficult to locate, we locate the CEEF in the Brownfield site that may have to be expanded to meet the footprint demand.

Note, the space needed by CEEF in each port varies substantially depending on scenarios. For example, in E+ONS most of the energy export activities concentrate in WA ports. Whereas RE–Const uses blue hydrogen to produce ammonia and the energy activities in SA port and VIC-East is higher as compared to other scenarios.

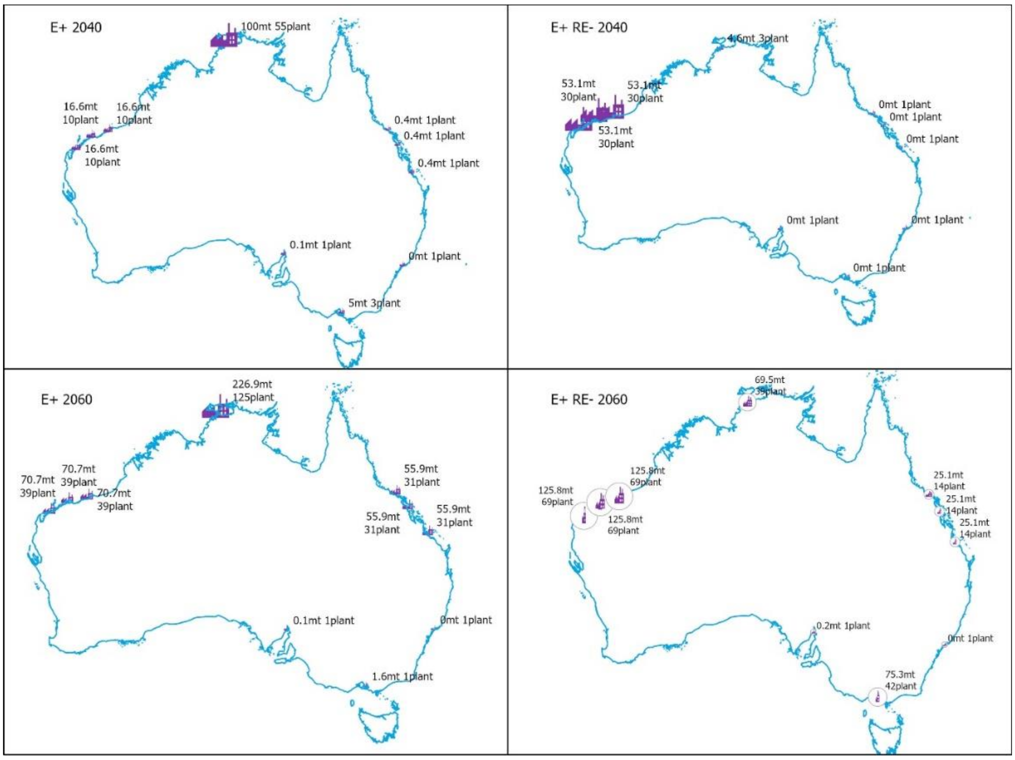
Figure 21 | Map showing the location of CEEF in E+ 2060 with the number of Haber Bosch plant



3.1 Ammonia production in CEEF in two scenarios

Figure 22 presents the number of Haber Bosch trains in the E+ scenario in 2060. CEEF near NT port will have Haber Bosch plant with 108 train with a capacity of 5000tpd, a desalination plant to supply water and 216 ammonia storage tanks. Similarly, each port of QLD will have Haber Bosch plant with 19 train and roughly 150MLD capacity desalination plants. Three ports in WA will have Haber Bosch plant with 58 trains whereas a Haber Bosch plant with 2 train in SA and 1 train in VIC East.

