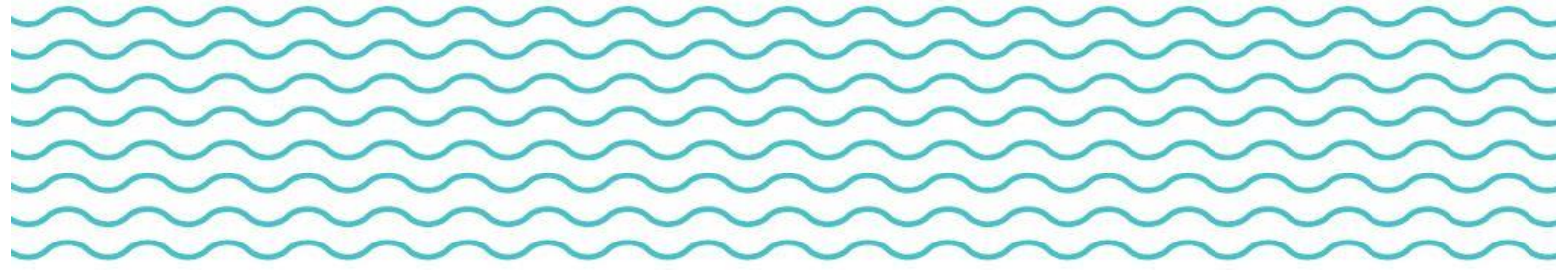# GLOBAL CCS INSTITUTE

Replacing 10% of NSW Natural Gas Supply with Clean Hydrogen: Comparison of Hydrogen Production Options

Prepared for the Department of Regional New South Wales

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June 2020

Contents

1. Executive Summary

The Department of Regional NSW retained the Global CCS Institute to produce a report describing and comparing options for the production of clean hydrogen (H_2) in NSW. This study considers a scenario where sufficient clean hydrogen is produced to achieve a 10% H_2:90% CH_4 (natural gas) mix by volume in the NSW gas network and supply the same total energy as is currently supplied by natural gas alone. This requires the production of 30,490t of clean hydrogen per year.

Options considered were reformation of natural gas with carbon capture and storage (CCS), coal gasification with CCS, and electrolysis of water using renewable electricity. The study is based upon published reports and literature and is general in nature. It is not a detailed study of any specific proposed clean hydrogen production facility. **Nonetheless, it is clear that the best option for the production of clean hydrogen in NSW considering cost, scale, resource use, and emissions abatement outcomes is to utilise coal or gas with CCS.**

The production cost of clean hydrogen from coal gasification with CCS or steam methane reformation with CCS is one third to one half of renewable powered electrolysis, and is expected to remain so beyond 2030.

Table 1. Estimated cost of clean hydrogen production

	Coal Gasification + CCS	Steam Methane Reformation + CCS	Renewable Electricity Powered Electrolysis
Estimated Cost in Australia in 2020 (AUD/kgH$_2$)	$2.90	$2.50	$8
Estimated Cost in Australia in 2030 (AUD/kgH$_2$)	$2.25	$2.10	$5

These costs are based on recently published reports by the International Energy Agency (IEA), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the International Renewable Energy Association (IRENA), and the Hydrogen Council. They are approximate for Australia.

The scale of facilities for coal gasification with CCS or steam methane reformation with CCS required to replace 10% of NSW natural gas demand with clean hydrogen is small and familiar compared to existing facilities making project development less difficult. A renewable powered electrolyser project at this scale would be unprecedented.

There are seven facilities currently operating that produce hydrogen from coal (or similar products) or gas with CCS with capacities of between 200t H_2 per day and 1,300t H_2 per day. The oldest of these facilities commenced operation in 1982. The most recent commenced operation in 2020. Producing 30,490t H_2 per year, or 83.5t H_2 per day[1] from coal or gas with CCS would require the development of a small facility that is well within the experience of several technology vendors and project developers. In comparison, the world's largest renewable electricity powered electrolyser in Fukushima Japan can only produce up to 2.4t of clean hydrogen per day. A renewable powered electrolyser project that could produce 83.5t of hydrogen per day would be unprecedented.

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[1] Quantity of H_2 required to replace 10% of NSW natural gas demand by volume

Coal gasification with CCS or steam methane reformation with CCS requires modest amounts of relatively plentiful resources (coal, gas, pore space for CO_2 storage), whereas renewable hydrogen requires very large amounts of relatively scarce resources (renewable electricity and land with excellent wind resources).

Resource requirements are summarised in Table 2. The electrolysis of water requires very large amounts of electricity. For the scenario considered in this study, a 550MW dedicated wind farm occupying over 23,000Ha of land would be required. That assumes an excellent wind resource with a capacity factor of 0.35. The production of the same quantity of clean hydrogen using coal or gas with CCS would require 232kt of coal or 5.8PJ of gas. These are about 5% of the coal demand of a 1.5GW coal fired power station and 40% of the gas demand of a 300MW combined cycle gas power plant operating at 95% capacity factor. The electricity requirements for coal and gas production pathways includes electricity used in the production of the coal or gas.

Table 2. Resource requirements for the production of 30,490t of clean hydrogen

	Coal Gasification + CCS	Steam Methane Reformation + CCS	Renewable Electricity Powered Electrolysis
Land (Ha)	503	503	23,500
Electricity (MWh)	106,000	58,000	1,677,000
Water (Ml)	274	192	274
Coal (kt)	232	0	0
Gas (PJ)	0	5.76	0
Pore space for CO_2 storage (tonnes of CO_2)	640,000	232,000	0

Coal gasification with CCS or steam methane reformation with CCS provides very much greater emissions abatement by allowing renewable electricity to be used as electricity in the grid rather than for the production of hydrogen which then displaces combustion of natural gas.

There is an abatement opportunity cost for using renewable electricity to produce clean hydrogen instead of using that renewable electricity in the grid. That opportunity cost is very significant even after considering the abatement delivered by the use of clean hydrogen in place of natural gas. Using renewable electricity in the grid (assuming a grid emissions intensity of 0.738tCO_2e/MWh), will deliver 5.6 times more abatement than using the same quantity of renewable electricity to produce hydrogen, which then displaces the combustion of natural gas. Even if the renewable electricity only displaces electricity generation from natural gas, which in NSW has an emission intensity of 0.45tCO_2e/MWh, it would still deliver 3.4 times more abatement in the grid than it would if used to produce hydrogen in electrolysers which then displaces the combustion of natural gas. Renewable electricity provides the greatest climate benefit when used directly as electricity and every effort should be made to ensure that benefit is maximised and the cost of abatement is minimised.

2. Current Global Hydrogen Production Methods

Currently almost 120Mt of hydrogen is produced annually; around 70Mt of pure hydrogen with the remainder being mixed with other gases, predominantly carbon monoxide (CO) in syngas (synthesis gas). The pure hydrogen is used mostly in refining (38Mt) and ammonia production (31Mt). Less than 0.01Mt of pure hydrogen is used in fuel cell electric vehicles. The syngas containing the remaining 49Mt of hydrogen is used mostly in methanol production (12Mt), direct reduction iron making (4Mt) and other industrial processes including as a source of high-heat (26Mt).[1]

Approximately 98% of hydrogen production is from the reformation of methane or the gasification of coal or similar materials of fossil-fuel origin (eg petcoke or ashphaltene). Only about 1% of hydrogen production from fossil fuels includes carbon capture and storage (CCS).[1], [2]

Approximatey 1.9% of hydrogen is produced as a bi-product of chlorine and caustic soda production. The International Energy Agency (IEA) estimates that less than 0.4% of hydrogen is produced by the electrolysis of water powered by renewable electricity.[1] This estimate is based upon the share of renewable electricity in global electricity generation, not on the sum of hydrogen produced from electrolysers with dedicated renewable generation. Dedicated renewable hydrogen production is difficult to estimate as electrolysers with dedicated renewable generation often may also be powered by grid electricity.

However, in the same report, the IEA also states that:

"*Less than 0.1% of dedicated hydrogen production globally comes from water electrolysis today.*"[2] and

"*Electrolysis currently accounts for 2% of global hydrogen production…*"[3] and

"*In addition to the hydrogen produced through water electrolysis, around 2% of total global hydrogen is created as a byproduct of chlor-alkali electrolysis in the production of chlorine and caustic soda.*"[4]

There is some uncertainty about the amount of hydrogen produced via electrolysis, probably due to cross categorisation between water electrolysis and brine electrolysis to produce chlorine and caustic soda, and also between dedicated and byproduct production of hydrogen. Figure 1 is a best estimate to unravel these factors and present actual production numbers.

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[2] IEA 2019, The Future of Hydrogen, Seizing today's opportunities, Page 42
[3] IEA 2019, The Future of Hydrogen, Seizing today's opportunities, Page 37
[4] IEA 2019, The Future of Hydrogen, Seizing today's opportunities, Page 43
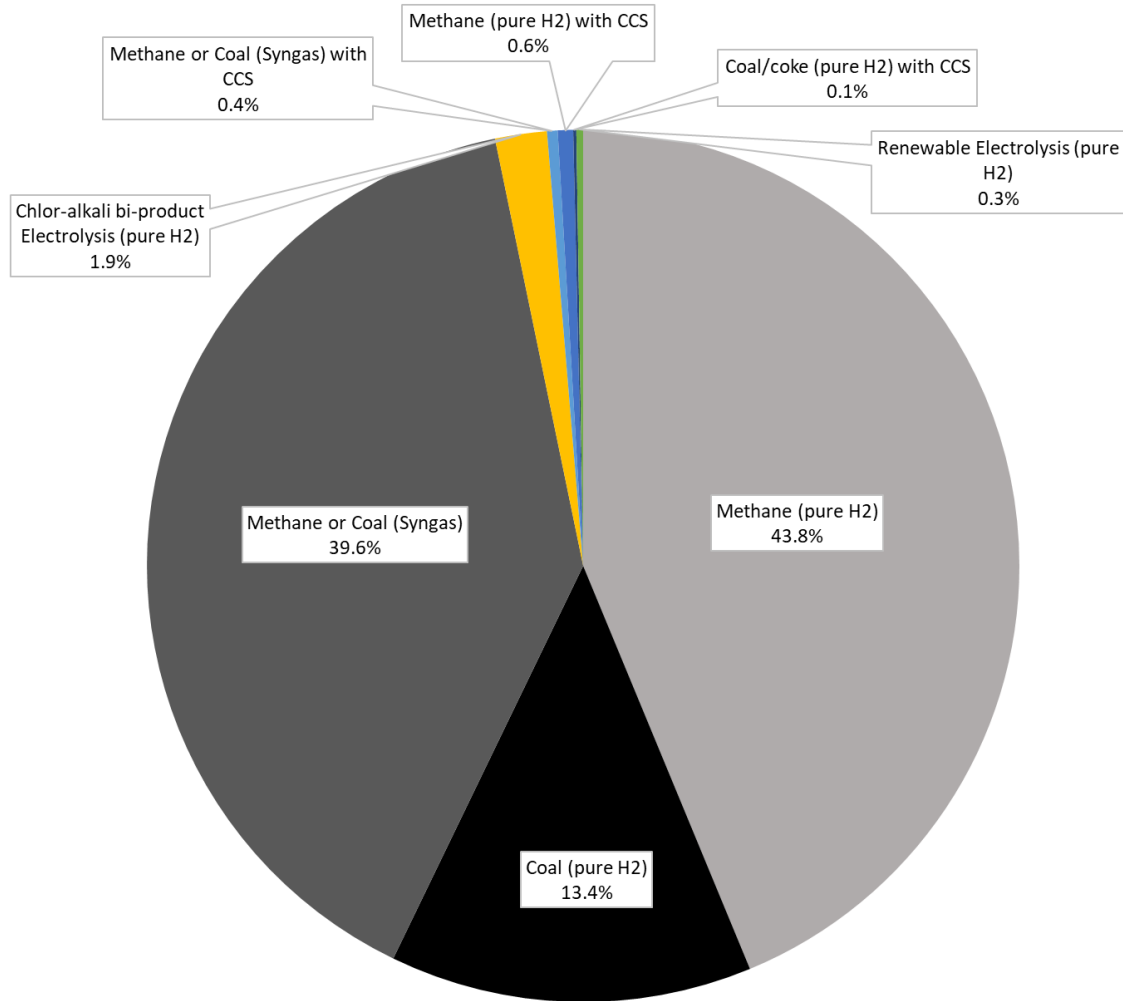
Total annual production of hydrogen is approximately 120Mt

Figure 1. Current global production of hydrogen.[1], [2]

As more than 97% of current hydrogen production is from fossil fuels without CCS, it is emissions intense, emitting around 830Mt of carbon dioxide (CO_2) per year. Low emission production methods for hydrogen include steam methane reformation (SMR), authothermal reformation of methane (ATR) or coal gasification; each with carbon capture and storage (CCS), and electrolysis of water powered by renewable electricity. These production methods produce clean hydrogen. Summary descriptions of clean hydrogen production technologies are at Appendix 1.

