Allam-Fetvedt Cycle Coal Poly-Gen Feasibility Study

Executive Summary

May 2021

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1.1 Key points

- One of Australia's biggest potential contributions to global decarbonisation would be as a global exporter of net-zero energy products
- Australian coal can become a key net-zero resource for the world as exported clean hydrogen
- The Allam Cycle plant is projected to produce clean hydrogen at or below $2.00 per kilogram[1] ($2.00/kg)
- The design features > 99% inherent carbon capture to capture 3.48 million tonnes of CO_2 per year
- The availability of economic and proven CO_2 sequestration sites is a critical dependency
- This plant would provide over 450 MWh of daily energy storage for renewables, providing power grid security (24/7 power) and grid firming capacity to support intermittent renewables
- Australia's thermal coal exports would be equivalent to 17.5 million tonnes of clean hydrogen, which could increase annual export revenues for Australia by 71% and decrease global CO_2 emissions by 43.5 million tonnes of CO_2 per year, with a potential export value of $35 billion

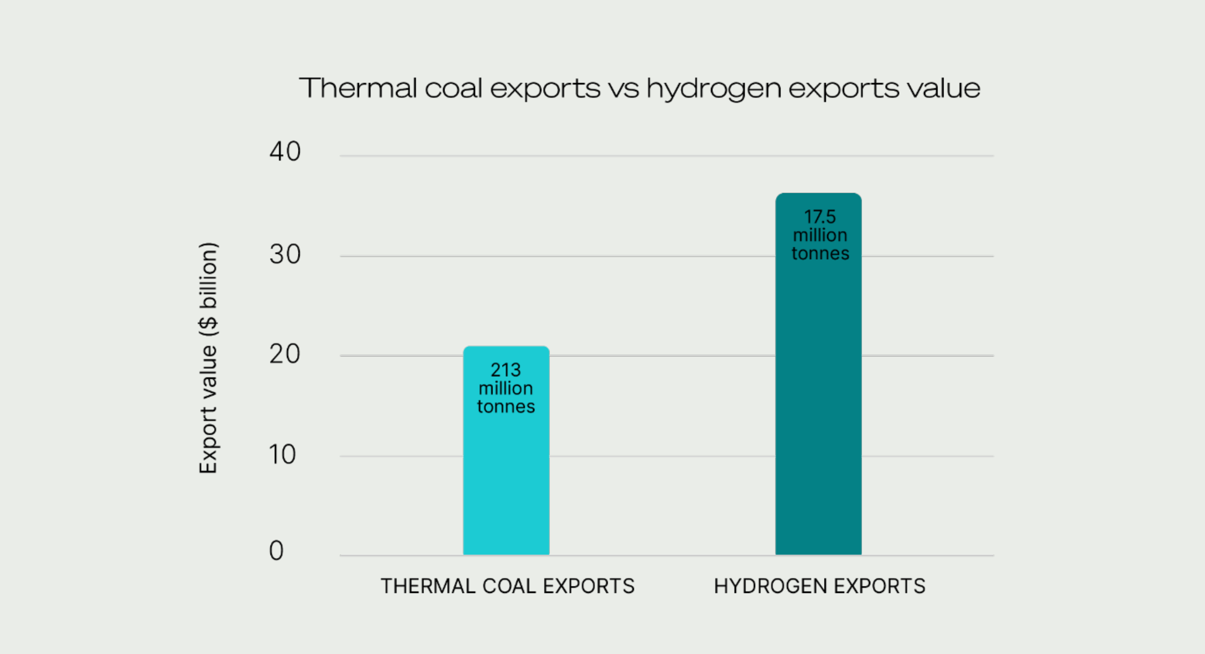
1.2 Introduction

Low Emission Technology Australia (**LETA**) have commissioned 8 Rivers Capital, LLC, (**8 Rivers**) to carry out a feasibility study in respect of deploying the Allam-Fetvedt Cycle (**Allam Cycle**) in poly-generation plants in Queensland (**plants**). With black coal as the fuel, the plants can produce both clean hydrogen at or below $2.00/kg for domestic consumption and global export, and clean electricity to balance and firm renewable generation domestically, while avoiding carbon dioxide (**CO_2**) emissions to the atmosphere. The Allam Cycle plants can also be deployed in other configurations, such as electricity only or using the hydrogen to produce clean hydrogen-derived nitrogen fertilisers.

Australia faces a nation-defining challenge and economy-altering opportunity. With access to large-scale carbon storage, Australian coal can become a key net-zero resource for the world as exported clean hydrogen and ammonia, provided that the associated carbon is efficiently separated and safely stored as part of the production process.