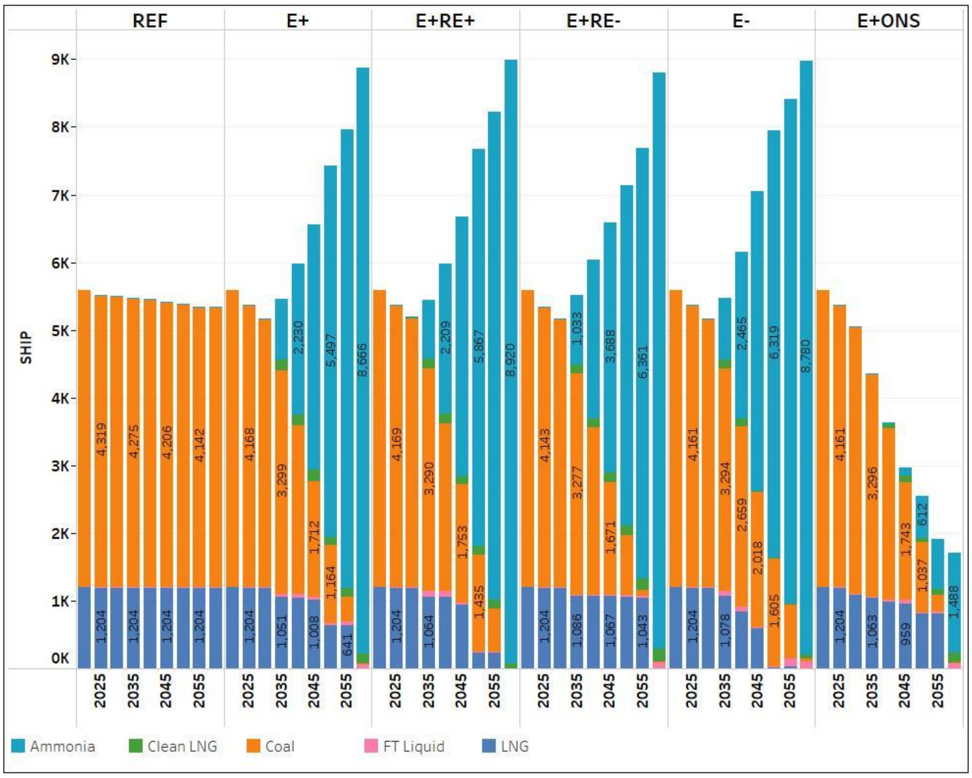
Figure 22 | Quantity of ammonia and number of Haber Bosch plants in CEEF sites in E+ and E+RE– in 2040 and 2060



3.2 Change in shipping infrastructure

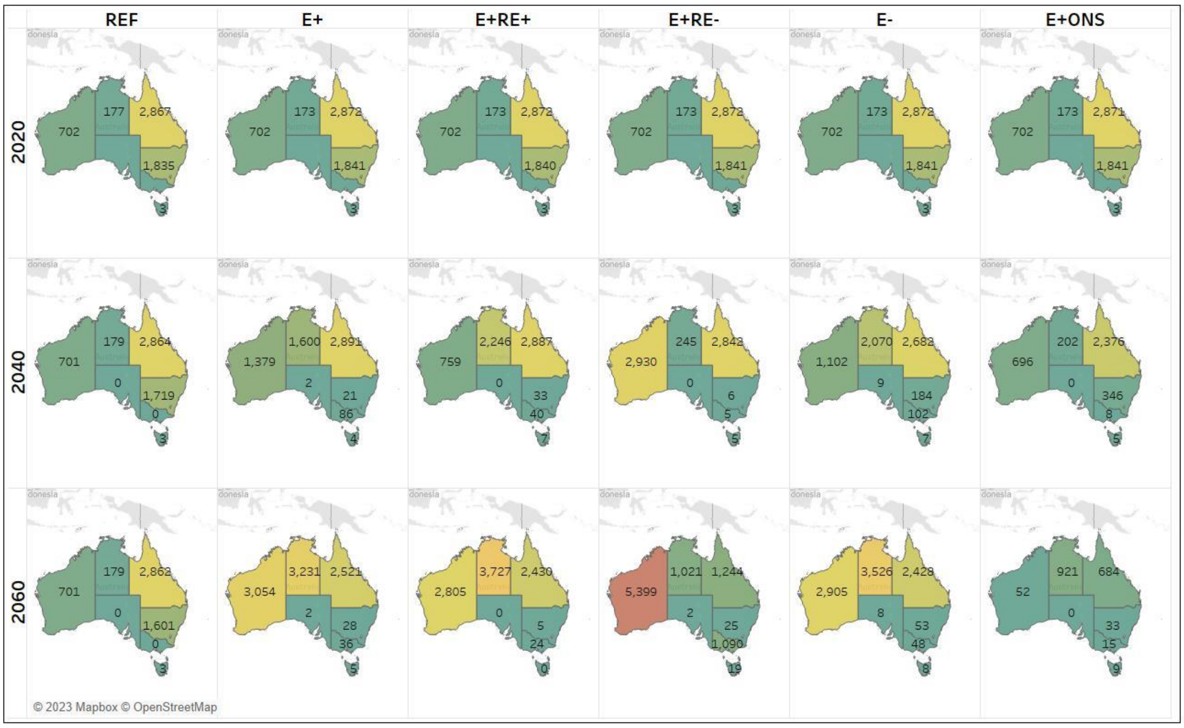
Australia uses ships to export the vast majority of energy export. Ships call for different energy export in NZAu scenarios is reported in Figure 23. Ship calls for coal and LNG export reduces from 2030 and ship call for ammonia increases after 2030.

