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BLUE HYDROGEN

GLOBAL CCS INSTITUTE

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Acknowledgements

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THE CIRCULAR CARBON ECONOMY: KEYSTONE TO GLOBAL SUSTAINABILITY SERIES assesses the opportunities and limits associated with transition toward more resilient, sustainable energy systems that address climate change, increase access to energy, and spark innovation for a thriving global economy.

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INTRODUCTION

Stopping global warming requires net greenhouse gas emissions to fall to zero and remain at zero thereafter. Put simply, all emissions must either cease, or be completely offset by the permanent removal of greenhouse gases (particularly carbon dioxide - CO_2) from the atmosphere. The time taken to reduce net emissions to zero, and thus the total mass of greenhouse gases in the atmosphere, will determine the final equilibrium temperature of the Earth. Almost all analysis concludes that reducing emissions rapidly enough to remain within a 1.5°Celsius carbon budget is practically impossible. Consequently, to limit global warming to 1.5°Celsius above pre-industrial times, greenhouse gas emissions must be reduced to net-zero as soon as possible, and then CO_2 must be permanently removed from the atmosphere to bring the total mass of greenhouse gases in the atmosphere below the 1.5° Celsius carbon budget.

This task is as immense as it is urgent. A conclusion that may be drawn from credible analysis and modelling of pathways to achieve net-zero emissions is that the lowest cost and risk approach will embrace the broadest portfolio of technologies and strategies, sometimes colloquially referred to as an "all of the above" approach. The King Abdullah Petroleum Studies and Research Center (KAPSARC) in the Kingdom of Saudi Arabia developed the Circular Carbon Economy (CCE) framework to more precisely describe this approach. This framework recognizes and values all emission reduction options (Williams 2019). The CCE builds upon the well-established Circular Economy concept, which consists of the "three Rs" which are Reduce, Reuse and Recycle. The Circular Economy is effective in describing an approach to sustainability considering the efficient utilization of resources and wastes however it is not sufficient to describe a wholistic approach to mitigating greenhouse gas emissions. This is because it does not explicitly make provision for the removal of carbon dioxide from the atmosphere (Carbon Direct Removal or CDR) or the prevention of carbon dioxide, once produced, from entering the atmosphere using carbon capture and storage (CCS). Rigorous analysis by the Intergovernmental Panel on Climate Change, the International Energy Agency, and many others all conclude that CCS and CDR, along side all other mitigation measures, are essential to achieve climate targets.

The Circular Carbon Economy adds a fourth "R" to the "three Rs" of the Circular Economy; Remove. Remove includes measures which remove CO_2 from atmosphere or prevent it from entering the atmosphere after it has been produced such as carbon capture and storage (CCS) at industrial and energy facilities, bio-energy with CCS (BECCS), Direct Air Capture (DAC) with geological storage, and afforestation.

This report explores the potential contribution of blue hydrogen, which has very low life-cycle CO_2 emissions, to climate mitigation. Blue hydrogen produced from fossil fuels with carbon capture and storage (CCS) can contribute to the Reduce dimension of the CCE by displacing the use of unabated fossil fuels in industrial and energy applications. Hydrogen produced from biomass with CCS can also contribute to the Remove dimension of the CCE as it has negative life-cycle emissions.

1.0 CURRENT PRODUCTION & USE

Near-zero emissions hydrogen (clean hydrogen) has the potential to make a significant contribution to emissions reduction in the power generation, transportation, and industrial sectors. Hydrogen can be burned in turbines or used in fuel cells to generate electricity, can be used in fuel cells to power electric vehicles, as a source of domestic and industrial heat, and as a feedstock for industrial processes. Hydrogen may also be used to store excess energy generated by intermittent renewable electricity sources when supply exceeds demand, albeit with significant losses. The virtue of hydrogen is that it produces zero carbon emissions at the point of use.

Currently approximately 120Mt of hydrogen is produced annually; around 75Mt 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 (39Mt) and ammonia production (33Mt). Less than 0.01Mt of pure hydrogen is used in fuel cell electric vehicles. The syngas containing the remaining 45Mt of hydrogen is used mostly in methanol production (14Mt), direct reduction iron making and other industrial processes including as a source of high-heat (IEA 2019; International Energy Agency (IEA) 2020 2020a).

Approximately 98% of current 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). Approximately 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. Approximately 98% of global hydrogen production is emissions intense, emitting around 830Mtpa of CO_2 (IEA 2019; Global CCS Institute 2020).

Low emission production methods for hydrogen available today include steam methane reformation (SMR), autothermal reformation of methane (ATR), or coal gasification; each with carbon capture and storage (CCS), and electrolysis of water powered by near zero emissions electricity such as renewable generation or nuclear power. Production of clean hydrogen from biomass through anaerobic digestion, fermentation, gasification or pyrolysis (all with CCS) are at earlier stages of commercialization. Production from biomass with CCS is attractive as it would deliver negative emissions, although it would compete with other sources of demand for biomass (International Energy Agency (IEA) 2020 2020a).