The world's largest renewable powered electrolyser commenced operation at the Fukushima Hydrogen Energy Research Field in Japan in March 2020. The electrolyser has a capacity of 10MW, and is powered by 20MW of solar PV cells [3]. Assuming that the facility has battery storage sufficient to store the excess energy produced by the PV array for later use by the electrolyser, it has the capacity to produce about 2.4 tonnes of clean hydrogen per day.[5]

Table 3 presents summary information on facilities that produce clean hydrogen using fossil fuels and CCS. The clean hydrogen production capacity of these facilities are typically hundreds of times larger than the world's largest renewable hydrogen production facility at Fukushima.

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[5] Asuming solar PV capacity factor of 0.25 for 20MW PV capacity and 50kWh per kg of H_2 produced

Table 3. Hydrogen Production from Fossil Fuels with CCS[2]

Facility	H_2 Production Capacity	H_2 Production Process	Hydrogen use	Operational Commencement
Enid Fertiliser	200 tonnes per day of H_2 in syngas	Methane reformation	Fertiliser production	1982
Great Plains Synfuel	1,300 tonnes per day of H_2 in syngas	Coal gasification	Synthetic natural gas production	2000
Air Products	500 tonnes H_2 per day	Methane reformation	Petroleum refining	2013
Coffeyville	200 tonnes H_2 per day	Petroleum coke gasification	Fertiliser production	2013
Quest	900 tonnes H_2 per day	Methane reformation	Bitumen upgrading (synthetic oil production)	2015
Alberta Carbon Trunk Line - Sturgeon	240 tonnes H_2 per day	Asphaltene residue gasification	Bitumen upgrading (synthetic oil production)	2020
Alberta Carbon Trunk Line - Nutrien	800 tonnes H_2 per day	Methane reformation	Fertiliser production	2020
Sinopec Qilu	100 tonnes H_2 per day (estimated)	Coal/Coke gasification	Fertiliser production	Expected 2021

2.1 Emissions Intensity of Hydrogen Production

Figure 2 shows the estimated CO_2 emissions per kilogram of hydrogen produced by production method. Scope one emissions from SMR, ATR or coal gasification are process emissions from the reformer or gasifier plus emissions from the combustion of fossil fuels to provide heat (where required). Emissions from purchased electricity assume a grid emissions intensity of 738kg/MWh[4]. For coal or natural gas production pathways, electricity emissions include electricity used in the production of the coal or gas[5] in addition to electricity used at the hydrogen production facility and for CCS. Hydrogen produced using renewable electricity firmed by grid power assumes a total capacity factor of 95% with 35% from wind and the remaining 60% from grid power.

Producing hydrogen from grid-powered electrolysers results in the highest emissions (~40kgCO_2/kgH_2). Coal gasification without CCS is also very emissions intense (~23kgCO_2/kgH_2). Production of hydrogen from methane without CCS produces around 9 kgCO_2/kgH_2. Coal or natural gas production pathways with CCS produce around 2-3 kgCO_2/kgH_2 including electricity emissions from the production of the coal or gas. Hydrogen produced using electrolysers powered by 100% renewable electricity have zero scope 1 emissions however any firming by grid power will result in significant scope 2 emissions. In the example shown in Figure 2, renewable powered electrolysers backed up by grid power to achieve an overall utilisation of 95% produces over 25kg of CO_2 per kg of hydrogen. This is more emissions intense than coal gasification without CCS. Clearly, adopting high-emissions hydrogen production pathways like grid powered electrolysis or coal gasification without CCS defeats the purpose of utilising hydrogen and should be avoided.
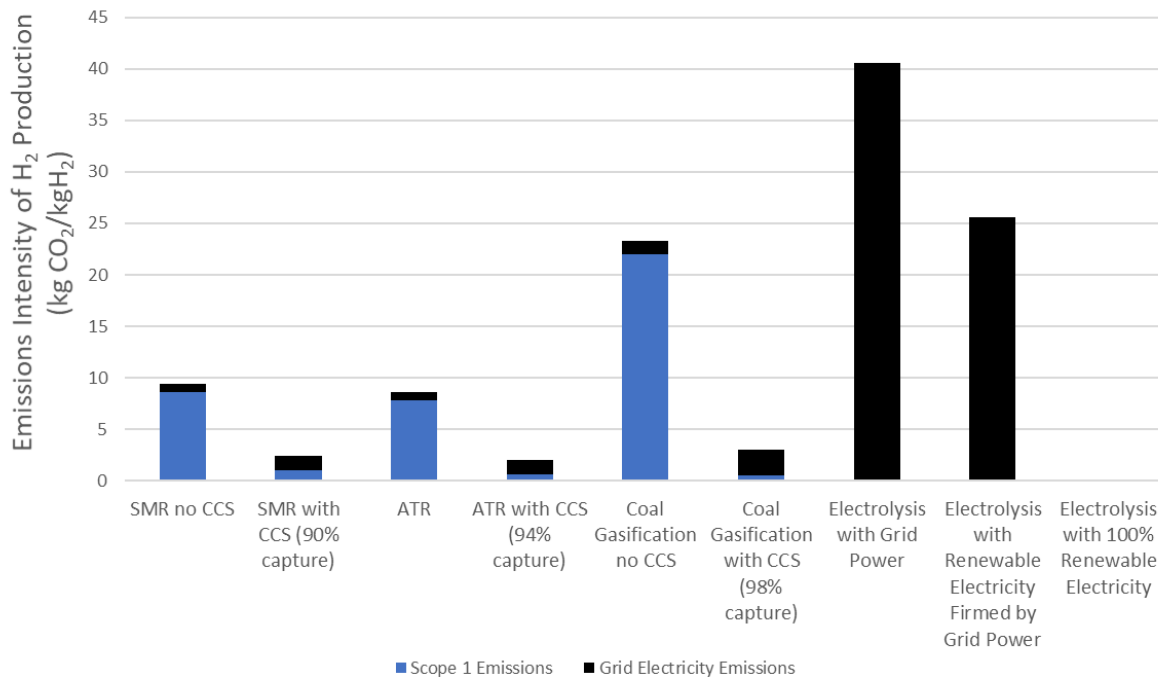
Figure 2. Estimated CO_2 emissions from different hydrogen production methods[1], [5]. Electricity emissions from coal and gas production pathways are full lifecycle emissions, including electricity used in gas/coal production. Electricity emissions assume CO_2 emissions intensity of 738kg/MWh[4]. Grid firmed renewable electrolysis assumes total capacity factor of 95% with 35% from wind and the remaining 60% from grid power. SMR = Steam Methane Reformation. ATR = Autothermal Reforming. CCS = Carbon Capture & Storage.

2.2 Cost of Clean Hydrogen Production

There is a range of costs of production of clean hydrogen for both fossil fuels with CCS and renewable powered electrolysis. Key determining factors of cost are the price of coal or natural gas, and the quality of the renewable energy resource (which impacts electricity price & capacity factor of the electrolysers) for renewable hydrogen. Overall, hydrogen produced from coal or gas with CCS is the lowest cost clean hydrogen today and is expected to remain so at least until 2030.[1]

Table 4 and Figure 3 summarise the cost of clean hydrogen production according to recent reports by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) [6], IEA [1], International Renewable Energy Association (IRENA) [7] and the Hydrogen Council[8]. These reports use a range of underlying assumptions that makes direct comparisons difficult. In the case of the IEA report, sufficient information was provided to allow the use of the same coal and gas prices as are used in the CSIRO report, although the IEA assumes slightly higher utilisation for SMR and coal gasification. The underlying assumptions for renewable hydrogen production via electrolysis in the IEA report are not clear. The estimates quoted in Table 4 from the CSIRO and IEA reports are both for production in Australia. The estimates taken from the IRENA and Hydrogen Council reports are for a mixture of USA and Europe or are unstated. All costs have been converted to 2018 Australian dollars (same basis as the CSIRO report), and are approximate. The capacity factors for renewable hydrogen assume no energy storage. Including energy storage would increase the overall cost of renewable hydrogen production (see section on *Scale of production facilities* in Section 3.2).

It is worth noting that the highest cost clean hydrogen is produced using electrolysers powered by renewable electricity that would otherwise be curtailed. CSIRO assumed *otherwise curtailed electricity* would have a low price of 2c/kWh. However, renewable electricity is scarce and relatively small

amounts of it are curtailed resulting in very low utilisation of the electyrolyser (10%) resulting in very high unit cost of production.

Table 4. Recent published estimates of cost of clean hydrogen production.[1], [6]–[8]

All costs in 2018AUD per kg of hydrogen	Dedicated Renewable Electricity Supply	Otherwise Curtailed Renewable Electricity Supply	Steam Methane Reformation with CCS	Black Coal Gasification with CCS
CSIRO 2018	**~$11** (35% capacity factor, electricity price 6c/kWh)	**~$26** (10% capacity factor, electricity price 2c/kWh)	**$2.27 - $2.77** (85% capacity factor, gas price $8/GJ)	**$2.57-$3.14** (85% capacity factor, coal price $3/GJ)
IEA 2019	**~$5.50** (underlying assumptions are unclear)	N/A	**~$2.60** (95% capacity factor, gas price $8/GJ)	**~$3.10** (95% capacity factor, coal price $3/GJ)
IRENA 2019	**~$4 – $10** (Low end is wind; 48% capacity factor & electricity price 3.3c/kWh. High end is PV; 26% capacity factor & electricity price 12c/kWh)	N/A	**~$2.10 – $3.10** (Low end is gas cost $4.20/GJ. High end is gas cost $11.40/GJ)	**~$2.60** (coal cost $2.10/GJ)
Hydrogen Council 2020	**~$9** (50% capacity factor & electricity price 8.2c/kWh)	N/A	**~$2.20** (underlying assumptions not stated)	**~$3.00** (underlying assumptions not stated)
Simple average of costs from these four reports.	**$8** Range: $4 - $11	**$26**	**$2.48** Range: $2.10-$3.10	**$2.89** Range: $2.57-$3.14

There is generally good agreement between the CSIRO, IEA, IRENA and the Hydrogen Council on the cost of producing clean hydrogen from natural gas or coal with CCS. This is not surprising as 98% of hydrogen is currently produced from natural gas or coal and there are seven fossil based hydrogen production facilities which utilise CCS at commercial scale. Thus, the cost of production of clean hydrogen from coal or natural gas with CCS is relatively well known. Current production costs are reported to be around AUD2.50/kg of hydrogen for gas with CCS and and approaching AUD3.00/kg hydrogen for black coal with CCS.