Figure 23 | Ship call by energy activity



Additionally, the location of the shipping port also changes depending on the scenarios. In E+, E+RE+ and E-, NT port will have more than 3200 ship calls, the highest as compared to other states. In E+RE–, more than two third of ships for energy export will depart from WA ports. In E+, E+RE+ and E-, ship call in QLD will reduce slightly, while the ship calls in NSW reduces substantially from 1840 in 2020 to around 30 in 2060 (See Figure 24).

Figure 24 | Ship call by state



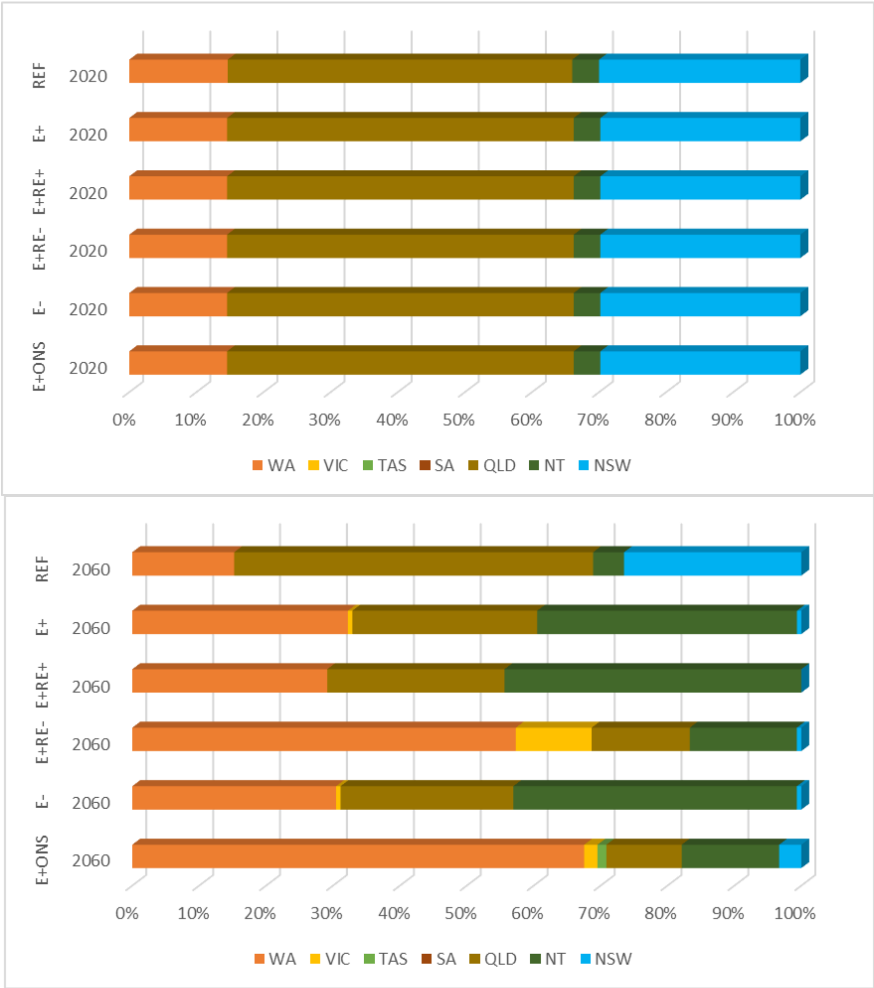
4 Takeaway messages

The five takeaway messages from energy export downscaling are as follows.

i. Australia will move away from fossil fuel export to clean energy export. By 2060 Australia would be exporting roughly 600mtpa of ammonia, 8mtpa of FT Liquid, and 0.4EJ per year of electricity cable to maintain existing energy export.

ii. The state-wise contribution to energy export change from QLD and NSW to WA and NT is seen in Figure 25. E+, E- and E+RE+ are more spatially distributed as compared to another scenario. In E+RE–, two third of energy is exported from WA.