Figure 2. shows estimates of the emission intensity of various hydrogen production pathways. The production pathways with the highest emissions are coal gasification without CCS, and electrolysis using power supplied by fossil generators; in this example, natural gas combined cycle generation (NGCC). Both have an emissions intensity of approximately 22kgCO_2/kgH_2. Further, using electricity from a power grid to increase the utilisation of renewable powered electrolysers will also produce high emissions hydrogen, unless the grid has an extremely low emissions intensity. If the grid has an emissions intensity equivalent to NGCC (400kg/MWh), and 63% of the power supplied to the electrolysers is from the grid (the remaining 37% being from dedicated renewable generation), the hydrogen produced will have an emissions intensity of approximately 14kgCO_2/kgH_2 – this compares to approximately 9-10kgCO_2/kgH_2 for conventional SMR without CCS. A significant conclusion from this analysis is that electrolysers should never be powered by electricity from a grid supplied by fossil generation. Hydrogen produced by electrolysers will produce higher CO_2 emissions than conventional SMR without CCS unless the electricity supplying the electrolyser has an emission intensity of around 165kgCO_2/MWh or less.[1]

[1] Note that all of these figures are approximate. NGCC has a range of emission intensities. Fugitive emissions from natural gas and coal production are not explicitly considered and will add to total lifecycle emissions from fossil pathways. Lifecycle emissions from construction and maintenance of renewable generation facilities, and biomass production are also not fully considered and will add to the emission intensity of those production pathways.

It is clear from Figure 2 that hydrogen produced from gas or coal with CCS, from biomass, or from electrolysers powered by near-zero emissions electricity will be clean hydrogen. It is also clear that hydrogen production by gasification of biomass with CCS can deliver very significant negative emissions making it an attractive option for climate mitigation purposes. However gasification of biomass to produce hydrogen is not yet fully commercialised, and would compete with other processes for biomass. Its deployment is thus constrained, at least in the near term.