There is a wider range of estimated costs for renewable hydrogen produced with electrolysers; AUD4.00/kg to AUD11.00/kg of hydrogen. The largest contribution to that variation arises from the assumed utilisation of the electrolyser (ie, capacity factor of the dedicated renewable generation capacity), the price of electricity and the capex for the electrolyser which is predominantly a function of scale (larger are lower capex per unit production capacity).
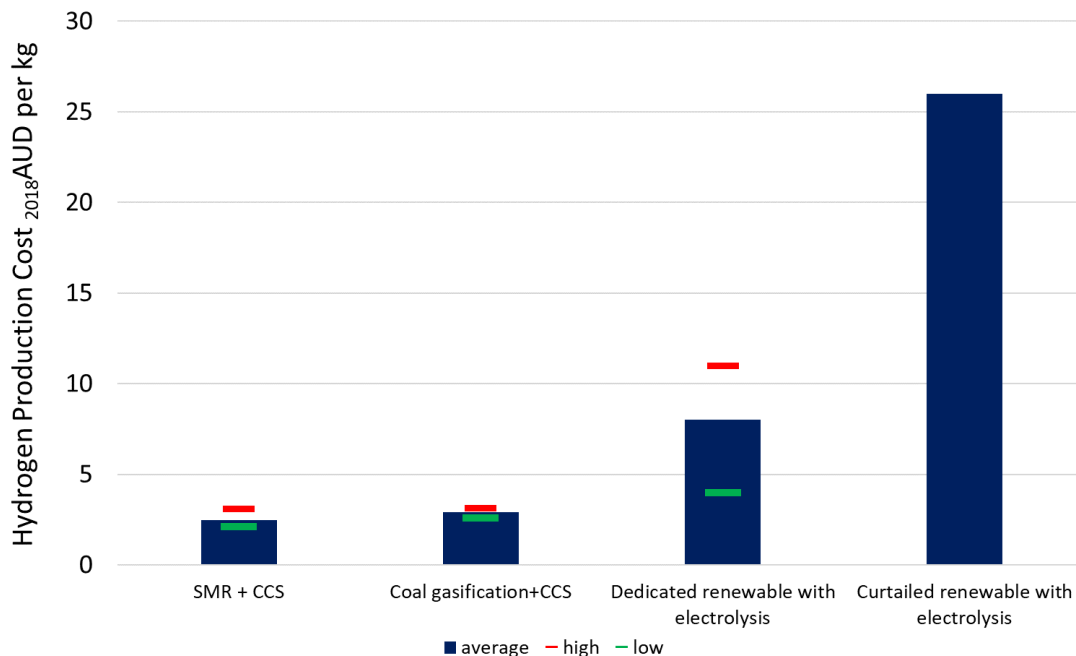

Figure 3. Estimated current cost of clean hydrogen production from recently published reports.[1], [6]–[8] (only one estmate of cost of curtailed renewable with electrolysis). SMR = steam methane reformation. CCS = carbon capture & storage

Cost Drivers

The main cost drivers for for hydrogen production from coal or natural gas with CCS is capital cost and fuel cost. In China, which operates over 100 coal gasifiers, capex accounts for approximately half the cost of clean hydrogen production from coal, coal contributes another 15-20% with the remainder being other operational costs.[1] It is similar for gas with CCS. According to the IEA, for steam methane reformation with CCS, capex accounts for around AUD0.90/kg H_2, opex (excluding cost of gas) for around AUD0.60/kg H_2 and for low cost gas (AUD4.30/GJ in USA) gas contributes AUD0.70/kg H_2. For high cost gas (AUD16/GJ in Europe), gas contributes AUD1.90 per kg H_2. It is notable that even where gas is expensive (AUD16/GJ), the cost of clean hydrogen production from steam methane reformation with CCS is still only around AUD3.40/kg.

The main cost drivers for renewable hydrogen are capex of the electrolysers, price of electricity and the utilisation of the electrolysers. This is illustrated in Figure 4 which uses data from the 2020 Hydrogen Council report[8]. In this case, all costs from the Hydrogen Council report (in USD) were simply converted to AUD assuming an exchange rate of 1AUD=0.7USD. Note that the capital costs for electrolysers used in Figure 4 are significantly less than assumed by the IEA and CSIRO. IEA assumes a capital cost of AUD1290/kW (assuming 1AUD=0.7USD) and the CSIRO assumed AUD3496/kW. The difference is most likely due to scale. CSIRO based its analysis on an electrolyser with a capacity of 444kgH_2 per day. The IEA report does not clearly state its assumed electrolyser size, however given its focus on electrolysers with a capacity of several tonnes of H_2 per day, it is likely the IEA used capital costs based on an electrolyser an order of magnitude larger than that assumed by the CSIRO.
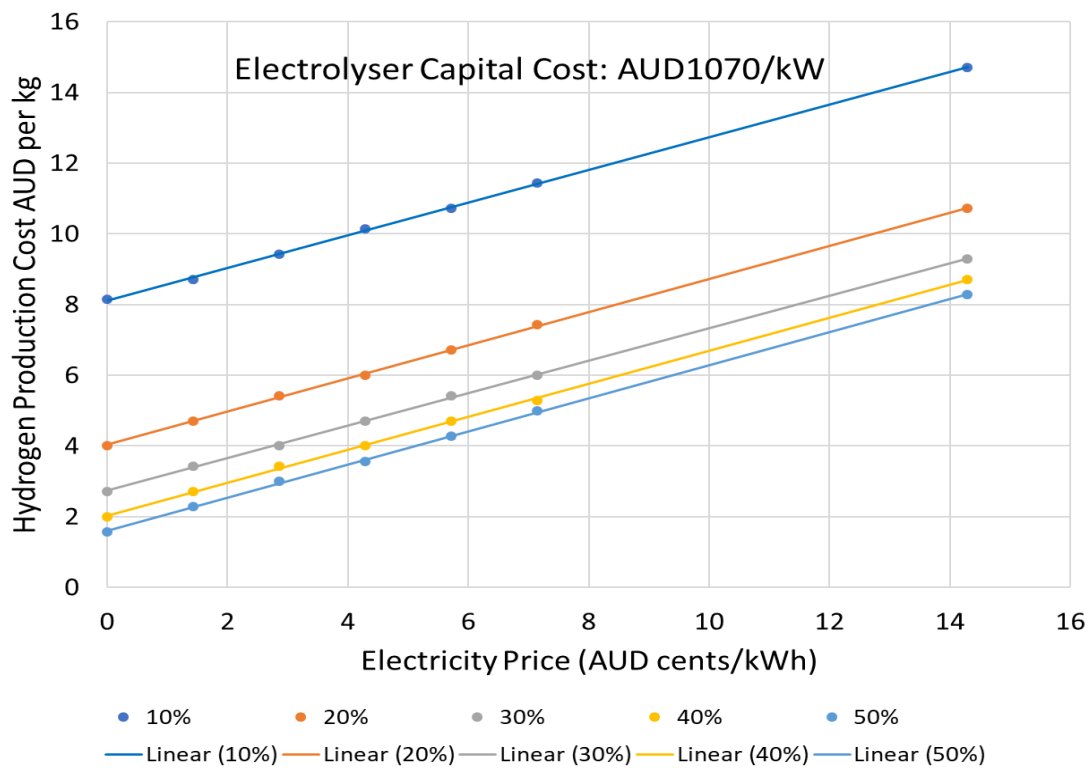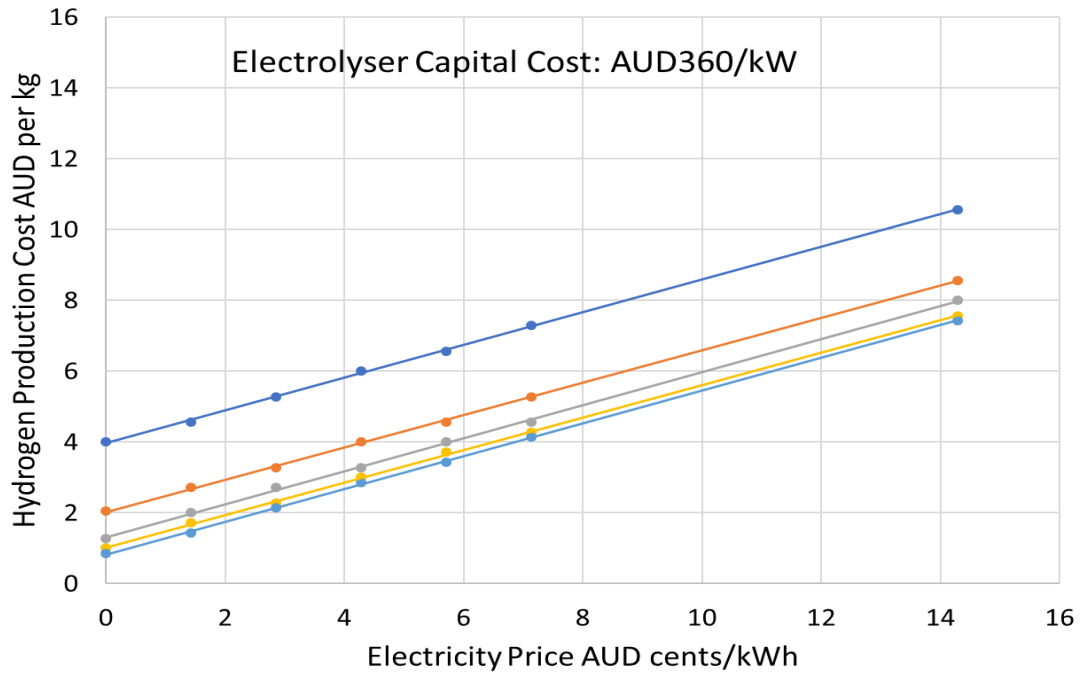
Figure 4. Cost of clean hydrogen production from electrolysis as a function of electricity price, utilization of the electrolyser (percentage figures) and capital cost.[8]

Hydrogen Production Costs in 2030

Whilst SMR and coal gasification technologies are all mature at commercial scale there is potential for CO_2 capture, transport and storage costs to reduce by 2030, due mainly to economies of scale provided by CCS hubs, and reductions in the cost of capital due to investors' reduced perception of risk. However CCS is a relatively small component of the overall cost of fossil based clean hydrogen production and so the cost reductions likely before 2030 are similarly modest. CSIRO project a cost of clean hydrogen production from SMR with CCS, and coal gasification with CCS by 2025 of AUD1.88 – 2.30/kgH_2 and AUD2.02-2.47/kgH2 respectively.[6] The midpoints of these ranges have been charted in Figure 5.