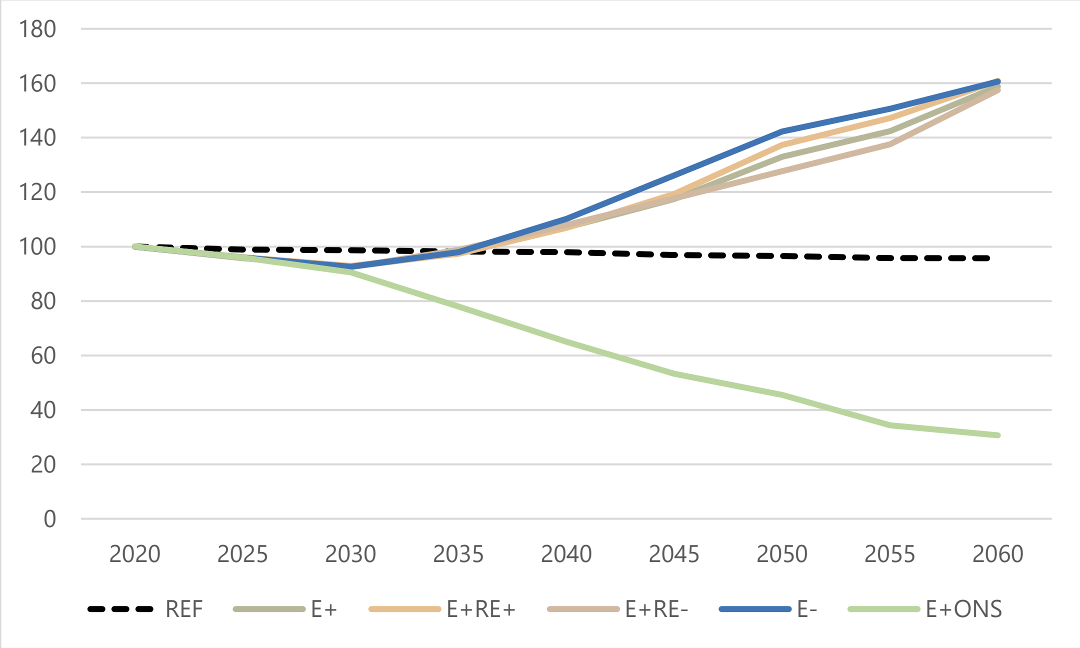
Figure 25 | Change in the export contribution by the state in 2020 and 2060.



iii. Energy export requires extensive scale up of export associated infrastructure with Haber Bosch plant with 350 train (with capacity of 5000tpd each), accompanied by 700 ammonia storage tanks and 5 desalination plants of 1GL per day capacity.

iv. Shipping infrastructure expands in all NZAu scenarios except E+ONS. Ship calls in E+ONS is roughly one-third of the total ship calls in 2020. For other scenarios, the ship calls is ~1.6 times the ship call in 2020 (See Figure 26).

Figure 26 | Change in ship calls as a percentage of ship calls in 2020



v. Shipping infrastructure also needs relocation and repurposing. In the reference scenario ~4000 ships are used for shipping coal and 1200 ships are required to ship LNG. The net zero transition will demand ships for ammonia and FT liquid export. This change in energy carriers requires extensive repurposing and/or new shipping infrastructure. Additionally, new shipping infrastructure may be needed in NT and WA, especially for ammonia export as energy export shifts from QLD and NSW to WA and NT.

5 Method

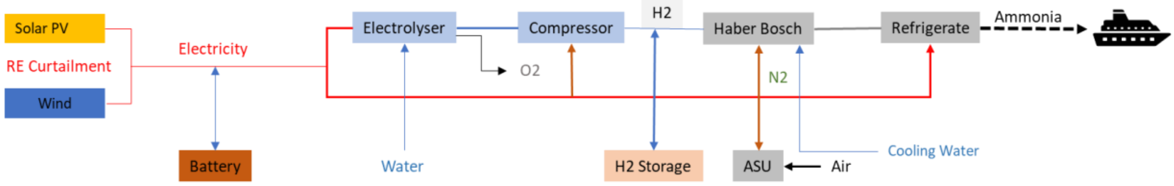
5.1 Data

This analysis draws on the energy flow data generated by RIO, the central model used by NZAu to ensure economy-wide compliance with a 2060 goal for net-zero energy exports. The dataset contains energy activities for all NZAu scenarios for each model year. From that dataset, we extract the energy activities and processes used to produce energy for export.