Figure 1. Current Annual H_2 Production – 120Mt

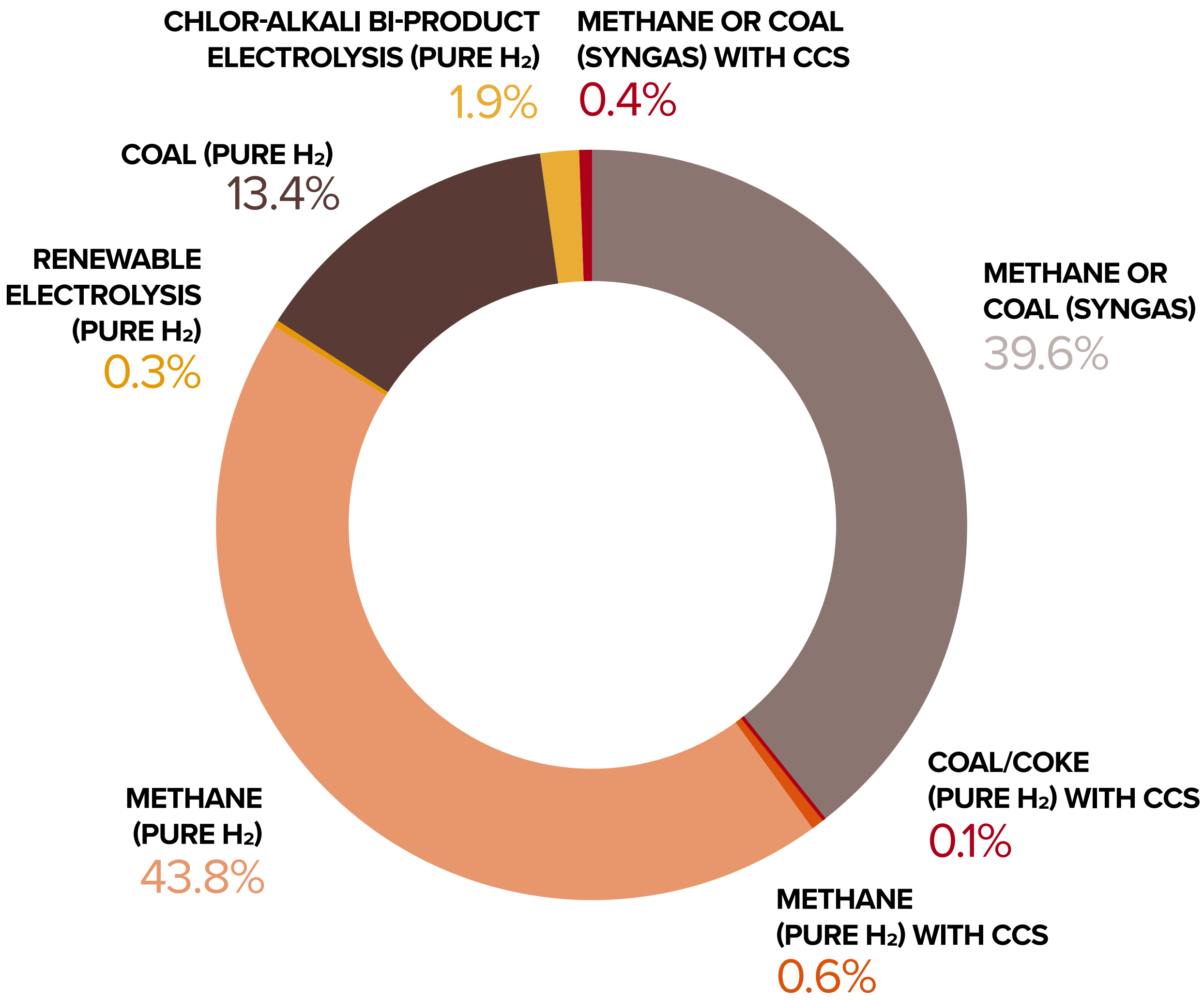
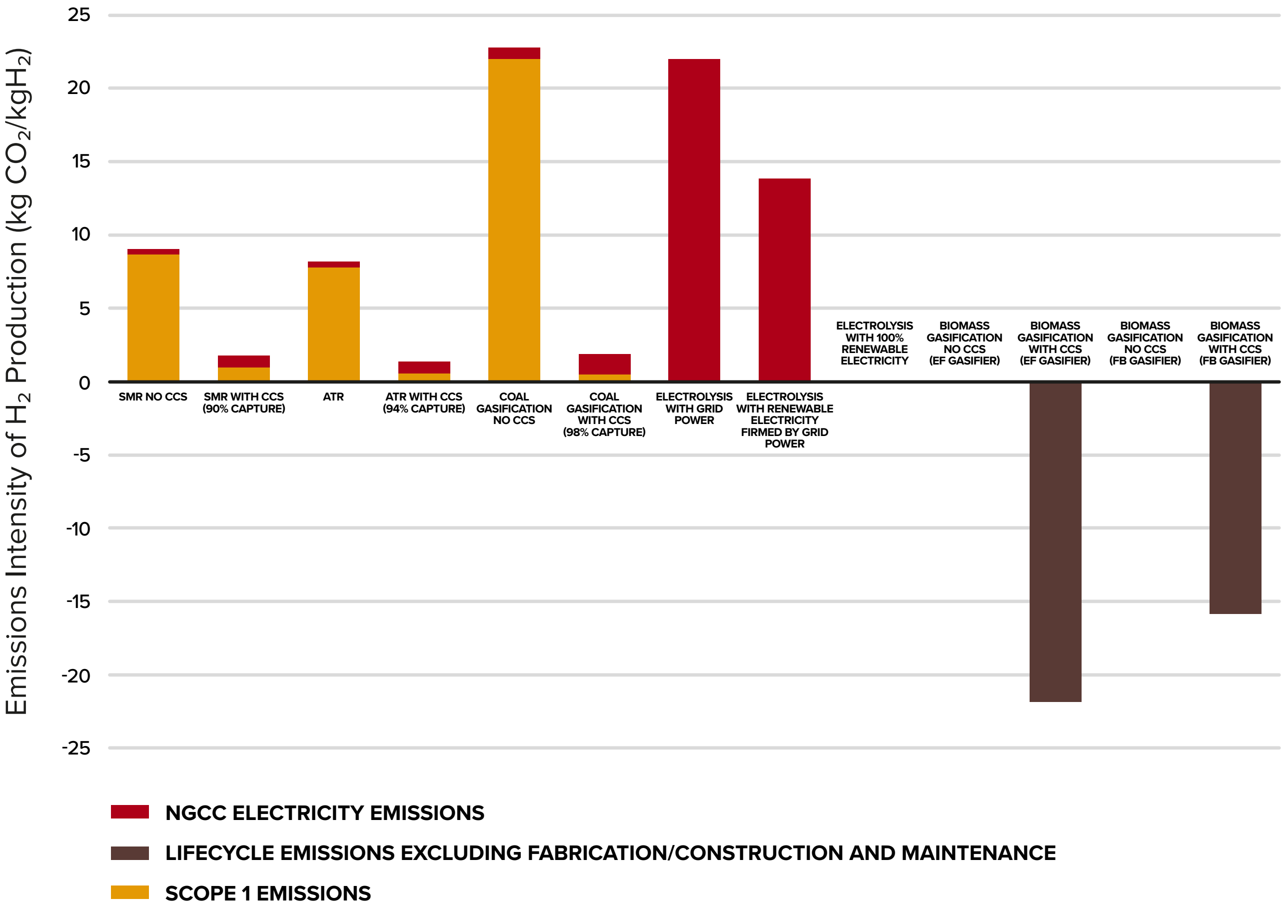


Figure 2. Emissions intensity of hydrogen production technologies. Assumes emissions intensity of NGCC of 400kgCO_2/MWh, 55kWh/kgH_2 for electrolysis, 37% of production from grid firmed electrolysis utilises zero emissions renewable electricity. EF = Entrained Flow. FB = Fluidised Bed. Electricity required for methane and coal production pathways are full-lifecycle including power used in methane and coal production from (Mehmeti et al. 2018). Emissions from biomass gasification are from (Salkuyeh, Saville & MacLean 2018). Fugitive emissions from natural gas and coal production are not explicitly considered and will add to total lifecycle emissions from fossil pathways. Lifecycle emissions from construction and maintenance of renewable generation facilities, and biomass production are also not fully considered and will add to the emission intensity of those production pathways.