Australia's thermal coal exports would be equivalent to 17.5 million tonnes of exportable clean hydrogen with the Allam Cycle analysed in this study, which would represent an increase of annual export revenues by 71% while reducing global[i] carbon dioxide (**CO_2**) emissions by 43.5 million tonnes per annum. This can also substantially reduce global nitrogen and sulphur oxide emissions (with a corresponding positive impact on human health and environmental advantages). Further, Allam Cycle plants can also utilise sub-export grade thermal coal, meaning the export opportunity is even larger than today's thermal coal exports.

[1] *All figures are in Australian dollars unless otherwise noted.*



The Allam Cycle is a breakthrough zero emissions technology which uses CO_2 instead of steam to drive a turbine, while inherently eliminating air pollution and capturing the CO_2. The Allam Cycle does this by burning fuel, including syngas derived from coal with pure oxygen rather than air.

The technology was tested on natural gas in Texas by NET Power, LLC (**NET Power**) funded by more than US$160 million in private sector investment. LETA and the US Department of Energy are currently co-funding a US$21 million syngas combustor programme, which will allow the Allam Cycle to be deployed on gasified coal and biomass.

The Allam Cycle's ability to ramp quickly means that plants can provide power grid firming capacity to support intermittent renewables. With increasing renewable penetration on the grid there will be a requirement for clean flexible firming capacity, providing essential grid security services to ensure grid stability at times when there is no sun or wind. Accordingly, the Allam Cycle technology is complementary to, not in competition with renewable electricity generation, and indeed is expected to enable deeper renewables deployment to occur.

1.3 Overall findings

This study finds that deployment of the Allam Cycle with Queensland black coal is feasible[2]. This summary illustrates the cost and performance of three cases:

1. Hydrogen exported as ammonia with peaking electricity (Clean Ammonia Production)
2. Hydrogen only with peaking electricity
3. Electricity only[3]

The study focussed on clean ammonia production since ammonia is functionally a hydrogen vector. Liquid ammonia allows for the safe and simple storage and transport of, high energy density, liquid fuel using existing global transportation infrastructure. The primary configuration[4] studied would produce 134 million kilograms per year of globally competitive clean hydrogen exports while also

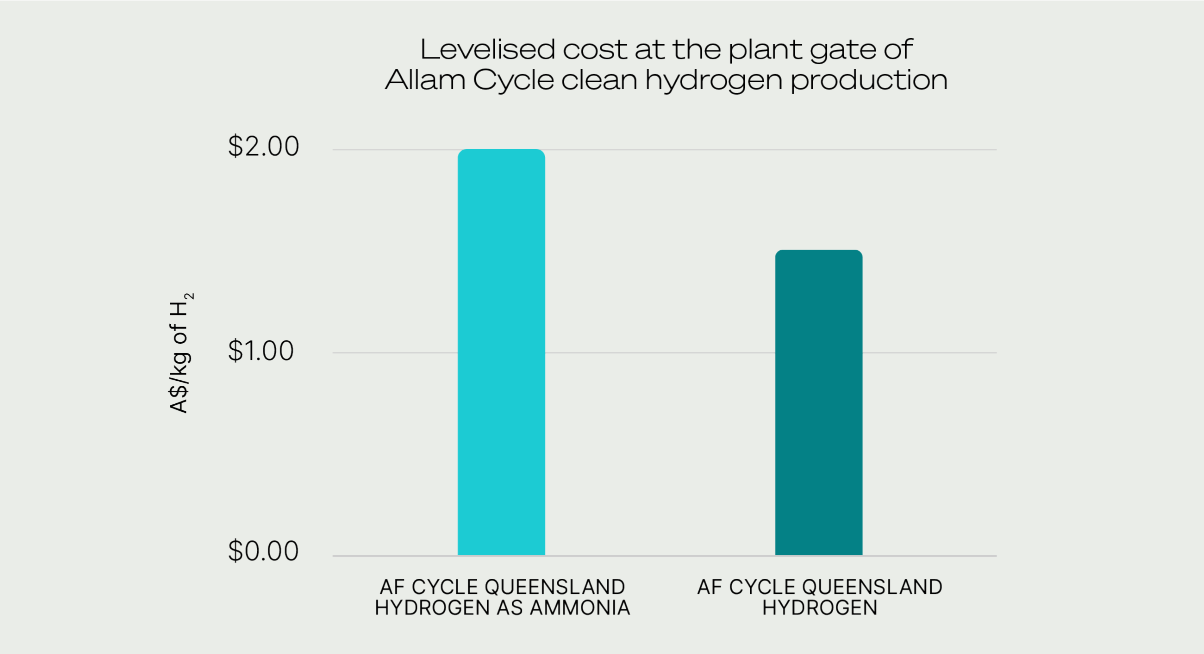
[2] *Given multiple developments of the Allam Cycle underway globally, the study has assumed that plants in Queensland are deployed on a next-of-a-kind basis (serial number 8 plus).*
[3] *The Feasibility Study primarily considered hydrogen and fertilizer export cases. Electricity only was considered as a sensitivity case.*
[4] *"Hydrogen exported as ammonia with peaking electricity case".*