Hydrogen production costs from electrolysers may reduce by 2030 simply through economies of scale that will accrue from increasing electrolyser capacity from a few tonnes per day to 500t H_2 per day. The IEA assumes that electrolyser capital costs will reduce to around AUD1000 per kW by 2030.[1] Using the lower chart in Figure 4, a renewable electricity price of 6c/kWh and a capacity factor of 35% (interpolating between 30% and 40% on the chart) indicates a hydrogen production cost of around AUD5.00 per kilogram. These costs are shown in Figure 5.
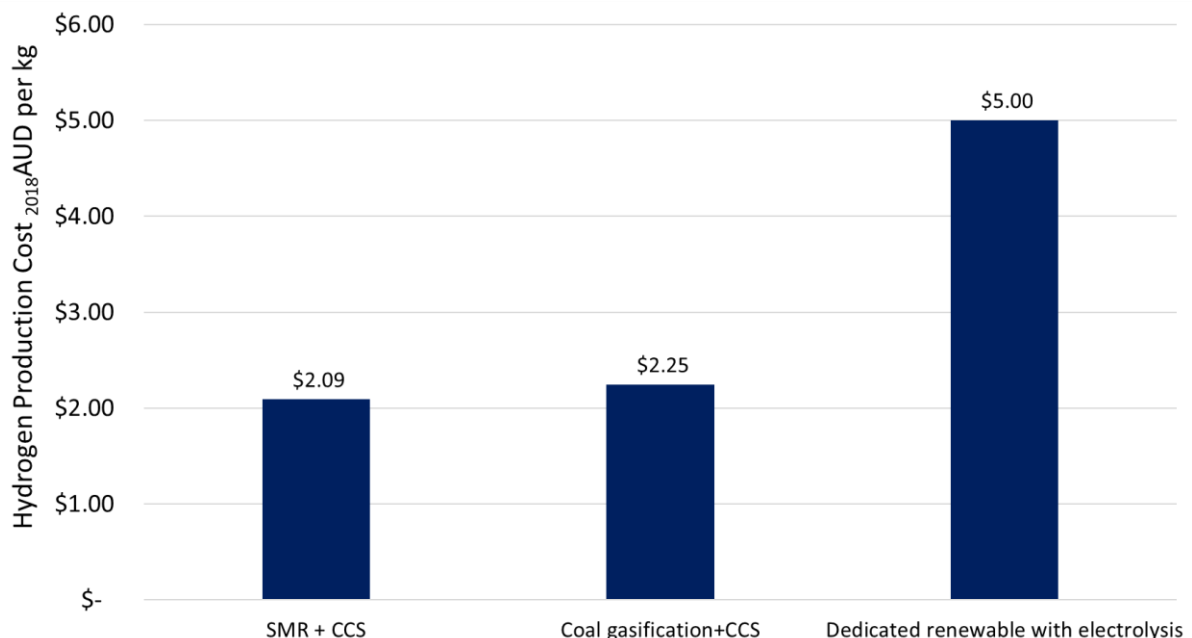

Figure 5. Approximate expected clean hydrogen production costs in Australia in 2030. Key assumptions: Gas price: AUD8/GJ. Coal price: AUD3/GJ. Renewable electricity price and capacity factor: AUD 6c/kWh and 35%. Electolyser Capex: ~AUD1000/kW. SMR = steam methane reformation. CCS = carbon capture & storage

CSIRO estimated a much lower cost for hydrogen production from electrolysers (Proton Exchange Membranes) in 2025 at AUD2.29-2.79/kgH_2.[6] However, this estimate appears to be for electrolysers powered by grid electricity which is the highest emissions intensity option for producing hydrogen (40kgCO_2/kgH_2). To arrive at this cost estimate, CSIRO assumed a capacity factor of 95% and an electricity cost of 4c/kWh. This combination is simply impossible if the electrolyser was powered with 100% renewable electricity. A capacity factor of 95% would require dedicated renewable electricity generation capacity at least 2.7 times larger[6] than the electrolyser capacity, plus sufficient battery

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[6] Assumes a capacity factor for dedicated renewable generation of 0.35

storage to store excess electricity generated for later use by the electrolyser. Battery storage is estimated by Lazard to cost between AUD23c and AUD43c per kWh[9][7] for four hours of storage. Significantly more than four hours of storage would be required. The cost of electricity storage alone would exceed 4c/kWh by a significant margin. Thus, the CSIRO cost estimate must be for grid powered electrolysis which is the most emissions intense option of producing hydrogen and should be avoided.

3. Clean Hydrogen Supply – Comparison of Options

The following analysis describes the key resource requirements for the production of clean hydrogen from natural gas or coal with CCS and from electrolysis of water powered by renewable energy. The quantity of hydrogen to be supplied is to achieve a 10% H_2:90% CH_4 mix by volume in the NSW gas network and supply the same total energy as is currently supplied by natural gas alone. The total energy requirement is assumed to be 127.67PJ, which was the average gas demand in NSW between 2014 and 2019.[10]

3.1 Calculation of H_2 supply requirement

The average natural gas demand in NSW between 2014 and 2019 was 127.67PJ.[10]

Table 5. Higher heating values of gas mixtures (all at 15°C & 1 Bar)

Gas Mixture	Higher Heating Value (MJ/m^3)
100% CH_4	38.2
100% H_2	12.1
10%H_2, 90%CH_4	35.6

Table 6. Volume and mass of gases in 10%H_2:90%CH_4 mix to deliver 127.67PJ (all at 15C & 1 Bar)

Gas Mixture	Volume (m^3)	Mass (kg)
10%H_2, 90%CH_4	3.587×10^9	2.452×10^9
H_2	3.587×10^8	3.049×10^7
CH_4	3.229×10^9	2.421×10^9

Therefore, 30,490 tonnes of H_2 must be supplied per year or 83.5 tonnes per day.

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[7] Assuming 1AUD = 0.7USD

3.2 Calculation of resource requirements to produce 30,490 tonnes of H_2

Table 7 summarises the resource requirements for the production of 30,490t of clean hydrogen. Key resource requirements are also shown in Figures 6 and 7.

Table 7. Resource requirement to produce 30,490 tonnes of hydrogen

Resource	Coal Gasification	Steam Methane Reformation	Coal Gasification + CCS	Steam Methane Reformation + CCS	Renewable Electrolysis of water
Water (ML) [8,9]	274	137	274	192	274[10]
Electricity[11] **(MWh)**	52,443	33,844	106,105	58,236	1,677,000[12]
Wind Power Installed Capacity[13] **or Solar PV Installed Capacity**[14]	N/A	N/A	N/A	N/A	547MW wind or 766MW solar PV
Coal (t)[15]	231,720	N/A	231,720	N/A	N/A
Gas (PJ)[16]	N/A	5.8	N/A	5.8	N/A
Land for Renewable Power Generation[17]	N/A	N/A	N/A	N/A	23,519Ha (wind) or 1,914Ha (solar PV)
Land for Plant (Ha)	3	3	3	3	3
Land for CO$_2$ Transport and Injection (Ha)[18]	N/A	N/A	500	500	N/A

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[8] 6.3kg water required per kg of H_2 for SMR with CCS, 4.5kg water required per kg H2 without CCS. [20]

[9] 9kg water required per kg of H_2 for coal gasification with CCS [6]

[10] 9kg water required per kg of H_2 for electrolysis [1]

[11] Electricity requirement for coal and gas production pathways are for the full lifecycle including power used in the production of coal and gas. [5]

[12] 55kWh/kg H_2 (higher heating value) [1]

[13] Capacity Factor = 0.35

[14] Capacity Factor = 0.25

[15] 7.6kg coal per kg H_2: [21].

[16] 3.7kg CH4 per kg H2: [22].

[17] Wind: 43Ha/MW; Solar PV: 2.5Ha/MW

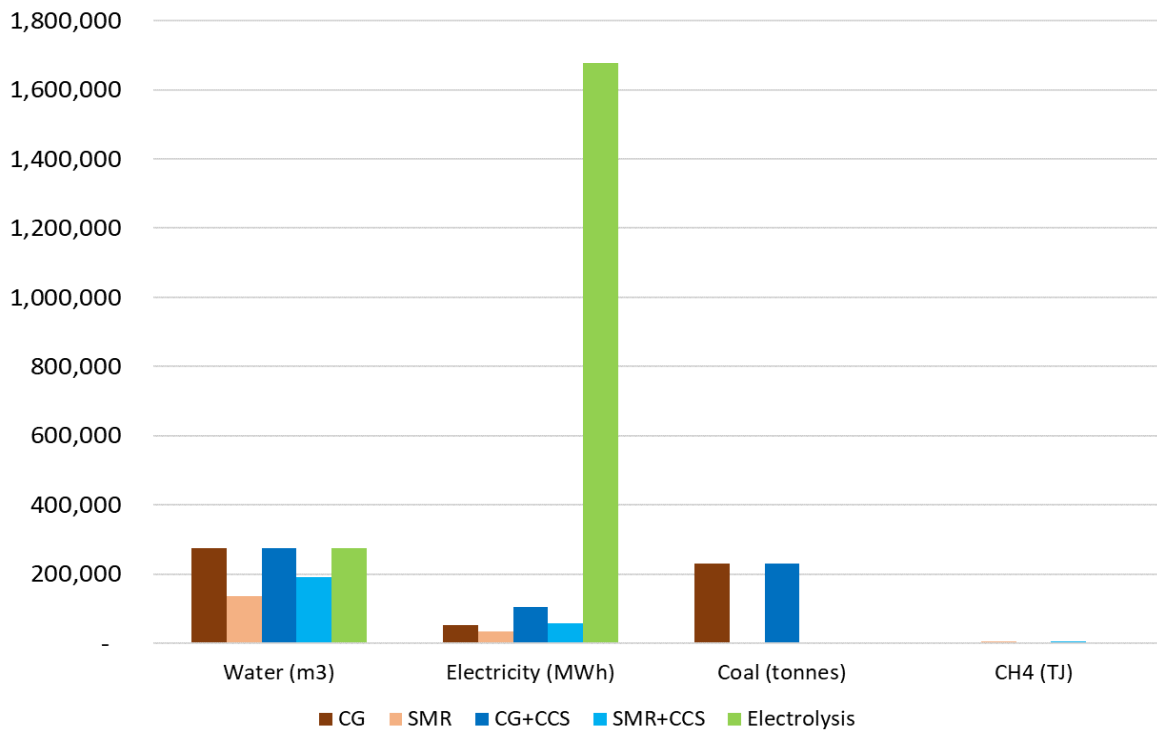[18] Assumes 500km pipeline and 10m wide pipeline corridor.

Figure 6. Estimated demand for water, electricity, coal and methane to supply 30,490 tonnes of hydrogen using coal gasification, steam methane reforming (SMR), coal gasification with carbon capture & storage (CCS), steam methane reforming with CCS and electrolysis of water. Electricity requirement for fossil fuel production pathways includes electricity used in the production of the coal or gas.
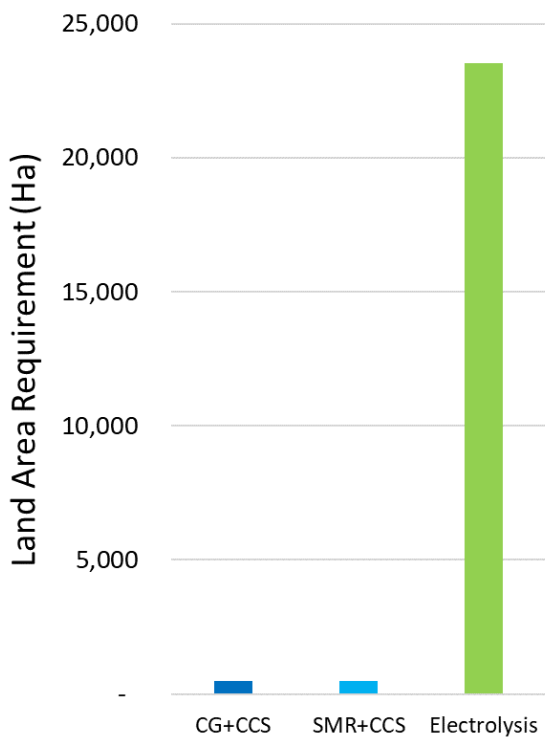

Figure 7. Estimated land requirement to supply 30,490 tonnes of hydrogen using coal gasification (CG) with CCS, steam methane reforming with CCS and electrolysis of water. CG+CCS and SMR+CCS includes plant (3Ha) and land for a 500km CO_2 pipeline (500Ha). Electrolysis includes plant (3Ha) and land for a 550MW wind farm (23,522Ha).

Scale of Production Facilities

Annual production of 30,490 tonnes of hydrogen requires daily production of 83.5 tonnes. This quantity is compared to a selection of facilities that utilise electrolysis or fossil based production with CCS in Table 8.

Producing sufficient hydrogen to meet NSW gas demand through a 10% H_2:90% methane mix (by volume) would require the world's smallest SMR or coal gasification plant with CCS (excluding pilot and demonstration plants). Such a plant would have a small land requirement of a few hectares.