Facilities producing hydrogen from fossil fuels with CCS have been operating at commercial scale, producing up to 1,300t of hydrogen per day, per facility, for decades (Global CCS Institute 2019). Table 1. lists current hydrogen production facilities with CCS.

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 (Renew Economy 2020). 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 2.4t of clean hydrogen per day.

Much larger scale renewable hydrogen production facilities are currently being planned and developed. These facilities benefit from economies of scale and access to outstanding renewable resources. The world's largest renewable hydrogen production facility is being planned in Australia. The Asian Renewable Energy Hub (AREH) project, if it proceeds to construction, will produce 4800t per day of hydrogen from electrolysers powered by 23GW of solar PV and wind power ('The Asian Renewable Energy Hub' 2020a). The Neom project in Saudi Arabia will produce 650t of hydrogen per day from electrolysers powered by 4GW of solar PV and wind. Both the AREH project in Australia's remote north-west and the Neom project in Saudi Arabia have excellent solar and wind resources.

Table 1. Hydrogen Production from Fossil Fuels with CCS

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

Table 2. Examples of the world's largest renewable hydrogen production facilities

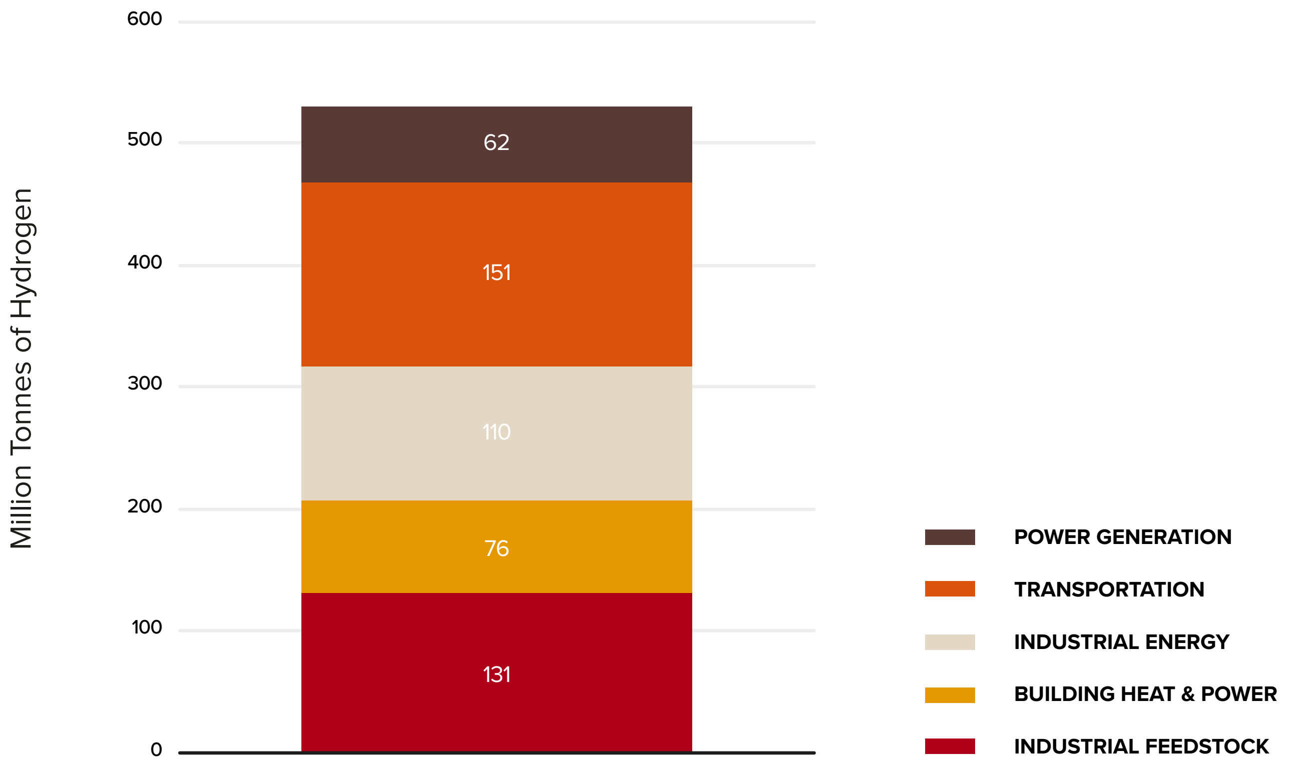
FACILITY	H_2 PRODUCTION CAPACITY	H_2 PRODUCTION PROCESS	OPERATIONAL COMMENCEMENT
Fukushima	2.4 tonnes H_2 per day	10MW electrolysers powered by 20MW solar PV	2019
Neom	650 tonnes H_2 per day	4GW wind and solar PV powered electrolysers	Expected after 2025
AREH	4800 tonnes H_2 per day	23GW wind and solar PV powered electrolysers	Possible after 2028

2.0 EMISSIONS ABATEMENT OPPORTUNITY

As a carbon free energy carrier and feedstock to industrial processes, clean hydrogen could have a significant role in decarbonising the global economy across a range of sectors. The Hydrogen Council estimates that demand for hydrogen could exceed 530Mtpa by 2050, and if that demand was met by clean hydrogen, could deliver 6Bt CO_2 abatement in that year(Hydrogen Council 2017). This estimate is subject to many assumptions about the demand for clean hydrogen, its applications and the energy sources that the hydrogen would displace, however it illustrates the potential of clean hydrogen to support multi-gigatonne scale abatement across the global economy.