routinely providing daily peaking electricity of up to 91.3 MWe, which can be used to balance the power grid while providing critical grid firming capacity. Surplus renewable power can also be drawn from the grid when it is available for later dispatch during peak demand periods allowing Allam Cycle plants to also provide services like large-scale grid batteries.

When demand for electricity is very high, the plant can peak at up to 128.8 MWe by turning down the air separation unit (**ASU**), gasifier, and ammonia plant to 80% capacity and can reach 196.6 MWe by further turning down the ASU and Gasifier and temporarily shutting down the ammonia plant.

During times of extreme demand, that typically only occurs once or twice a year, the Gasifier and chemical synthesis Facility can be turned off while the Allam Cycle is run on natural gas and stored oxygen. This configuration would allow the Allam Cycle to peak to roughly 330 MWe, and thereby play a vital role in avoiding blackouts and large-scale loss of electricity supply, including through the 24/7 provision of critical grid security services such as system strength.

The figure below shows that for the hydrogen exported as ammonia, the levelised cost of production is $2.00/kg of hydrogen at the plant gate (Australia's target price is $2.00 to $3.00 per kilogram of hydrogen at the plant gate)[5], while the hydrogen only case can produce sub $2.00/kg hydrogen.



The study also considered a scaled-up case as a sensitivity, which could further reduce the cost[6]. The plant can effectively be configured with either two or three gasifier trains and to generate a mix of peaking electricity and hydrogen that suits the specific circumstances.

The study found that the availability of economic, proven CO_2 sequestration sites is a critical dependency. Further government support and enablement of the development of suitable CO_2 sequestration sites will significantly de-risk deployment.

An Allam Cycle plant could also be deployed in an electricity only configuration[7], although the superior efficiencies and flexibility derived from being a poly-generation facility are not captured. This configuration still provides a compelling case for clean, dispatchable electricity generation to support a zero-carbon grid, subject to market participants or stakeholders being prepared to pay for this flexibility. With this configuration surplus renewable power will also be able to be drawn from the grid

[5] National hydrogen roadmap, *page xix.*
[6] *"Scaled up/hydrogen only case as ramping of the AFC is limited to ASU turndown"*
[7] *"Electricity only case"*

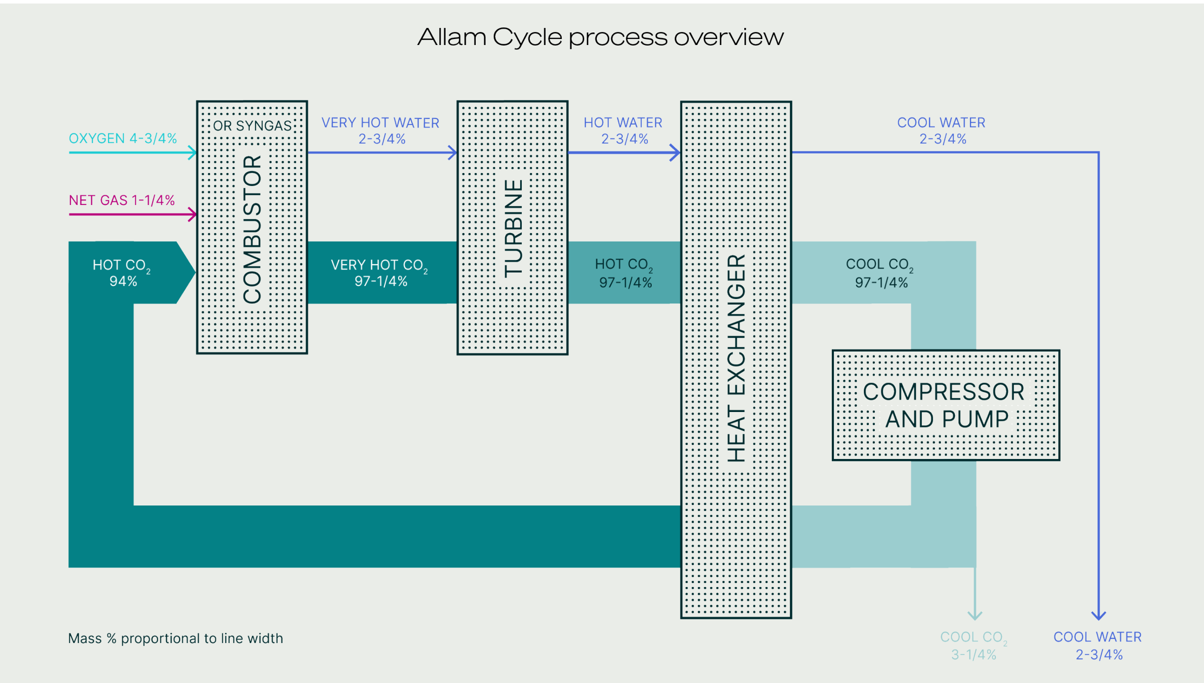
when it is available for later dispatch during peak demand periods thereby providing services like large-scale grid batteries.