For comparison, the Coffeyville facility, which has double the required hydrogen production capacity as well as a 1,300 ton per day ammonia unit and a 3000 ton per day urea-ammonium nitrate unit is located on a 14Ha site.[19] Additional land would be required for the CO_2 pipeline and injection infrastructure. For a plant of this size, a six inch diameter pipe would be sufficient for CO_2 transport. The Coffeyville plant (double the capacity required to supply 30,490 t of hydrogen per year) utilises an eight inch pipeline to transport CO_2 112km to the injection site. The land required to host the pipeline depends on its length. Assuming a 500km pipeline and 10 meter wide pipeline corridor, the land requirement would be 500Ha. The actual CO_2 injection well and additional compression (if required) has a trivial land requirement of the order of hundreds of square meters.

Meeting the same hydrogen demand using renewable powered electrolysis would require the construction of a 550MW electrolyser, which is 55 times larger than the largest operating renewable powered electrolyser. The electrolyser plant would require around 2.5 Ha[20]. Over 23,000 Ha of land would be necessary to host 550 MW of wind generation capacity (assumes dedicated renewable supply and no battery storage). Wind has been selected over solar PV in this example due to its higher capacity factor (0.35 for wind vs 0.25 for solar) which is favourable in terms of the cost of production (see bottom chart of Figure 4. Hydrogen production cost at 35% capacity factor is approximately AUD1/kg less than at 25% capacity factor).

The capacity of the electrolyser can be reduced if it has higher utilisation. For example, doubling the capacity of dedicated renewable generation from 550MW to 1.1GW of wind and installing sufficient battery capacity to store excess electricity would effectively double the utilisation of the electrolyser to 0.7. In this case, only a 275MW electrolyser would be required, however the land requirement for the wind farm would double to 47,000Ha and significant battery storage would be required. Battery storage is estimated by Lazard to cost between AUD23c and AUD43c per kWh[9][21] for four hours of storage. Significantly more than four hours of storage would likely be required. This would significantly increase the cost of clean hydrogen production.

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[19] https://www.cvrpartners.com/Operations/index.html
[20] Based on Hydrogenics layout for a 20MW electrolyser described in [23]
[21] Assuming 1AUD = 0.7USD

Table 8. Comparison of scale of clean hydrogen production – supply 10%H_2 mix in NSW gas supply vs selection of H_2 production facilities.

Facility	Comment	H_2 Production Capacity	Production Method	Multiple of Capacity to Supply 10% H_2 mix in NSW Gas
Enid Fertiliser	World's smallest SMR plant with CCS	200 tonnes per day of H_2 in syngas	Methane reformation with CCS	0.5
Great Plains Synfuel	World's largest H_2 production facility with CCS	1,300 tonnes per day of H_2 in syngas	Coal Gasification with CCS	0.07
Coffeyville	Small gasification plant	200 tonnes H_2 per day	Petroleum coke gasification with CCS	0.5
Sinopec Qilu	World's smallest H_2 production facility with CCS	100 tonnes H_2 per day	Coal/Coke gasification with CCS – in construction	1
Fukushima Hydrogen Energy Research Field[3]	World's largest operating renewable powered H_2 production facility	2.4 tonnes H_2 per day	Renewable powered electrolysis utilising 20MW PV capacity to supply a 10MW electrolyser	35 (assumes PV capacity is double electrolyser capacity, with battery storage ie, capacity factor of 0.5)
Gigastack Renewable Hydrogen Project [11]	At FEED stage funded by UK BEIS.	17.5 tonnes H_2 per day[22]	Renewable powered electrolysis utilising offshore wind to supply a 100MW electrolyser	4.8

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[22] Assumes capacity factor for offshore wind of 0.4

3.3 Calculation of Emissions Abatement Potential of Renewable Electricity

Producing sufficient hydrogen to meet NSW gas demand through a 10% H_2:90% methane mix using electrolysis would require 1,677,000MWh. There is an abatement opportunity cost associated with using this quantity of renewable electricity to produce hydrogen instead of displacing unabated coal (or gas) generation from the electricity grid. As the following analysis shows, using renewable electricity in the NSW electricity grid to displace coal fired generation delivers almost seven times more abatement than using renewable electricity to produce hydrogen which then displaces natural gas in the gas system.

In 2018/19 the average emissions intensity of NSW coal fired power stations was 0.88t CO_2/MWh.[12] Consequently, using 1,677,000MWh of renewable electricity to displace coal fired power generation in the grid, instead of being used for electrolysis, would deliver 1,476,000 tCO_2e of abatement.

However, the use of clean hydrogen produced by electrolysis in NSW' reticulated gas system will provide emissions abatement by displacing natural gas. That abatement must also be considered. The energy value (higher heating value) of the clean hydrogen produced by using 1,677,000MWh of electricity in electrolysers is 4.32PJ. The emission factor for combustion of natural gas is 51.53kgCO_2e/GJ. Thus the use of this quantity of clean hydrogen in the NSW gas network to displace natural gas will deliver 223,000 t CO_2e of abatement.

The difference, comparing using 1,677,000MWh of renewable electricity to produce clean hydrogen which is then utilised in the NSW gas system vs using 1,677,000MWh of renewable electricity to displace coal fired power generation in the grid is shown in Table 9.

Table 9. Net abatement from options for the use of renewable electricity.

Option	Net Abatement (tCO$_2$e)
Renewable electricity used to displace unabated coal fired power generation in the NSW grid	1,476,000
Renewable electricity used to produce hydrogen which displaces combustion of natural gas in NSW	223,000
Difference	1,253,000

Using the renewable electricity as electricity instead of diverting it to produce hydrogen for use in the NSW gas network would increase emission abatement by over 1.2MtCO_2e. The reasons for this large difference are:

- Around 30% of the energy is lost in the process of converting electricity to hydrogen via electrolysis.
- Coal has a much higher emission factor than natural gas (90.23 kgCO_2e/GJ vs 51.53kgCO_2e/GJ). Almost twice as much abatement is accrued by displacing coal compared to methane per unit energy.
- Coal fired power stations have a thermal efficiency of only around 33%. Displacing one GJ of electricity production from a coal power plant prevents emissions from the combustion of 3GJ of coal.

The ratio of emissions abatement from direct use of renewable electricity to displace grid generation, to emissions abatement from the displacement of natural gas by hydrogen generated using the same quantity of renewable electricity can be calculated as follows.

Er =   Energy value of the renewable electricity in GJ

Ac =   emission abatement if renewable electricity is used to displace grid power in tonnes CO_2e

Ag =   emission abatement if renewable electricity is used to produce hydrogen which then displaces natural gas in the gas system in tonnes CO_2e

PEMeff =   efficiency of conversion of electrical energy to hydrogen: 0.71 (converted from $55kWh/kgH_2$ - HHV)

EFc =   Emissions intensity of grid generation - assume coal generation: 244kg CO_2e/GJ (converted from 0.88t/MWh)

EFg =   Emission factor for natural gas combustion: 51.53kgCO_2e/GJ

$$\frac{Ac}{Ag} = \frac{Er * EFc}{Er * PEMeff * EFg}$$

$$Ac = \left(\frac{EFc}{PEMeff * EFg}\right) * Ag$$

Substituting values for variables:

$$Ac = \left(\frac{244}{0.71 * 51.53}\right) * Ag$$

$$\boldsymbol{Ac = 6.67Ag}$$

Thus, using renewable electricity in the NSW electricity grid to displace coal fired generation delivers almost seven times more abatement than using renewable electricity to produce hydrogen which then displaces natural gas in the gas system.[23]

The above equation can be used for any grid generation technology or emissions intensity. This is shown in the graph at Figure 8. For example, if it is assumed that the renewable electricity instead displaces gas fired generation, then direct use of renewable electricity would deliver approximately 3.4 times as much abatement than using renewable electricity to produce hydrogen which then displaces natural gas in the gas system in NSW.[24]

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[23] Differences between the result using this equation and the result calculated at the beginning of this section are due to rounding.
[24] From [12], emissions intensity of NSW gas generation in 2018/19 was 0.45tCO2e/MWh = 126kg/GJ of electricity.
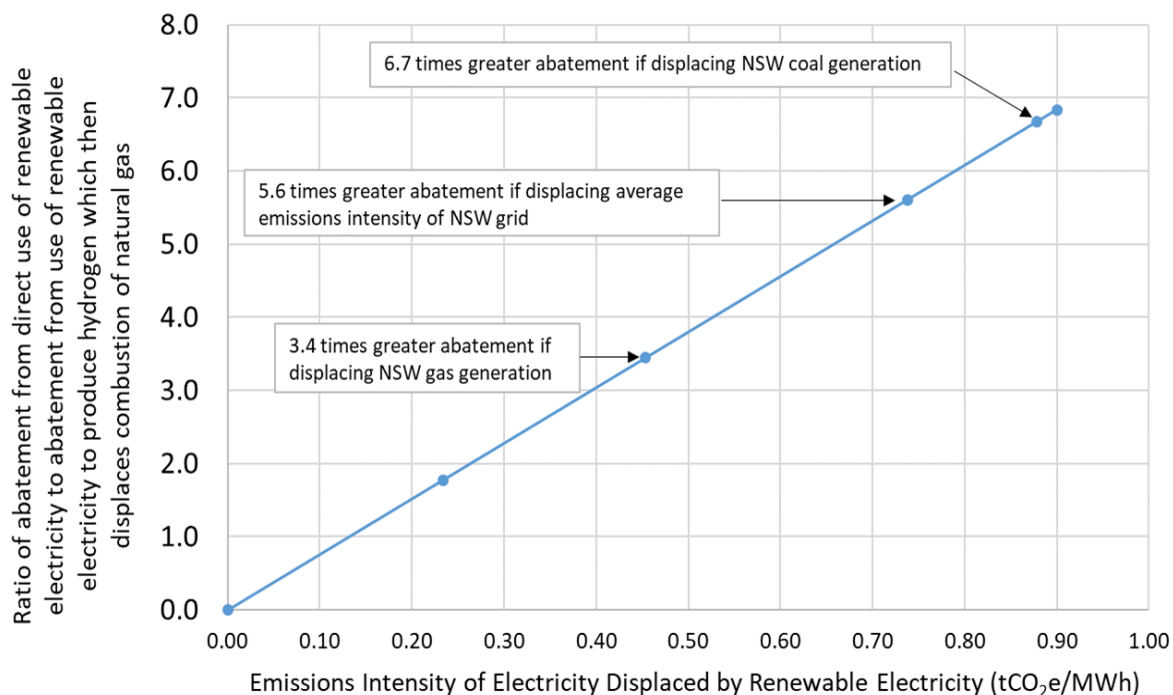
Figure 8. Relationship between abatement from direct use of renewable electricity in the NSW electricity grid and abatement if renewable electricity is used to produce hydrogen which then displaces the combustion of natural gas.

As can be seen from Figure 8, greater abatement is achieved through direct use of renewable electricity in the grid, than by using it to produce hydrogen which then displaces natural gas consumption unless the emissions intensity of the grid is already extremely low; less than $0.15tCO_2e/MWh$.

3.4 Discussion of Clean Hydrogen Production Options

Climate Benefit

The production of clean hydrogen by electrolysers using renewable electricity emits zero greenhouse gases (ignoring lifecycle emissions). Producing clean hydrogen from coal or gas with CCS emits between 0.4 and 4.4kg of CO_2 per kg of H_2 depending upon the capture configuration (ignoring lifecycle emissions). Renewable hydrogen has a clear emissions advantage over fossil hydrogen with CCS.

However, when considering emissions abatement more holistically, several times more abatement is delivered by utilising renewable electricity in the electricity grid compared to using it to produce hydrogen that then displaces natural gas combustion. The renewable electricity required to produce 10% (by volume) of NSW' natural gas demand would deliver almost $1.5MtCO_2e$ of abatement if used to displace coal fired generation in the grid. If it displaced gas fired generation, it would deliver over $0.7MtCO_2e$ of abatement. Used to produce hydrogen which displaces natural gas, that quantity of renewable electricity would only deliver $0.2MtCO_2e$.