Meeting that demand would require scaling up production capacity for clean hydrogen from less than 2Mtpa today to over 500Mtpa in less than 30 years. Rapid ramp-up of production capacity is a critical requisite for hydrogen to play a significant role in achieving ambitious climate targets.

Figure 3. Potential Clean Hydrogen Demand in 2050 -adapted from (Hydrogen Council 2017)



3.0 CLEAN HYDROGEN PRODUCTION COSTS

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.(IEA 2019)

Table 3 and Figure 4 summarise the cost of clean hydrogen production according to recent reports by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Bruce et al. 2018), the International Energy Agency (IEA 2019; International Energy Agency (IEA) 2020 2020a), the International Renewable Energy Association (IRENA) (International Renewable Energy Agency 2019) and the Hydrogen Council (Hydrogen Council 2020). These reports use a range of underlying assumptions (e.g. cost of fuels and electricity, capacity factors for renewable generation) that must be considered when comparing their results. Actual costs will always be site and project specific.

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 less than USD2c/kWh. However, renewable electricity is currently scarce and relatively small amounts of it are curtailed resulting in very low utilisation of the electyrolyser (10%) and a very high unit cost of production. This explains the high cost of clean hydrogen production from curtailed renewable electricity calculated by CSIRO.

It is also worth noting that the lowest estimate of cost for hydrogen from electrolysis by the IEA assumes a low electricity cost of USD2c/kWh and a capacity factor of 57%. The IEA report does not state that the electricity is supplied from renewable sources. Achieving a 57% capacity factor and 2c/kWh cost of electricity from solar PV or wind will not be possible in most locations. However, where excellent wind and solar PV resources are collocated, and abundant land is available at low cost, this may be achievable such as at the proposed Neom and AREH renewable hydrogen facilities.

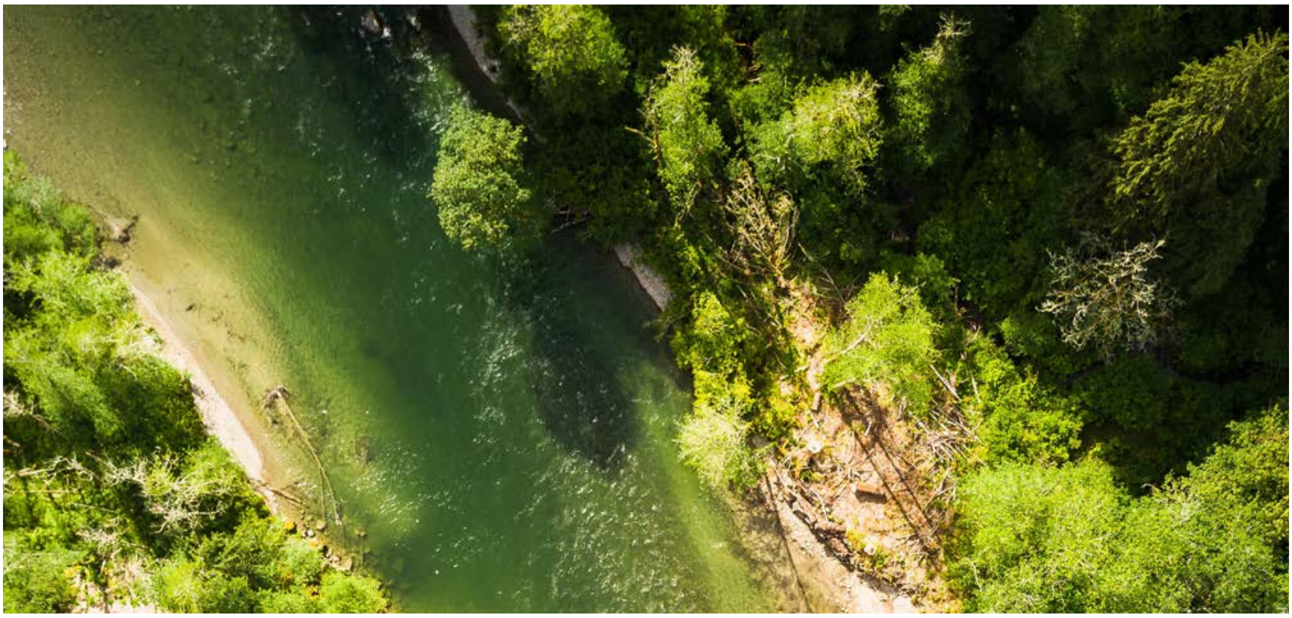


Table 3. Recent published estimates of cost of clean hydrogen production.(IEA 2019; Bruce et al. 2018; International Renewable Energy Agency 2019; Hydrogen Council 2020)