1.4 Path to net negative emissions

The environmental performance of the Allam Cycle can achieve net-negative emissions by building a biomass gasification facility to provide a portion of the syngas to the plant. It thereby captures CO_2 drawn from the atmosphere into the feedstock biomass (commonly called bio-energy carbon capture and storage, or BECCS), and sequesters the captured CO_2 deep underground. Supplying feedstock syngas from biomass into the Allam Cycle would transition the plant to producing net-carbon *negative* hydrogen or ammonia. The portion of syngas from biomass could be ramped up over time as demand for carbon removal increases.

1.5 Technology overview

The Allam Cycle is a transformational technology that enables a step change in the performance, efficiency, and cost of clean electricity from zero-emission fossil-fuel-based electrical generating units by using direct-fired supercritical CO_2 (**sCO_2**) as the working fluid in the turbine with oxy-combustion in a synthetic air environment. The system features > 99% inherent carbon capture and can convert other waste streams into value-added by-products. Water will be cleaned and re-used within the process, with the facility capable of operating on a zero liquid discharge basis, thereby minimising the requirement for make-up water.

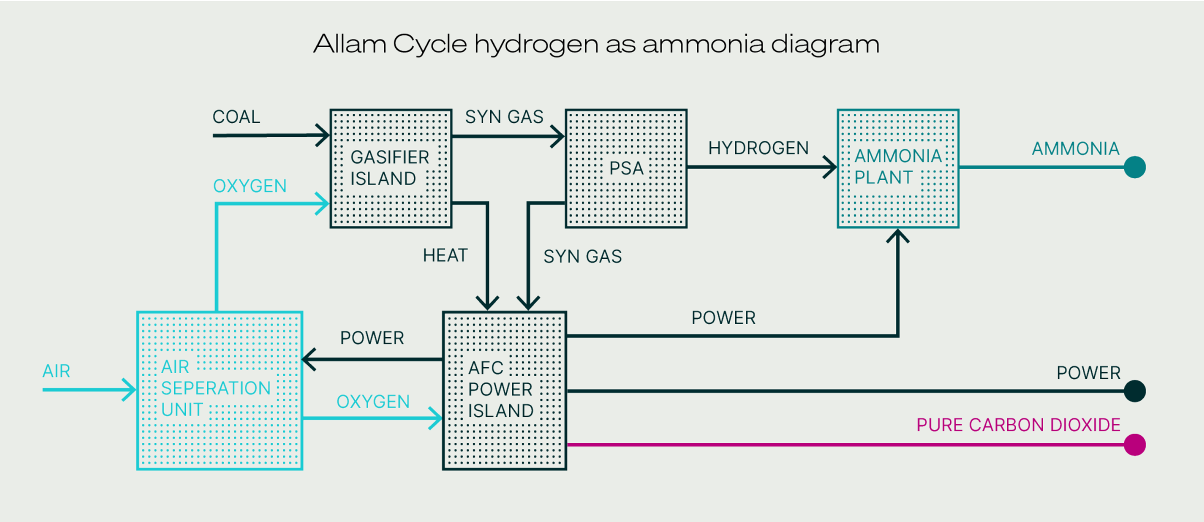


The Allam Cycle can be fuelled with a gasified coal or biomass-derived syngas feedstock. Within the system, hydrogen is first separated from the syngas feedstock with a Pressure Swing Absorber (**PSA**) and the Allam Cycle then utilises the carbon-monoxide rich co-product gas as fuel in the main Allam Cycle power cycle. This process captures the CO_2 from hydrogen production while producing substantial volumes of high-efficiency electricity with carbon capture, creating a clean hydrogen product from Queensland black coal. This operational profile is a unique characteristic of the Allam Cycle, enabling the highly efficient production of clean power and hydrogen, allowing for a process that is low cost, zero (or negative) emissions, and at a scale of production sufficient to enable deep decarbonisation of Australia's energy systems and those of export partners.