Assuming an emissions intensity of $1kgCO_2/kgH_2$ (scope 1) for production of clean hydrogen from coal or natural gas with CCS, and including lifecycle scope 2 emissions from purchased electricity, the net emission abatement of replacing 10% of NSW natural gas (by volume) would be $0.12MtCO_2e$ for coal with CCS and almost $0.16MtCO_2e$ for gas with CCS. Choosing this production option would allow

renewable electricity to be used in the grid where it delivers the greatest emissions abatement. Table 10 summarises the net emissions abatement from various options.

Table 10. Net emissions abatement of options[25].

Option	Net Emissions Abatement (tCO$_2$e)
Replace 10% by volume of NSW natural gas with H$_2$ produced using coal with CCS and grid power.	120,000
Replace 10% by volume of NSW natural gas with H$_2$ produced using natural gas with CCS and grid power.	156,000
Replace 10% by volume of NSW natural gas with H$_2$ produced using 1,677,000MWh of renewable electricity.	223,000
Use 1,677,000MWh of renewable electricity in the grid (assuming 0.738tCO$_2$e/MWh emissions intensity of the grid). – No clean hydrogen production.	1,238,000
Use 1,677,000MWh of renewable electricity in the grid (assuming 0.738tCO$_2$e/MWh emissions intensity of the grid) and replace 10% by volume of NSW natural gas with H$_2$ produced using coal with CCS and grid power.	1,358,000
Use 1,677,000MWh of renewable electricity in the grid (assuming 0.738tCO2e/MWh emissions intensity of the grid) and replace 10% by volume of NSW natural gas with H$_2$ produced using gas with CCS and grid power.	1,394,000

If choosing between using renewable electricity as electricity in the grid, or using renewable electricity to produce hydrogen to replace natural gas, the former has a clear and significant climate advantage. On the basis of emission abatement, the best option is to produce clean hydrogen from gas with CCS and use renewable electricity to displace unabated fossil fuel generation in the grid.

Resource Use

The production of clean hydrogen using electrolysers or coal or gas with CCS require similar amounts of water, around 6kg/kgH$_2$ for gas plus CCS and 9kg/kgH$_2$ for coal plus CCS or electrolysis.[6] Electrolysis has extremely high electricity demand of 55kWh/kgH$_2$ compared to 1.9kWh/kgH$_2$ for gas plus CCS and 3.5kWh/kgH$_2$ for coal plus CCS (lifecycle electricity demand).[1], [5] Producing the 1,677,000 MWh of electricity necessary to produce the requisite quantity of hydrogen would require over 23,500Ha for a dedicated windfarm in a location with excellent wind resources (CF = 0.35). Coal or gas with CCS would require 503Ha of land assuming a 500km long CO$_2$ pipeline was required to transport it to the storage resource. The coal and gas requirements for hydrogen production are modest at 232kt of coal or 5.8PJ of gas for the requisite amount of hydrogen. These are about 5% of the coal demand of a 1.5GW coal fired power station and 40% of the gas demand of a 300MW combined cycle gas power plant operating at 95% capacity factor.

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[25] Emissions avoided from displacement of natural gas (229,000tCO$_2$e) by hydrogen, minus scope 1 emissions from clean hydrogen production using coal or gas with CCS (assume 1kgCO$_2$/kgH$_2$, 30,490t CO$_2$e), minus emissions from lifecycle grid power consumed by H$_2$ production from coal or gas with CCS. Assume emissions intensity of the NSW grid is 0.738tCO$_2$e/MWh.

From a resource use perspective, production of clean hydrogen from coal or natural gas with CCS has a very significant advantage over renewable powered electrolysis as they require modest amounts of plentiful primary resources (coal, gas & pore space for CO_2 storage) and modest amounts of land and electricity. Renewable hydrogen requires very large amounts of scarce resources (renewable electricity and land with excellent wind resources).

Maturity at Scale

Clean hydrogen production from coal or natural gas with CCS has been operating at the 200 tonne to 1,300 tonne per day scale for decades. A plant capable of producing around 100 tonnes per day of clean hydrogen would be amongst the smallest fossil fuel based clean hydrogen production facilities, but would be the largest renewable powered electrolyser plant, by production capacity in the world by a factor of 35. The largest currently operating renewable powered electrolyser can produce approximately 2.4 tonnes of clean hydrogen per day.

This is very small scale for coal or natural gas with CCS. Developing a coal gasification or SMR project with CCS at this small scale would is well within the experience of several suppliers or project developers.The challenge for coal or gas with CCS would be doing the storage site characterisation necessary to obtain the regulatory approvals for geological CO_2 storage, and constructing the CO_2 pipeline. Whilst neither of these activities are novel, both require capital investment and lead time.

In all cases, the technology risk is very small as all technologies are mature. Electrolysers are modular so scaling up by a factor of 35 just requires installing 35 times as many electrolysers. Even so, developing such a large renewable electrolyser project would be novel. The most significant challenge would be finding and acquiring access to a site for the 550MW wind farm needed to power the electrolysers.

Cost

Production of hydrogen from coal or gas with CCS is currently less than AUD3 per kg compared to around AUD8/kg for renewable powered electrolysis. By 2030, the cost of hydrogen production using renewable powered electrolysis may drop to AUD5/kg and to around $2.10-$2.30/kg using gas or black coal with CCS

In Australia, clean hydrogen produced from coal or gas with CCS is expected to remain around one third to one half of the cost of clean hydrogen produced by renewable powered electrolysers, at least until 2030.

4. Conclusion

All things considered, production of clean hydrogen from coal or natural gas with CCS is a better option than producing clean hydrogen from renewable powered electrolysers in Australia for the following reasons.

- The production cost of clean hydrogen from coal or natural gas with CCS is less than half that of renewable powered electrolysis.
- It requires relatively modest amounts of plentiful resources (coal, gas, pore space for CO_2 storage), whereas renewable hydrogen requires very large amounts of relatively scarce resources (renewable electricity and land with excellent wind resources).
- The scale of facilities required is small and familiar compared to existing facilities making project development less difficult. A renewable powered electrolyser project at this scale is unprecedented.
- It provides very much greater emissions abatement by allowing renewable electricity to be used as electricity in the grid to displace coal fired generation where it delivers almost seven times more emissions abatement than if it was used to produce hydrogen which then displaces combustion of natural gas.

Table 11 presents a summary comparison of these options.

Table 11. Comparison of Options

	Coal Gasification + CCS	Steam Methane Reformation + CCS	Renewable Electricity Powered Electrolysis
Cost in 2020 (AUD/kgH$_2$)	$2.90	$2.50	$8
Cost in 2030 (AUD/kgH$_2$)	$2.25	$2.10	$5
Technology Maturity	Mature, commercially available	Mature, commercially available	Mature, commercially available
Scale of Facilities Currently in Operation (tonnes of clean H$_2$ produced per day per facility)	200-1,300	200-900	Up to 2.4
Scale of Facility required to produce 83.5t of clean H$_2$ per day compared to facilities currently in operation	Very small	Very small	35 times larger than the world's largest
Resource Requirements to produce 83.5t of clean H$_2$ per day			
Land (Ha)	503	503	23,500
Electricity (MWh)	106,000	58,000	1,677,000
Water (Ml)	274	192	274
Coal (kt)	232	0	0
Gas (PJ)	0	5.76	0
Pore space for CO$_2$ storage (tonnes of CO$_2$)[26]	640,000	232,000	0

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[26] Assumes 7.6kgCO$_2$ captured per kg H$_2$ for SMR + CCS and 21kgCO$_2$ captured per kgH$_2$ for CG +CCS

Appendix 1. Description of Technologies

Steam Methane Reforming (CO₂ Capture Options also shown)

Syngas Production for Industrial Processes

A typical synthesis gas (syngas) production process via steam methane reforming (SMR) for industrial processes is presented in Figure A1. Examples of industrial processes include direct reduced iron, methanol production and ammonia production. In ammonia production, CO₂ removal is typically integrated into the process for downstream fertiliser (urea) production, resulting in a high concentration of CO₂, ready for transport and storage.
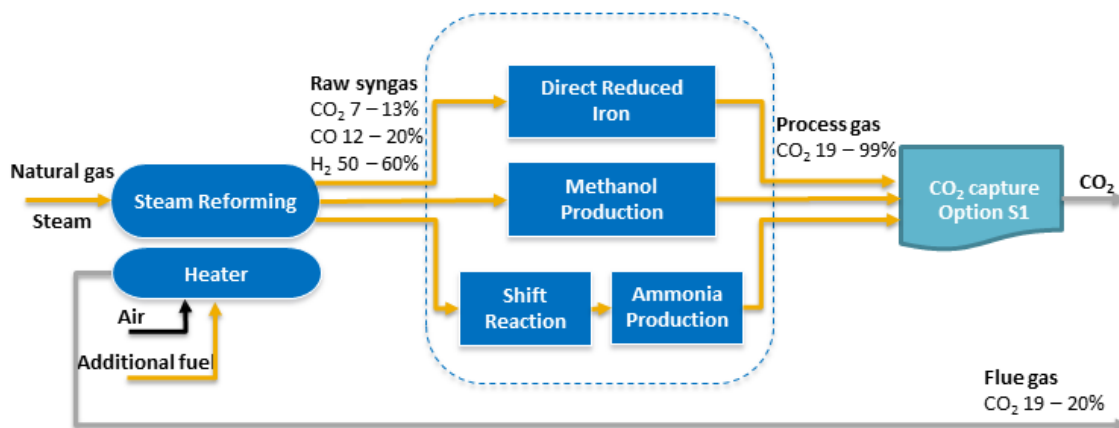
Figure A1. Process flow diagram for syngas production via SMR with CO₂ capture after the industrial process. The balance of all gas streams consists of N₂, CH₄ and H₂O.

Pure Hydrogen Production

A typical pure hydrogen production process via SMR is presented in Figure A2. Pure hydrogen production from methane requires that the syngas (mixture of H₂ and CO) be put through a water-gas shift reaction to produce more H₂ and CO₂, followed by CO₂ capture using pressure swing adsorption. The gas exiting the shift reaction contains around 60 per cent of the total CO₂ produced in a typical hydrogen SMR plant. The remaining 40 per cent of CO₂ is mainly produced from the combustion of the additional fuel (normally natural gas) to heat the steam reformer (700 – 1,000 °C). In Figure A2, the pressure swing adsorption (PSA) tail gas containing residual hydrogen and methane is used as fuel to continuously heat the steam reformer. This heat is required because the overall SMR reaction is endothermic as shown in following equations. Thus, all the CO₂ (if not captured in option S2 or S3) ends up in the flue gas of the SMR heater.

Methane steam reforming:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \;\; (\Delta H^o_{298} = 206 \; kJ/mol)$$

Water-gas shift:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \;\; (\Delta H^o_{298} = -41 \; kJ/mol)$$
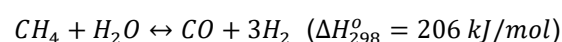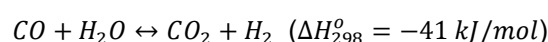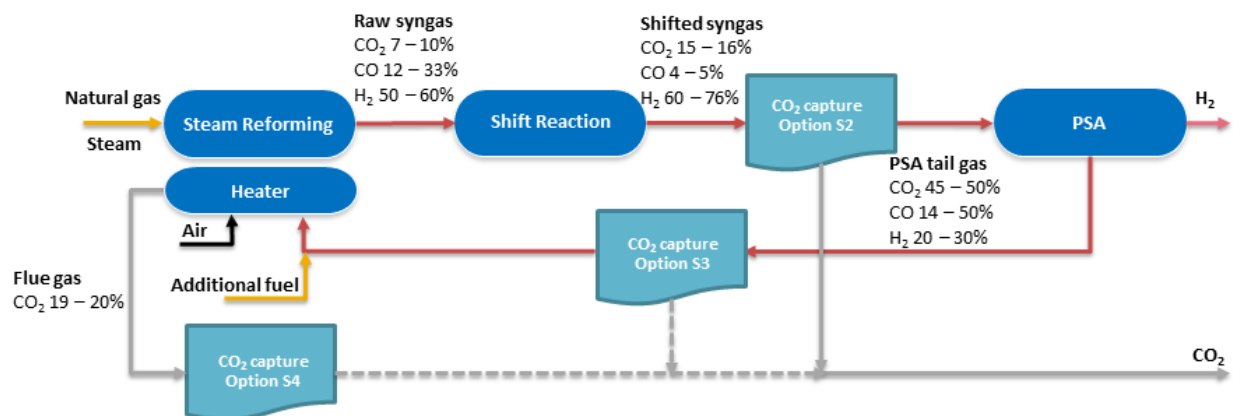
Figure A2. Process flow diagram for hydrogen production via SMR with three CO_2 capture options. PSA is pressure swing adsorption. The balance of all gas streams consists of N_2, CH_4 and H_2O.