ALL COSTS IN USD 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[3]	**$7.70** (35% capacity factor, electricity price 6c/kWh)	**$18.20** (10% capacity factor, electricity price 2c/kWh)	**$1.60 - $1.90** (Gas price is $8/GJ)	**$1.80 - $2.20** (Coal price is $3/GJ)
IEA 2020	**$2.30 – $6.60[4]** (Low end is 57% capacity factor and electricity cost 2c/kWh. High end is 57% capacity factor and electricity cost 10c/kWh)	N/A	**$1.40 – $2.40** (Low end is gas price $3/GJ. High end is gas cost $9/GJ)	**$2.05 - $2.20** (Low end is coal price 43c/GJ. High end is coal cost $1.15/GJ)
IRENA 2019	**$2.70 – $6.90** (Low end is wind; 48% capacity factor & electricity price 2.3c/kWh. High end is PV; 26% capacity factor & electricity price 8.5c/kWh)	N/A	**$1.50 – $2.30** (Low end is gas price $3/GJ. High end is gas price $8/GJ)	**$1.80** (Coal price is $1.50/GJ)
Hydrogen Council 2020	**$6.00** (50% capacity factor & electricity price 5.7c/kWh)	N/A	**$2.10** (assumes "European gas prices")	**$2.10** (Coal price is $60/tonne)

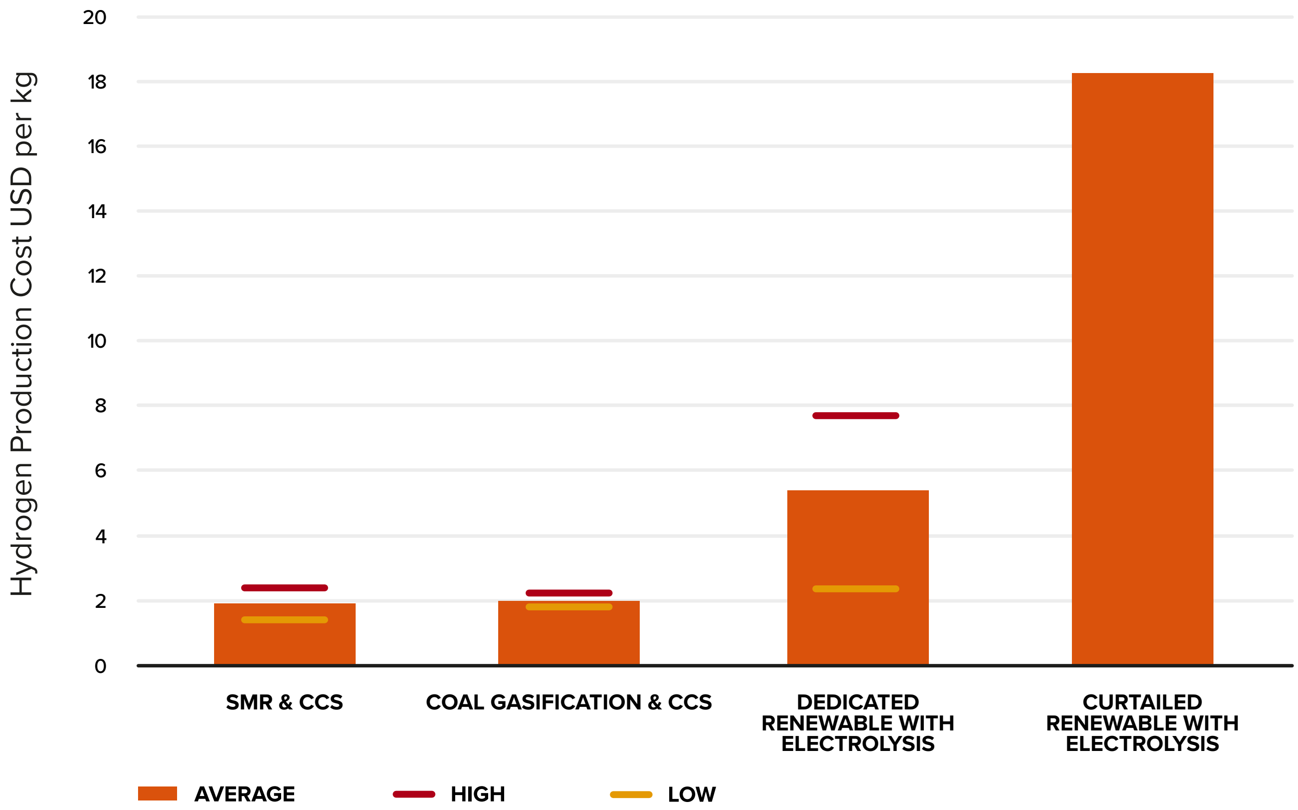
There is generally good agreement between the CSIRO, IEA, IRENA and the Hydrogen Council on the cost of producing clean hydrogen from natural gas or coal with CCS. This is not surprising as 98% of hydrogen is currently produced from natural gas or coal and there are seven fossil based hydrogen production 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 USD2/kg of hydrogen for gas or coal with CCS.