1.6 Plant configuration

One of the benefits of the Allam Cycle is the flexibility to deploy in a range of configurations, including poly-generation. This study considered a range of cases, with the focus being on primary production of clean hydrogen (as ammonia), with co-generation of flexible peaking electricity with 24/7 grid support services. The figure below sets out the high-level plant configuration for this case.

Coal is converted to syngas in a high temperature (1300°C) gasification process in the gasifier island. Heat from the gasification of coal is integrated with the Allam Cycle to provide enhanced efficiency to the process while the hydrogen-rich syngas is sent to a PSA to separate the hydrogen content. The remaining syngas is used as fuel for the Allam Cycle. The separated hydrogen can be used to continuously produce ammonia (without production associated carbon emissions) and to generate the main revenue stream for the Facility. Meanwhile the syngas left over after hydrogen separation can be used to generate electricity in the Allam Cycle Power Island. The Allam Cycle Power Island can rapidly respond to fluctuations in energy demand by storing part of the syngas during times of low power demand and quickly ramping to full capacity during times of higher power demand. The overall Facility is also capable of running in a state where power is purchased from the grid. The configuration studied assumes this is performed daily to take advantage of daily power price fluctuations.



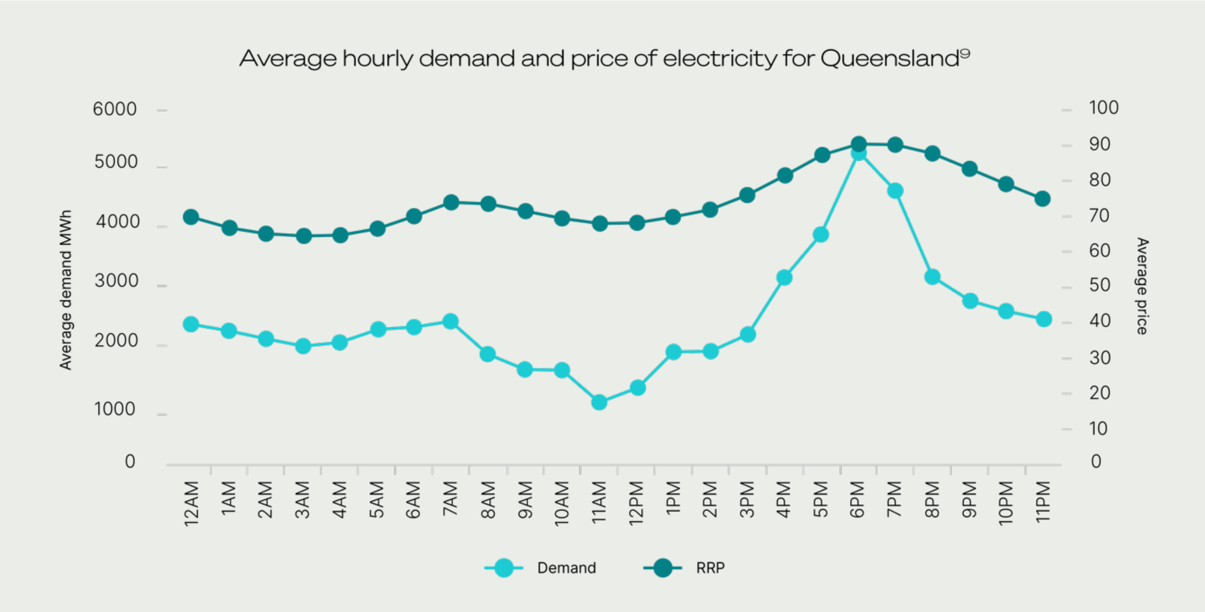
1.7 Plant flexibility

The Gasifier and Ammonia plants run 24/7 while the Allam Cycle has the ability to rapidly ramp power output up or down to meet peak demand periods. The overall Facility is also capable of running in a state where power is purchased from the grid. This provides the flexibility required to balance fluctuating electrical loads from wind and solar and provide services like large-scale grid batteries.

The poly-generation Allam Cycle plant in this study was designed to provide 24/7 hydrogen[8] and peaking power. The daily Queensland electrical price peaks for 5.5 hours a day as the sun sets and solar generation decreases. For 18.5 hours a day, the plant will act like a large-scale grid battery and be a net power importer, buying 27.0 MWe off the grid, and effectively storing that energy as syngas for later use. Then starting late afternoon, the Facility will utilise stored syngas and oxygen to produce 91.3 MWe when it is needed most, then ramping down after demand has reduced. Throughout, hydrogen production remains constant, as does the provision of critical grid security services, even while the Allam Cycle is operating at different power outputs.