5.2 Analysis

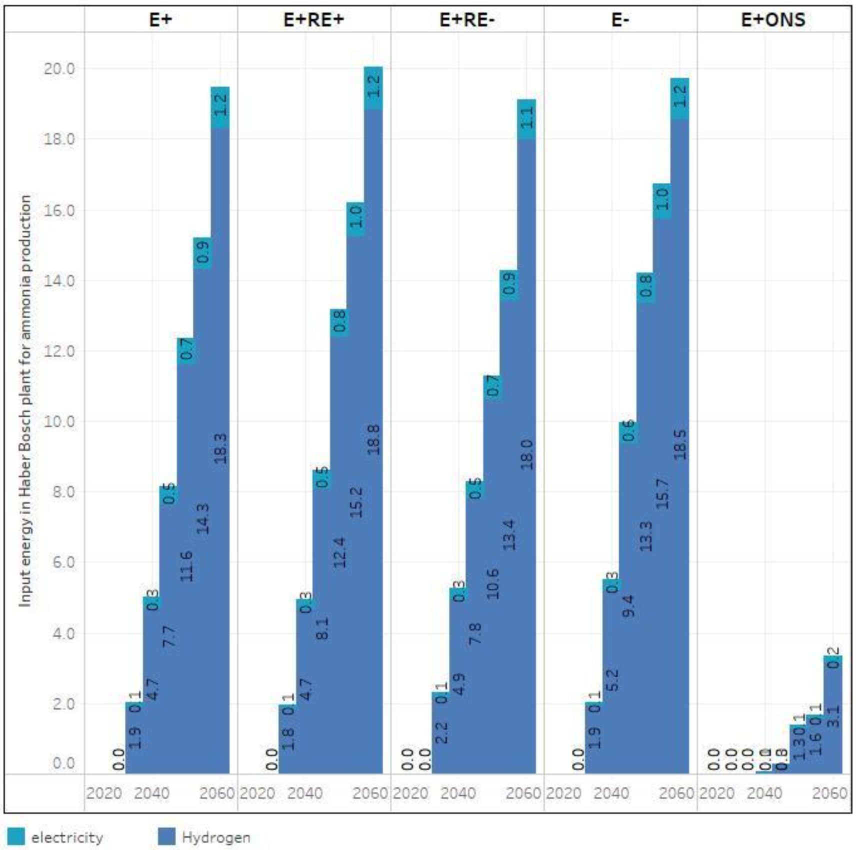
This analysis briefly discusses all forms of energy exported from Australia in NZAu scenarios but focuses on Ammonia production and export arrangement.
Ammonia has several advantages as an energy carrier for export in Australia [9, 10] and has been chosen to represent all clean hydrogen energy carriers in the Net Zero Australia study. To produce ammonia for export, hydrogen produced via electrolysis in the inland export zones is compressed and transported via pipeline to a Haber-Bosch plant within a Candidate Energy Export Facility (CEEF). Depending on the scenario, hydrogen may also be produced in a CEEF through ATR+CC. We assume the Haber Bosch plant contains a number of identical and parallel Haber Bosch trains, each of which produces 5000 tpd of ammonia. The desalination plant will be co-located with Haber Bosch plant near the port. The ammonia is liquified, stored in ammonia storage tanks and then shipped for export. Figure 27 is the notional ammonia export process. This analysis uses this production process as a basis to downscale the energy export in NZAu.

Figure 27 | Schematic process of ammonia production (Based on Figure 3 from Wang, Walsh [11])



We start by extracting input and output energy flow data associated with the Haber Bosch process and other energy exports. As seen in Figure 28, electricity and hydrogen are two key inputs in the Haber Bosch process. Some of the ammonia is produced for domestic consumption, therefore we exclude the ammonia produced for domestic use. Then, the energy value of ammonia (GWh) is converted to ammonia on a mass basis (tonnes). We divide the ammonia production on a mass basis by the Haber-Bosch production capacity (5000tpd per train) to calculate the number of trains. Then we use the Haber Bosch plant footprint factor to calculate the area needed for ammonia production. We also find storage capacity and its footprint. Then using ship throughput, we calculate the number of ship calls in each port.