There is a wider range of estimated costs for renewable hydrogen produced with electrolysers; USD2.30/kg to USD7.70/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).

[3] Converted from AUD assuming 1AUD =0.7USD

[4] These estimates are for electrolysis. The IEA report does not specify the source of electricity as renewable.

Figure 4. Simple average and range of estimated current cost of clean hydrogen production from recently published reports.(International Energy Agency (IEA) 2020 2020b)(International Renewable Energy Agency 2019) (Hydrogen Council 2020)(Bruce et al. 2018) (only one estimate of cost of curtailed renewable with electrolysis). SMR = steam methane reformation. CCS = carbon capture & storage.

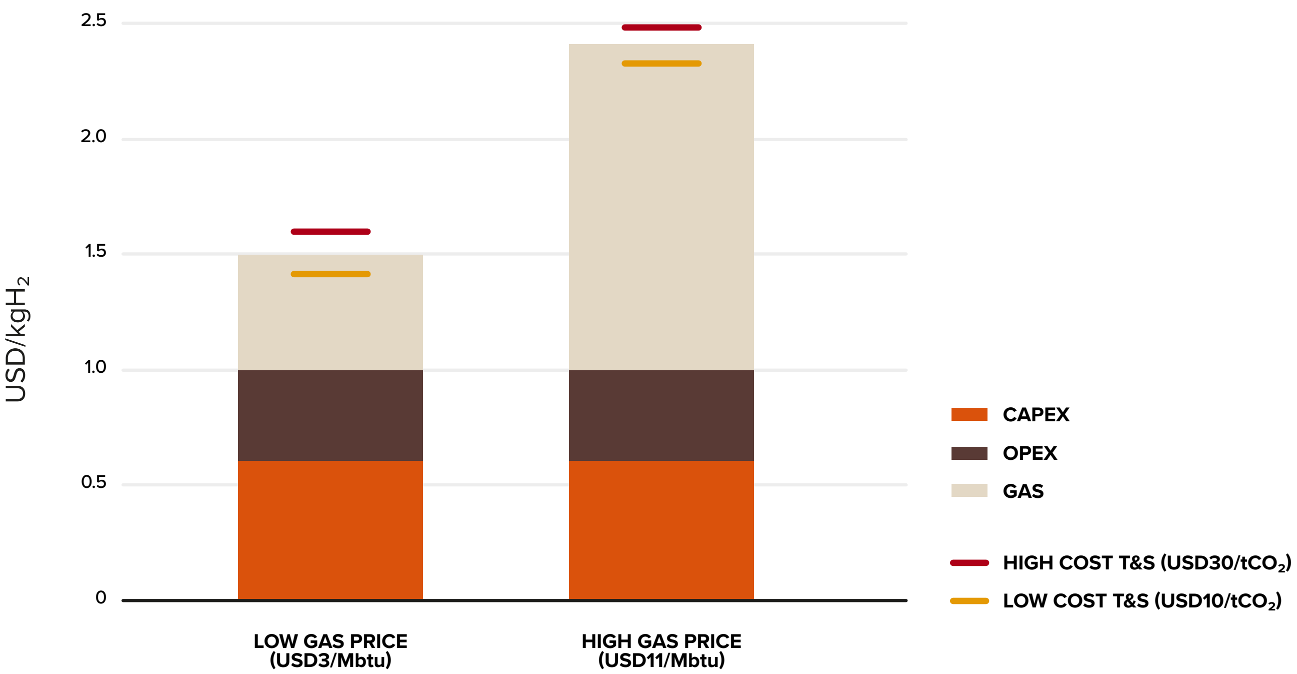


4.0 COST DRIVERS FOR HYDROGEN PRODUCTION VIA FOSSIL PATHWAYS WITH CCS

The cost of producing clean hydrogen from gas with CCS can vary significantly from place to place due to differences in fuel costs. In locations with low cost gas (USD3/MBtu)[5], capex is the largest cost component and the overall cost is USD1.50/kg H_2. In locations with very high cost gas, gas is the largest cost component. It is notable that even assuming a very high gas price (USD11/MBtu) the overall cost of blue hydrogen produced from SMR with CCS is only USD2.40/kg H_2 – see Figure 5 (IEA 2019).