[8] *Subject to an allowance for maintenance downtime (90% capacity factor assumed).*

Secondly, for the highest power demand days, the plant could turn down hydrogen production to peak above 196.6 MWe. This provides additional flexibility and renewables support.



Operating in this manner, the plant would provide over 450 MWh of daily energy storage for renewables, with the ability to peak to roughly 330 MWe during times of extreme power demand.

1.8 Environmental performance

The Allam Cycle plant considered in this study will produce electricity and clean hydrogen / ammonia at large scale with > 99% carbon capture. Current fossil fuel-powered electricity generation and ammonia production technologies without carbon capture and storage are carbon-intensive and emit significant quantities of CO_2 and other greenhouse gases (**GHG**) into the atmosphere. When comparing the carbon emissions of the Allam Cycle to other ammonia production technologies (natural gas, heavy oil, naphtha), the Allam Cycle coal-to-ammonia process is significantly cleaner, reducing carbon emissions by over 98% compared to average emissions of 2.867 tonnes CO_2 / tonnes ammonia from other fossil fuel energy sources, while maintaining a high level of efficiency.

Further, the plant has a positive environmental profile in respect of other considerations typically associated with coal fuelled power plants. In the Allam Cycle plant, the coal is transported into the gasifier using the available CO_2 instead of nitrogen, thereby eliminating nitrous oxide formation. Additionally, the use of sCO_2 instead of steam greatly reduces the water demand. The CO_2 generated in the Allam Cycle is captured and is appropriately managed by way of subsequent sequestration or provision to other industrial processes. Other waste streams including elemental sulphur, fly ash, wastewater, mercury, volatile organic compounds (VOC), and particulates have been carefully considered during the design of the Facility and are either eliminated or converted to valuable by-products of the plant.

1.9 Technical performance

A process model for the plant has been developed in Aspen Plus.[ii] Vendor data has been used for the simulation of each sub-process in the system.

- The hydrogen as ammonia case would consume approximately 1.6 million tonnes of coal per annum and produce 0.75 million tonnes of clean ammonia per year containing approximately 134 million kg of clean hydrogen, and the plant would be further capable of daily peaking to 91.3 MWe. Over 3.48 million tonnes of CO_2 emissions would be avoided by capture and sequestration per year.
- Under the hydrogen only case 1.6 million tonnes of coal would be consumed per year and would produce 130 million kg of clean hydrogen, and the plant would be further capable of daily peaking to 129.5 MWe. Over 3.48 million tonnes of CO_2 emissions would be avoided by capture and sequestration per year.
- The electricity only case would consume approximately 0.9 million tonnes of coal per annum, produce an average of 229.6 MWe of electricity, and over 1.5 million tonnes of CO_2 emissions would be avoided by capture and sequestration per year.

The performance of the cases is set out the in table below:

Allam Cycle plant performance		**Hydrogen as ammonia**	**Hydrogen only**	**Electricity only case**
Coal thermal input to gasifier	MW in LHV	1,251	1,251	663
Net power output (for 5.5 hours / day)	MWe	91.3	129.5	N/A
Net power consumed (for 18.5 hours / day)	MWe	27.0	11.3	N/A
Net power output (average)	MWe	0.1	38.36	229.6
Coal input	m tonnes pa	1.61	1.62	0.86
Ammonia output	m tonnes pa	0.75	N/A	N/A
H_2 in ammonia output	m kg pa	133.8	130	N/A
CO_2 captured	m tonnes pa	3.48	3.48	1.56

Total overnight costs and product costs

Estimated total overnight cost[iii] for the base configuration with hydrogen as ammonia is A$2.6 billion. The figure below outlines the levelised cost of product (LCOP) for the three cases

Levelised cost of production (LCOP) at plant gate	**Hydrogen as ammonia case**	**Hydrogen only case**	**Electricity only case**
	A$/tonne ammonia	*A$/kg Hydrogen*	*A$/MWh*
Capital costs	248	1.18	66
Operating costs (including sequestration)	140	0.72	38
Fuel costs	81	0.46	18
Net electricity revenue	(8)	(0.18)	N/A
CO_2 incentive revenue	(92)	(0.52)	(17)
Argon revenue	(13)	(0.07)	(6)
LCOP at plant gate	**$356**	**$1.58**	**$100**

The LCOP of A$356/tonne of ammonia is equivalent to a hydrogen price of A$2.00/kg. The study also considered a hydrogen only case, producing gaseous hydrogen. Results for this case support an A$1.58/kg hydrogen price at the plant gate[9].

Key assumptions underpinning the analysis are set out in the table below.