Figure 28 | Schematic process of ammonia production (Based on Figure 3 from Wang, Walsh [11])



In the dataset, the quantity of Ammonia exported is expressed in GWh. The higher heating value (HHV) of ammonia (22.5 MJ/kg) to calculate the amount of ammonia in a ton for a given amount of energy (t-NH_3/GWh)[1, 9]. We calculate a GWh of ammonia is equivalent to 160.45 tonnes of ammonia.

5.2.1 Plant capacity and number of Haber Bosch trains

Ammonia plant capacities are based on an annualised ammonia production equivalent to 5 ktpd as defined in the NZAu MASS pack [1]. Taking a capacity factor of 90%, this sizes the plant at 5.5 ktpd, or 2.03 Mtpa (noting that annualised production remains at 5 ktpd). This allows the calculation of the number of required ammonia production plants to meet export demand. Ammonia is exported from different NZAu scenarios using NZAu ports. There are three ports in WA, one in NT and three in QLD. Export quantities are split equally between these three ports.

5.2.2 The land footprint for the Haber Bosch train

Land footprints of existing ammonia plants were analysed to estimate the land required for NZAu ammonia plants. Ammonia plants are often combined with the production of more complex nitrogen-based compounds (urea, ammonium nitrate, ammonium phosphate, etc). It is difficult to differentiate the amount of land that is taken up by the ammonia production components and the rest. Three examples were found where the differentiation could easily be made. These were Yara Pilbara Fertilisers (WA), Dyno Nobel Louisanna (USA) and Yara Belle Plaine (Canada). Plant footprints were estimated using mapping software and nameplate capacities determined from the company's available data. The plant footprints and extrapolated footprint for a 5 ktpd plant are given in Table 7.

Table 7 | Existing ammonia plant footprints

Plant	Capacity (kt/y)	Area (km^2)	Area for 5 ktpd plant (km^2)
Yara Pilbara Fertilisers	850	0.2418	0.54
Dyno Nobel Louisanna	800	0.3101	0.74
Yara Belle Plaine	678.9	0.2256	0.63
Average	–	0.2592	0.64

Given green ammonia plants will not require any natural gas reforming and processing equipment, the trains will be smaller than existing natural gas-based ammonia plants. To accommodate, the average extrapolated area for a 5 ktpd train has been scaled down by 25%. Note that this conservative scaling will facilitate buffer zones between trains. Thus, a 5 ktpd green ammonia production train used in NZAu will be sized at 0.48 km^2.

5.2.3 Ammonia storage at the terminal

Haber Bosch plants produce ammonia on a constant basis; however, shipping is intermittent. Thus, storage of ammonia at ports is required to synchronize ammonia production and shipment. A basis of 20 days of storage of ammonia production has been taken, meaning each ammonia plant must be associated with 100 kt of storage.

Ammonia is conventionally stored at large scales as a saturated liquid at atmospheric pressure (and thus at -33 ºC). Because of ambient heat transfer, the boiloff gas is condensed through refrigeration cycles before being returned to storage. Tanks are designed with high levels of insulation to minimise boil-off.
Engineering company McDermott is currently constructing two (2) 50 kt ammonia storage tanks for the Qatar Fertilizer Company (QAFCO) plant in Mesaieed, Qatar[12]. These tanks are constructed out of single-walled concrete and incorporate a refrigeration cycle to offset heat leakage. The tanks each are 50 m in diameter and 40.5 m high. The direct footprint of these tanks is therefore 1963 m^2 (~39 m^2/kt). Analysis of ammonia facilities shows that tanks have a buffer of approximately 10x their footprint between them and other equipment (not including other tanks). Thus, the footprint of a 50kt tank and associated buffer can be approximated as 20,000 m^2 (0.02 km^2). Per 5ktpd Haber-Bosch ammonia synthesis plant, two storage tanks and thus 0.04 km^2 of land will be required for 20 days of storage. Note, due to high ship calls and constant production of ammonia, the requirement for a storage tank could be reduced by optimizing the shipping process.

5.2.4 Other sources of energy export

We follow a step-wise process to downscale other sources of energy export. For FT Liquid, clean LNG and electricity export through cable, this analysis presents the input, output and quantity of energy exported. For Coal and LNG, we use historical data and merge it with NZAu prediction to show fossil fuel export. We also calculate the quantity of export in tons and its state-wise production.

5.2.5 Shipping arrangement

Port throughput

The annual energy-related export throughputs of the ten export terminals have been recorded. The 2018 calendar year was selected as representative of pre COVID shipping behaviour. Both total shipping tonnage and number of vessels calls per commodity is reported in Table 8. Only energy and iron related commodities were included.