Summary of Key Operational Parameters for SMR with CO_2 Capture

Table A1 summarises CO_2 capture and emission information for various configurations of SMR plants with CCS:

- Base Case – SMR plant for hydrogen production (no CO_2 capture)
- Option S1 – SMR with integrated industrial process and CO_2 capture
- Option S2 – SMR plant with CO_2 capture from shifted syngas for hydrogen production
- Option S3 – SMR plant with CO_2 capture from PSA tail gas for hydrogen production
- Option S4 – SMR plant with CO_2 capture from SMR flue gas for hydrogen production

Table A1. Summary information of hydrogen/syngas production via steam methane reforming with CO_2 capture options. GCCSI analysis based on information from [13], [14], [15].

	Base case	CO₂ capture option S1	CO₂ capture option S2	CO₂ capture option S3	CO₂ capture option S4
Case	SMR w/o CO_2 capture	SMR + CO_2 capture from industrial process	SMR + CO_2 capture from shifted syngas	SMR + CO_2 capture from PSA tail gas	SMR + CO_2 capture from SMR flue gas
CO_2 concentration at capture inlet (volume)	-	~40-99 %	15-16 %	45-50 %	19-20 %
Gas pressure at capture inlet	-	~ 1 bar	~23 bar	~1.3 bar	~ 1 bar
CO_2 capture efficiency	-	90 %	90 %	90-95 %	90 %
Total proportion of CO_2 captured	0%	54 %[27]	54-64 %	52-53 %	90 %
Scope 1 CO_2 emissions	8.6 kg /kg	4.2 kg / kg	3.3 – 4.2 kg / kg	4.3 – 4.4 kg / kg	1.0 kg / kg
Total CO_2 emissions including lifecycle emissions from purchased electricity[28]	9.4 kg /kg	5.6 kg / kg	4.7 – 5.6 kg / kg	5.7–5.8 kg / kg	2.4 kg / kg

Autothermal Methane Reforming (CO₂ Capture Options also shown)

Autothermal reforming (ATR) combines the two processes of partially oxidizing natural gas with oxygen, and catalytically reforming natural gas with steam. Due to the combustion of some of the methane in the reaction vessel, the total reaction of autothermal reforming is exothermic as shown in the equations below. This means that ATR can achieve a heat balance when heat exchangers are integrated and no additional energy or fuel (which would produce additional CO_2 – shown as a *Heater* in the SMR process flow diagrams) is required to maintain the reaction.
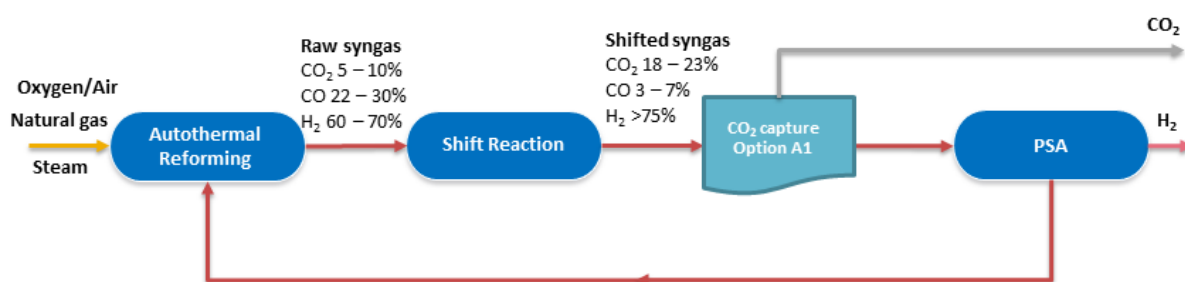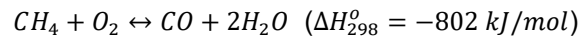

Figure A3. Process flow diagram for hydrogen production via ATR with CO_2 capture. PSA is pressure swing adsorption. The balance of all gas streams consists of N_2, CH_4 and H_2O.

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[27] Compared to the CO_2 emissions from the steam methane reforming plant (excludes any additional CO_2 emissions that may arise from the industrial process in which the syngas is utilised)
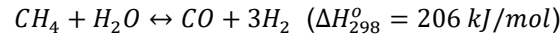
[28] Assumes grid power emissions intensity of 738kgCO₂/MWh and includes electricity used in the production of the coal or gas.
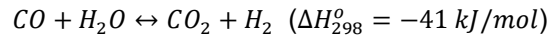
Methane combustion:

$$CH_4 + O_2 \leftrightarrow CO + 2H_2O \ \ (\Delta H^o_{298} = -802 \ kJ/mol)$$

Methane steam reforming:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \ \ (\Delta H^o_{298} = 206 \ kJ/mol)$$

Water-gas shift:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \ \ (\Delta H^o_{298} = -41 \ kJ/mol)$$

An ATR reactor operates at high temperatures around 950 - 1,100°C and high pressures of up to 100 bar. It allows high methane conversion and high syngas pressure at the outlet. The high-pressure condition of the syngas allows CO_2 capture using mature physical absorbent technologies (i.e. Selexol, Rectisol).

Summary of Key Operational Parameters for ATR with CO_2 Capture

Table A2 summarises CO_2 capture and emission information in ATR plants with CCS.

- Base Case – ATR plant for hydrogen production (no CO_2 capture)
- Option A1 – ATR plant with CO_2 capture from shifted syngas for hydrogen production

Table A2. Summary information of hydrogen production via autothermal reforming with CO_2 capture. GCCSI analysis based on information from [16] and [2]

Case number	Base case	CO₂ capture option A1
Case	ATR with heat integration w/o CO_2 capture	ATR with heat integration +CO_2
CO_2 concentration at capture inlet	-	18-23 %
Gas pressure at capture inlet	-	35-100 bar
CO_2 capture efficiency	-	~94 %
Total proportion of CO_2 captured	0 %	~94 %
Scope 1 CO_2 emission in syngas/	7.8 – 7.9 kg /kg	~0.4-0.8 kg / kg
Total CO_2 emissions including lifecycle emissions from purchased electricity[29]	8.6 – 8.7 kg /kg	~1.8 – 2.2 kg / kg

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[29] Assumes grid power emissions intensity of 738kgCO₂/MWh and includes electricity used in the production of the coal or gas.

Coal Gasification (CO$_2$ Capture Options also shown)

The coal gasification process is presented in Figure A4. CO$_2$ removal via acid gas removal is an integral part of the coal gasification process using physical absorption technologies (i.e. Selexol, Rectisol). CO$_2$ capture option C1 shown in Figure A4 only requires an add-on process of CO$_2$ compression and dehydration. Because a large proportion of CO$_2$ is separated via acid gas removal, the amount of CO$_2$ entering additional CO$_2$ capture option C2 is relatively small.
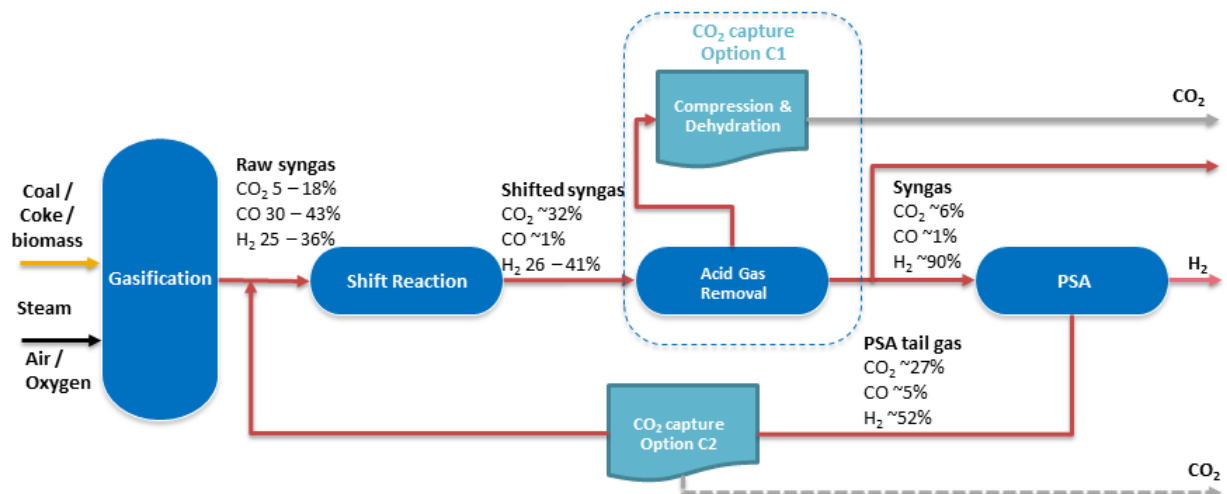
Figure A4. Process flow diagram for hydrogen/syngas production via coal gasification with CO$_2$ capture. PSA is pressure swing adsorption. It also applies to petroleum coke and biomass gasification. The balance of all gas streams consists of N$_2$, CH$_4$ and H$_2$O.

Summary of Key Operational Parameters for Coal Gasification with CO$_2$ Capture

Table A3 summarises CO$_2$ capture and emission information in coal gasification plants with CCS

- Base Case – Coal gasification plant (no CO$_2$ capture)
- Option C1 – Coal gasification plant with CO$_2$ capture from shifted syngas (compression & dehydration)
- Option C2 – Coal gasification plant with dedicated CO$_2$ capture after acid gas removal (in addition to capture from shifted syngas)

Table A3. Summary information for hydrogen production via coal gasification with CO_2 capture. GCCSI analysis based on information from [17],[2]

	Base case	CO₂ capture option C1	CO₂ capture option C2
Case	Coal gasification w/o CO_2 capture	Coal gasification + CO_2 capture from shifted syngas	Coal gasification + dedicated CO_2 capture after acid gas removal
CO_2 concentration at capture inlet	-	25-42 %*	~5-6 %
Gas pressure at capture inlet	-	35-57 bar*	53 bar
CO_2 Capture efficiency	-	90-95 %	90 %
Total proportion of CO_2 captured	0%	90 %[30]	98 %[31]
Scope 1 CO_2 emission in syngas/ hydrogen production	19.0 – 24.5 kg / kg[32]	2.1-2.7 kg / kg	0.4-0.6 kg / kg
Total CO_2 emissions including lifecycle emissions from purchased electricity[33]	20.3– 25.8 kg / kg	4.7-5.3 kg / kg	3.0 -3.2 kg / kg

*Variations due to the application of different gasification technologies.