Key assumptions	
WACC (real, tax adjusted)	4.1%
Coal price (real, $/tonne)	38
Construction period (years)	3
Operations period (years)	30
Capacity factor	90%
CO_2 revenue price ($/tonne CO_2)[10]	20

[9] This case was analysed by scaling up relevant blocks from the primary case, with adjustments for economies of scale, and has a higher degree of uncertainty than the rest of the study.
[10] Assumes an ACCU price of $20 by the time the plant is operational, and that CO_2 sequestered underground is eligible.

1.10 Technical performance

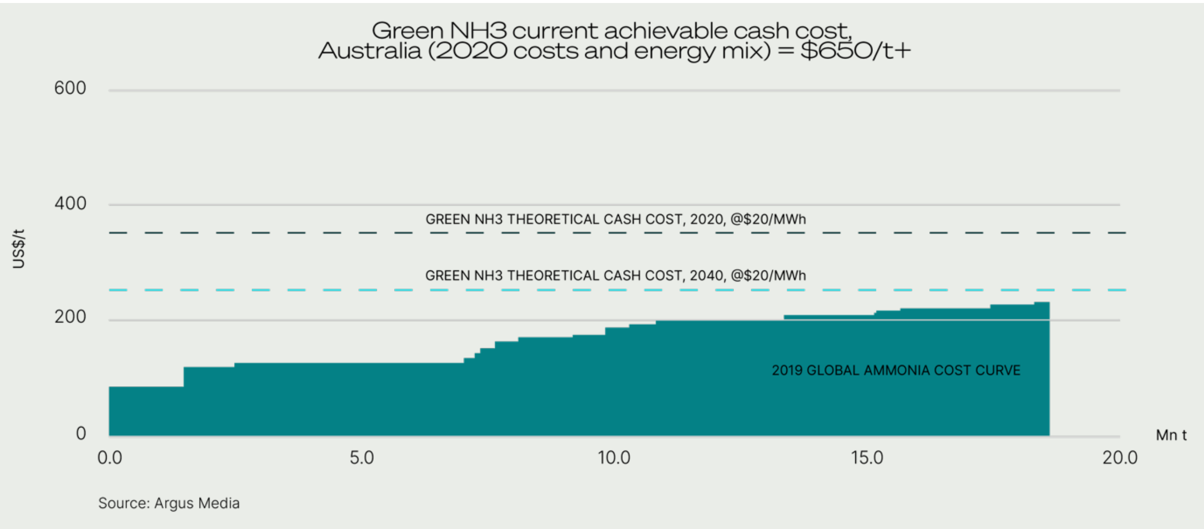
Australia's biggest potential contribution to world-wide decarbonisation would be as a global exporter of net-zero energy products. Energy importers (like Australia's traditional trading partners China, Japan and Korea) are expected to address their domestic decarbonisation goals by shifting imports from coal and gas to hydrogen and ammonia, which can be combusted in existing gas power plants (hydrogen) and coal power plants (ammonia) and used as fuel for transportation and industrial process heat.

As such, Australia can transition from exporting hydrocarbons-as-coal to exporting coal-as-hydrogen, separating the carbon, and storing it securely in Australia's deep geological saline reservoirs. This opportunity is particularly salient for thermal coal, which could continue to be exported to its current customers should they decide to reduce their coal consumption.

Australia has begun down the path to net-zero energy exports with renewables, fast tracking the 26 GW Asian Renewable Energy Hub in Western Australia which will export hydrogen and ammonia. The Queensland government is supportive of a 3.6 GW solar clean ammonia export project near the Port of Gladstone. What is less well understood is that high value clean hydrogen could be the future of Australia's abundant thermal coal, with projects that are complementary to renewables. They can provide critical 24/7 grid security services and flexible peaking power to balance renewables on the grid, and Allam Cycle hydrogen plants could co-locate with electrolyser projects, sharing hydrogen export infrastructure, and consuming the oxygen produced from splitting the water molecule H_2O, reducing capital costs and boosting revenue for the renewable electrolysers.

This feasibility study shows that an Allam Cycle system could produce clean hydrogen at the plant gate for A$2.00/kg or below, while providing peaking electricity. Australia could become a dominant exporter of clean hydrogen, cost competitive even against carbon-emitting ammonia plants, as well as clean ammonia produced via electrolysis.

Globally ammonia fluctuates around A$320 (US$250)/tonne, moderately above the actual production costs, as shown in the graph below, equivalent to A$1.81/kg of hydrogen.



Global Ammonia Cost Curve and Green Ammonia Cost Estimates[iv]

Ammonia is expected to be the primary transport mechanism for hydrogen from all fuels, as it cuts shipping cost by a third and can be reconverted back to hydrogen once received or consumed directly.[v] These Allam Cycle plants would also produce dispatchable clean electricity which can provide essential grid security services on a 24/7 basis and balance solar and wind generation on the Australian power grid, providing electricity that is affordable, clean, and reliable.