Note that quality of data for each port varies greatly, with some port authorities providing clear breakdowns of shipping per commodity and others providing substantially less granularity. Where reasonable, data fields have been estimated (i.e. where number of vessel calls are not provided, an estimate has been made by scaling calls at other ports by tonnage). It should also be noted that number of vessel calls are much more relevant than tonnage – ports are more likely to be limited by the number of vessels which can visit per year rather than export tonnage (which varies substantially by commodity).

Table 8 | Tonnage and number of calls for export terminals in 2018

Port	Calls	Tonnage	Details	Reference
Gladstone	1888	121.2	Coal – 687 vessels (68.9 Mt) LNG – 298 vessels (19.4 Mt) LPG – 12 vessels (7.8 Mt)	[13]
Hay Point	1179*	118	Coal exports only	[14]
Abbot Point	288*	29	Coal exports only	[14]
Newcastle	1769	159	Coal exports only	[15]
Hastings	73	1	LNG – 54 vessels Steel – 19 vessels	[16]
Darwin	204		LNG – 165 vessels (10.7* Mt) LPG – 39 vessels (25.4* Mt)	[17]
Bonython	–	–		–
Dampier	3112	172.9	LNG – 332* vessels (21.6 Mt) LPG – 1* vessel (0.4 Mt) Ammonium – 0.4 Mt Condensate – 3.9 Mt Iron ore – 780 vessels (141 Mt)	[18]
Port Hedland	3252	588	LNG – 4* vessels (0.2 Mt) Iron Ore – 3255 vessels (588 Mt)	[19]
Ashburton	137*	9	LNG – 137* vessels (8.9 Mt)	[20]

*The number has been *estimated* from another detail provided about the port (tonnage or vessel calls)

Ship call

We calculate ship calls for coal, LNG, Ammonia and FT Liquid. We divide the total coal exported per ship by the total ship calls used to export coal in Hay Point from 2018 January to 2022 December to calculate the coal ship using information from Ports Australia [21]. According to the statistics, Hay Point Port exported ~412Mt of coal during this period and received 4273 ship calls. The average ship capacity is therefore 96000 tons per ship.

Similarly for LNG, we use statistics from Gladstone Ports Corporation [13] and calculated an average LNG ship capacity of 65000 tons. We use a shipping capacity of 105,000 m^3 [1] to calculate the ship calls required for ammonia. Based on 680 kg liquid ammonia per 1m^3 liquid ammonia, we calculate an ammonia ship exports 70400 tons per ship.

Calculating the weight of FT liquid is difficult as the molecular density of FT liquid varies by its product. Based on the domestic use of FT Liquid, the majority of it is used for Aviation Turbine Fuel, therefore we use 43.71MJ/kg of conversion factor from Gofman [22]. Therefore, we assume FT liquid as refined fuel. US Energy Information Administration uses Average Freight Rate Assessment (AFRA) system to inform about the ship capacity by fuel type. Refined oil carrier range up to 120DWT[23]. Which is in the range of LNG carriers in Australia. We assume FT liquid carrier will ship the same load as the LNG carrier ~65000 tons.

This analysis briefly explores the berthing requirement for the ship in port. Although, berth requirement depends on several factors such as type of energy sources, flow rate and size; we provide a rough calculation of berth number. We assume one ship takes 16 hours for filling or loading and the berth operates 90% of the days in a year. Based on this calculation we assume; one berth serves 492 ships in a year. The existing number of berth in different port are reported in Table 9.

Table 9 | Number of berths in NZAu port

State	Ship berth	Port	Source
NT	4	Port of Darwin	[24]
WA	51	Port Hedland, Ashburton, Dampier	[7, 8, 25]
QLD	27	Gladstone Port, Port of Abbot Point and Hay Point	[26, 27]
VIC	7	Port of Hastings	[28]
NSW	11	Newcastle	[29]

5.3 Candidate Energy Export facility (CEEF)

NZAu assumes the quantity of energy export remains constant at ~15EJ per year. However, the fossil fuel-based energy sources like coal will be replaced with clean energy sources like ammonia. Existing energy export facilities host a wide range of facilities such as LNG export facilities and coal export terminals. In NZAu, ammonia dominates the energy export sources. Ammonia is produced using industrial processes needing production facilities, a supply of desalinated water for process cooling, and storage facilities. Therefore, we conceptualize the ammonia production area as a candidate energy export facility (CEEF). CEEF will have:

a) Haber Bosch plants that have several trains each with 5000tpd production capacity
b) The desalination plant supplying desalinated water to the Haber Bosch plant
c) Ammonia storage facility
d) In some but not all scenarios the facility will also host ATR+CC plants to supply hydrogen to Haber Bosch plant

The total land footprint for energy export in NZAu is the sum of the area needed for the Haber Bosch plant, the desalination plant that feeds water to the Haber Bosch plant and the storage terminal (Table 10 provides the land footprint factors).