Hydrogen as a By-product of Chlor-Alkali Production

Hydrogen is produced as a by-product of chlorine and caustic soda production through the electrolysis of brine (concentrated NaCl in water). The process uses an electrolysis cell with an ion exchange membrane separating a bath of brine (NaCl) with an anode to which a positive voltage is applied, from a bath of caustic soda (NaOH) with a cathode to which a negative voltage is applied. Concentrated brine is fed to the anode side of the cell. Chlorine ions release an electron to the anode to form chlorine gas (Cl_2). The sodium ions pass through the membrane to the cathode side of the cell. At the cathode, water is reduced to hydrogen gas, leaving hydroxide ions which then combine with sodium ions to produce sodium hydroxide (caustic soda - NaOH).

The main products of the cell are caustic soda and chlorine with hydrogen produced as a bi-product in the following ratios; 80 tonnes NaOH : 71 tonnes Cl_2 : 2 tonnes H_2. Each tonne of hydrogen produced using this process requires approximately 0.8t of salt and 1100kWh of electricity[19]. This is not a feasible process for the production of hydrogen except as a by-product in the production of chlorine and caustic soda.

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[30] CO_2 produced from combustion to heat up the gasifier is utilised in the gasification plant for CO production [17], [24].
[31] CO_2 produced from combustion to heat up the gasifier is utilised in the gasification plant for CO production [17], [24].
[32] Data from [18]
[33] Assumes grid power emissions intensity of 738kgCO₂/MWh and includes electricity used in the production of the coal or gas.
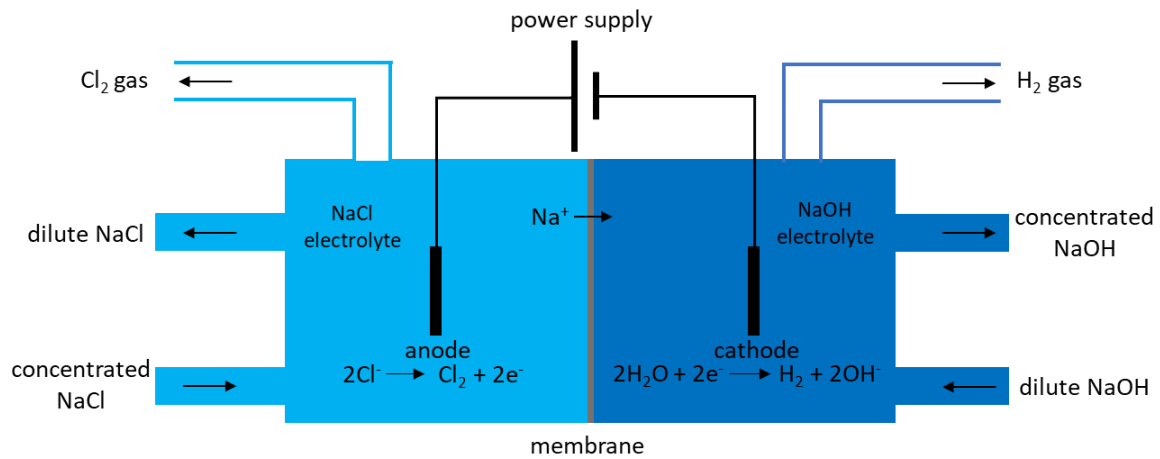
Figure A5. Chlor-alkali Electrolyser Cell

Hydrogen Production by Electrolysis of Water

There are two general classes of electrolysers that are commercially available, alkaline electrolysers and proton exchange membrane electrolysers. Solid oxide electrolysis cells are currently in development and have not yet been commercialized. All consume high purity water and electricity to produce hydrogen and oxygen but use different electrolysis cell configurations and charge carriers. All are based on the same overall chemical reaction.

$$2H_2O \rightarrow 2H_2 + O_2 \quad (\Delta H^o_{298} = 286 \; kJ/mol)$$
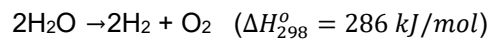
The above equation determines a minimum theoretical requirement of 9kg of pure water for every kilogram of hydrogen produced. Actual water requirements will be slightly higher due to inefficiencies and losses in the system.

The power requirements for these electrolysers are significant and are summarised in the table below. Desalination of sea water, if required due to scarcity of pure water, will consume an additional 3-4kWh per kg of hydrogen produced.

Table A4. Power requirements for electrolyser cells.[34]

	Alkaline Electrolysis Cells	**Proton Exchange Membrane Electrolysis Cells**	**Solid Oxide Electrolysis Cells**
Electricity required per kg of H_2 produced	48-52kWh	56-60kWh	41-45kWh*

* SOEC requires steam. The energy necessary to produce the steam is additional to the electricity required to be supplied to the cell.

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[34] Adapted from [1]. Based on lower heating value of hydrogen.

Alkaline Electrolysis

Alkaline electrolysis is a mature technology that uses an electrolysis cell with a membrane separating two baths of a caustic electrolyte (eg, KOH – potassium hydroxide solution). One side of the cell has an anode to which a positive voltage is applied. The other side of the cell has a cathode to which a negative voltage is applied. Water molecules pick up an extra electron dissociating into hydrogen gas and hydroxide ions (OH⁻) at the cathode. The hydroxide ions travel through the membrane to the cathode where they give up their extra electrons to form water and oxygen.
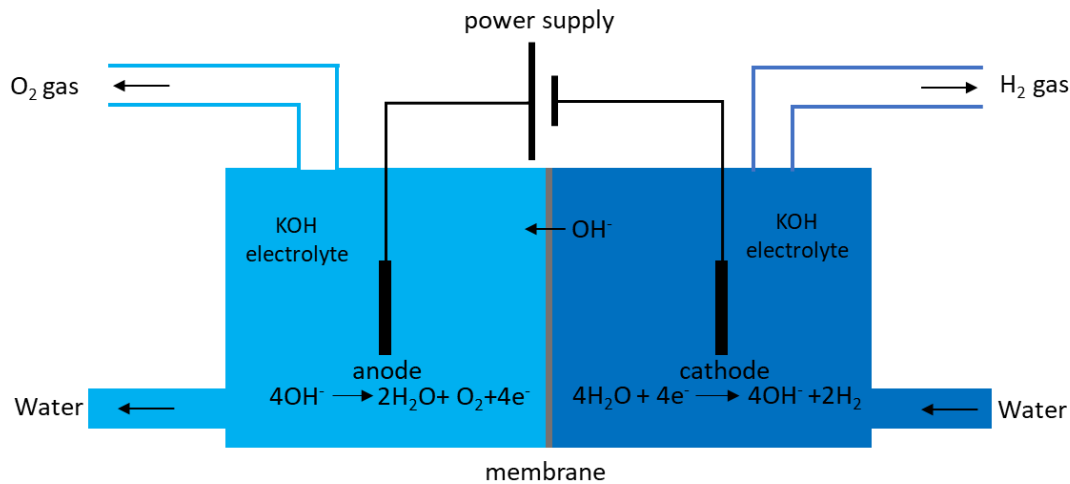
Figure A6. Alkaline Electrolyser Cell

Proton Exchange Membrane Electrolysis

Proton exchange membrane electrolysers are also a mature commercially available technology. They use pure water as the electrolyte with the cathode and anode sides of the cell separated by a proton exchange membrane through which hydrogen ions can pass. Water molecules give up two electrons at the anode and dissociate to oxygen gas and hydrogen ions. The hydrogen ions travel through the proton exchange membrane to the cathode where they pick up an electron forming hydrogen gas.
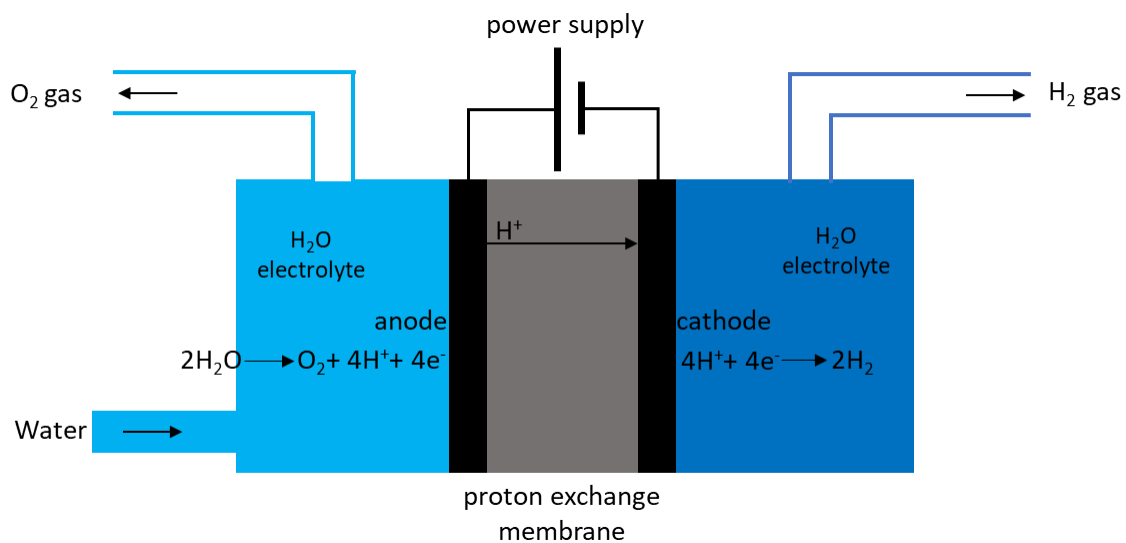

Figure A7. Proton Exchange Membrane Electrolyser Cell

Solid Oxide Electrolysis

Solid oxide electrolysis cells have not yet been commercialized. They operate at high temperature

(above 800C), consume steam instead of liquid water, and use a solid electrolyte. Their high temperature operation enables higher electrical efficiency of the cell but requires an additional heat source to supply the steam. Water molecules (as steam) pick up two electrons at the cathode and dissociate to hydrogen gas and oxygen ions. The oxygen ions travel through the solid electrolyte to the anode where they give up their excess electrons to form oxygen gas.
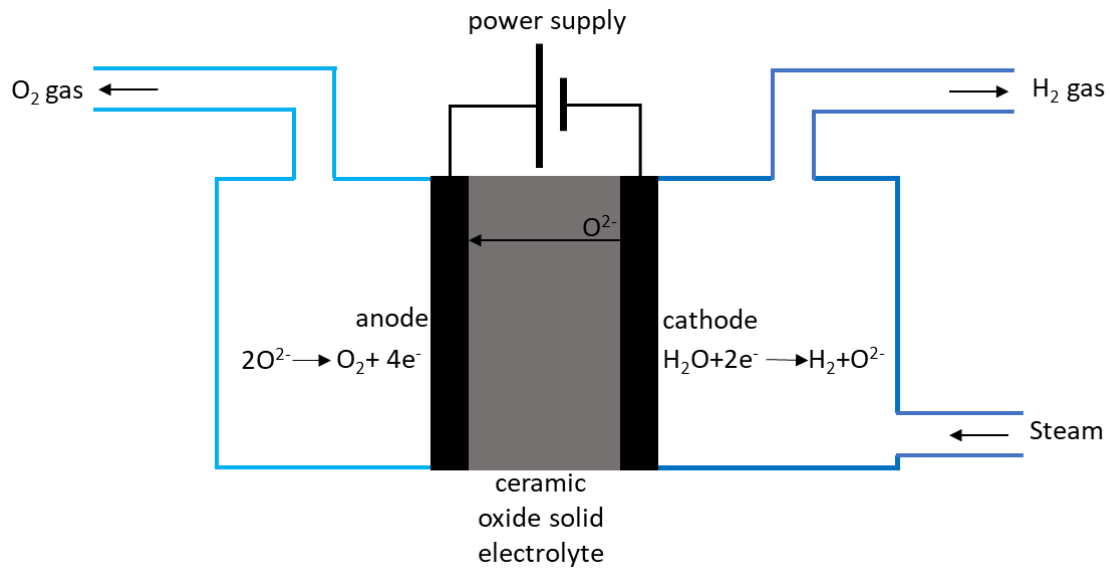

Figure A8. Solid Oxide Electrolyser Cell

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