Some of the same coal power plants currently importing Australian black coal may soon be on the market searching for clean and affordable ammonia to supplement and eventually replace those imports. Japan has been public about its plan to stop importing coal, and to transition to importing clean ammonia for use in existing and new thermal power plants, announcing their first purchase of clean ammonia from gas produced by Saudi Arabia in September of 2020. JERA, Japan's biggest power company, announced that they will co-fire 5.9 GW of their coal fleet on ammonia, aiming for 20% co-firing by 2035 and ramping up so that by 2050 all their thermal power plants will run on 100% ammonia.[vi]

A single Queensland Allam Cycle plant at the baseline scale presented in the Study could supply enough ammonia to fully convert a 208 MW coal plant to ammonia and would represent $300 million in annual export revenue to Australia at $400/tonne of ammonia. To convert JERA's 5.9 GW of coal would bring in $8.5 billion annually. In 2019, Australia sold $22.7 billion of thermal coal, with $9.6 billion of it going to Japan.[vii] Because hydrogen and ammonia are much more valuable than coal, exporting them would significantly increase Australia's export revenues, and balance of trade, while also contributing to global decarbonisation.

At $356 per tonne of ammonia, the cost of CO_2 abatement at Japanese coal facilities would be competitive. This cost is equivalent to $13.5/GJ, with which we can assume a $9/GJ premium over coal on the spot market. This fuel premium equals approximately US$73/tonne CO_2 avoided at the importing end. Given that importing nations like Japan often have limited renewables capacity and limited carbon storage availability, this is expected to be one of the most attractive decarbonisation alternatives.

Supplying Japan with enough ammonia for 30 GW of coal conversion would lead to export revenues exceeding $43 billion annually, doubling the value of Australia's total thermal coal exports. In 2019 ammonia sales exceeded $92 billion. The value of the new 75 million tonnes of hydrogen demand expected for decarbonisation in 2050 would add another $150 billion in annual sales at $2.00/kg of hydrogen[viii]. This illustrates how decarbonisation could increase the export value of Australian coal, if the carbon from the coal is captured to create a net-zero carbon product.

1.11 Wider benefits

As well as providing a pathway for clean export of coal (as hydrogen/ammonia) and clean electricity grid stabilisation benefits, deploying the technology in Queensland will have positive economic development benefits including over 200 direct full-time equivalent jobs per plant.

This is from the deployment of a single Baseline plant. Wider deployment of these plants will help provide a just transition for workers and communities whose longer-term livelihoods are currently dependant on coal and at risk.

1.12 Next steps

Following this study, the next step is to secure investment to proceed to the next phase of development, which is a pre-FEED and FEED (front end engineering and design) study, combined with a product, logistics and siting study. This will consider specific sites for plant deployment, including a techno-economic assessment of logistics, and refine the product mix. A baseline plant-scaled facility could be operational in the mid-2020s.

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[i] *Australia currently "exports" carbon dioxide emissions in the coal product, which are then released at the import destination. The plants would have the effect of removing that carbon export and instead locally sequestering.*
[ii] *Aspen Plus is a leading process simulation and design software used to create and analyze process models.*
[iii] *Total Overnight cost is the cost of the project if no interest was incurred during construction*
[iv] *Green shift to create 1 billion tonne 'green ammonia market. Argus Media group – www.argusmedia.com, https://bit.ly/2PdFH5l*

[v] *https://view.argusmedia.com/rs/584-BUW-606/images/Argus%20White%20Paper%20-%20Green%20Ammonia.pdf?mkt_tok=eyJpIjoiTkROa1pqWmxObU13WW1RMCIsInQiOiJhNTFycWhIZ1JCUW5pXC80YkRwcnpnNlVwMU53eVNvVW1vYWswOHA2MjIxQVhadXdid0tad1wvdnRtTGt3UU1lcEMxa0xtbXo5MDhvSDc1SEx4YWo4azdUS2s1NTNVbzA2eVlsOGZMWXJYTjNqZUtBMTl4RzZQaWpYOWJpRUJ6NEhRIn0%3D*
[vi] *https://www.argusmedia.com/en/news/2149578-japans-jera-to-phase-out-inefficient-coal-burn-by-2030*
[vii] *https://www.abc.net.au/news/2020-12-16/will-other-countries-replace-china-buying-australian-coal/12985956#:~:text=Australia%20is%20the%20world's%20second,the%20bulk%20going%20to%20Japan.*
[viii] *https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen*-Council.pdf