Table 10 | Land footprint for the CEEF

Aspect	Land footprint	Unit	Source
Haber Bosch plant	0.48	Sq km per plant sized 5000tpd	
Desalination plant	0.7	Sq km for 1000MLD plant	
Storage terminal	0.04	Sq km for 50 KT capacity	

5.4 Site selection for CEEF

The desalination plant supplying water for ammonia and the ATR+CC plant supplying hydrogen (noting ATR+CC supplies only a small quantity of hydrogen in all but E+RE–) is co-located with the Haber Bosch plant, the site selection process and desalination site selection for Haber Bosch is similar. Figure 29 provides the step-by-step process of CEEF location selection.

This identifies the candidate energy export facility for ammonia production using the following key criteria. The criteria aim to make the CEEF siting suitable from three aspects: the social, environmental, and financial aspects.

i. CEEF is located nearest possible port to facilitate export and easy supply of desalinated water near the sea.
ii. Exclude conservation areas (including national parks etc)
iii. Use existing brownfield sites or possible brownfield sites if available

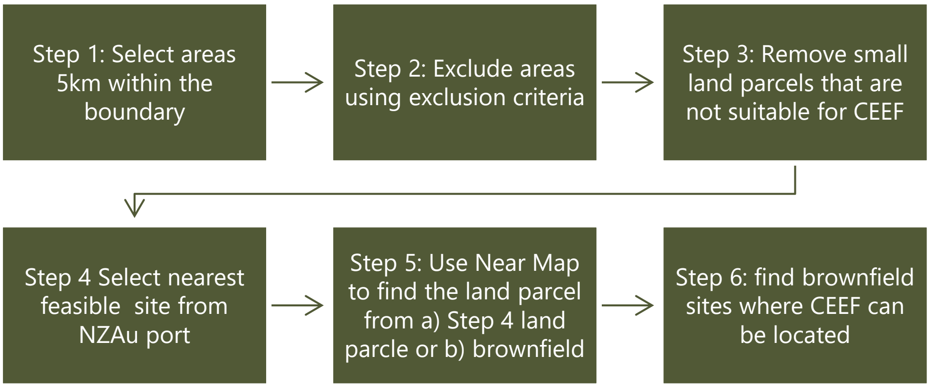
We use the same exclusion criteria mentioned in the MASS document and used for coastal desalination site selection in the *Downscaling – Water use and transmission* report for the NZAu [1]. Further, brownfield sites (including future brownfield sites due to the retirement of coal or LNG plant in NZAu scenarios) were explored using Near Map, especially in the Great Barrier Reef Marine bioregion, VIC and SA.

CEEF are located near to port to reduce the transport of ammonia to ships and reduce water transmission from sea to the desalination plant. We use a 5km buffer from the coastal area to select the CEEF site.
To reduce the possible environmental impact due to energy and desalination activities in the CEEF, we used two different strategies. Firstly, we use exclude areas that are ecologically sensitive using following the dataset.

- National reserves[30]
- Collaborative Australian Protected Area Database (CAPAD)[31]
- Ecological Communities of National Environmental Significance [32]
- Species of National Environmental Significance [33]

Secondly, because the port is predefined and some of the ports are in ecologically sensitive areas such as Northern QLD ports are located at the cost of the Great Barrier Reef. Because this port will be used to produce and export ammonia and also have a desalination plant collocated, we explored the use of brownfield sites in three ports located in the Northern QLD. A similar approach was used in VIC and NSW where port areas are congested due to dense economic activities.
Then we used the near map and topographic map in ARC GIS Pro to verify if the selected sites are contextual and don't fall into a reserve or conservation area.

Figure 29 | CEEF location identification process



NZAu assumes the sites using coal and fossil fuel processing will soon retire therefore the brownfields can be repurposed for clean energy production and processing to reduce the cost and environmental footprint of infrastructure provisioning.

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