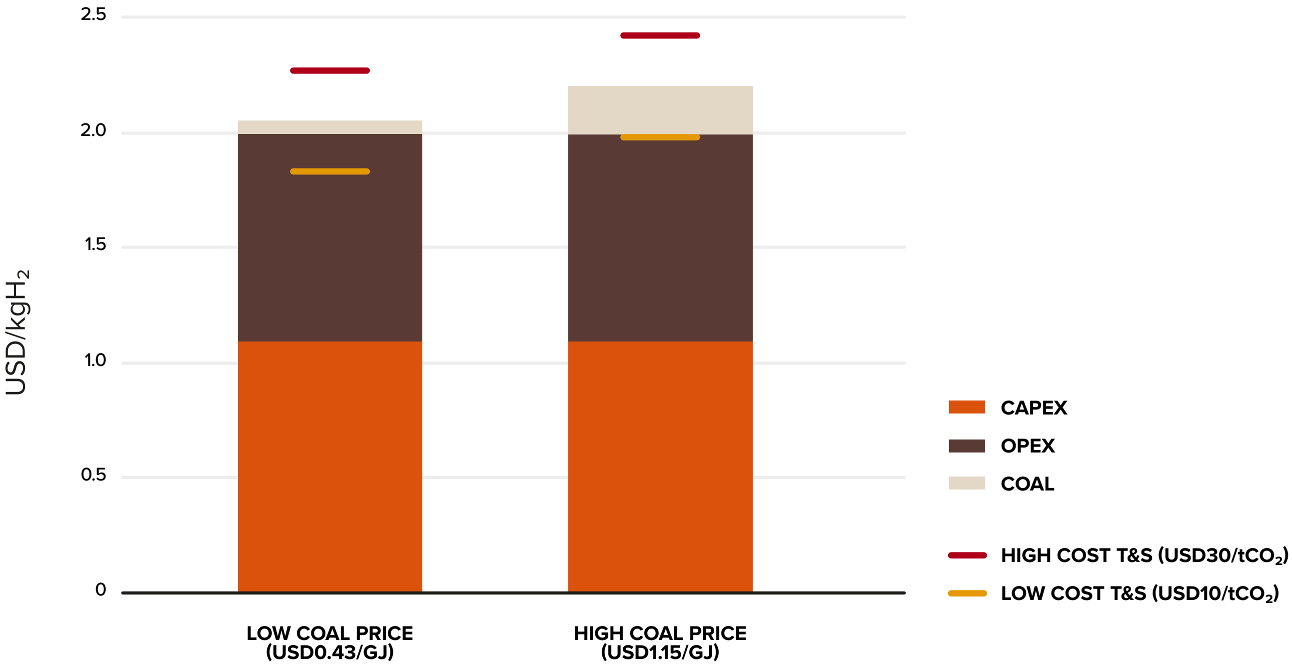
Producing hydrogen from coal gasification with CCS is more capital intensive than from steam methane reforming with CCS and this is reflected in its cost structure (see Figure 6). The cost of coal has relatively little impact on the cost of hydrogen production from coal gasification with CCS. Increasing the cost of coal from USD0.43/GJ to USD1.15/GJ increases the cost of hydrogen production from USD2.05/kg H_2 to USD2.20/kg H_2.

Figure 5. Components of cost of production of H_2 from natural gas – adapted from (IEA 2019). 1 MBtu is 1 million British Thermal Units = 1.055GJ. Stacked bars assume CO_2 transport and storage cost of USD20/tCO_2. High and low T&S cost sensitivities assume 8kgCO_2 captured per kg of H_2 produced.



[5] 1 MBtu is 1 million British Thermal Units = 1.055GJ

Figure 6. Components of cost of production of H_2 from natural gas – adapted from (IEA 2019) & (International Energy Agency (IEA) 2020 2020a). Stacked bars assume CO_2 transport and storage cost of USD20/tCO_2. High and low T&S cost sensitivities assume 22kgCO_2 captured per kg of H_2 produced.



The cost of transport and storage of CO_2 also has an impact on the total cost of production. Producing 1kg of hydrogen from coal and gas with CCS will require approximately 22kg and 8kg of CO_2 respectively to be transported and stored. Thus, the cost of hydrogen production from coal with CCS will be more sensitive to CO_2 transport and storage costs than gas. The costs quoted above and shown in the stacked bars in figures 5 and 6 assume a CO_2 transport and storage cost of USD20/t CO_2.

Also shown in figures 5 and 6 is the cost of hydrogen production for a low and high CO_2 transport and storage cost of USD10/tCO_2 and USD30/tCO_2. In summary, a USD10/t change in the cost of transport and storage of CO_2 results in a USD8c/kg and USD22c/kg change in the total cost of production of hydrogen from SMR with CCS and coal gasification with CCS respectively.

5.0 COST DRIVERS FOR RENEWABLE HYDROGEN PRODUCTION

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 7 which uses data from the 2020 Hydrogen Council report (Hydrogen Council 2020).

The capital cost of electrolysers will reduce as the scale of deployment increases. Recent analysis by IRENA finds that if the capital cost of electrolysers can be reduced by 80% from the current average of USD770/kW, the cost of hydrogen production would reduce from around USD5.90/kg to just over USD3.00/kg. Reducing the price for electricity from the current average of USD53/MWh to USD20/MW would further reduce the cost of hydrogen production to approximately USD1.70/kg at a capacity factor of 36% (Taibi et al. 2020).

Consequently, the availability of high quality renewable resources and sufficient land with a very low opportunity cost on which to site renewable electricity generation capacity are critical enablers of the production of renewable hydrogen at prices that are competitive with SMR or coal gasification with CCS.

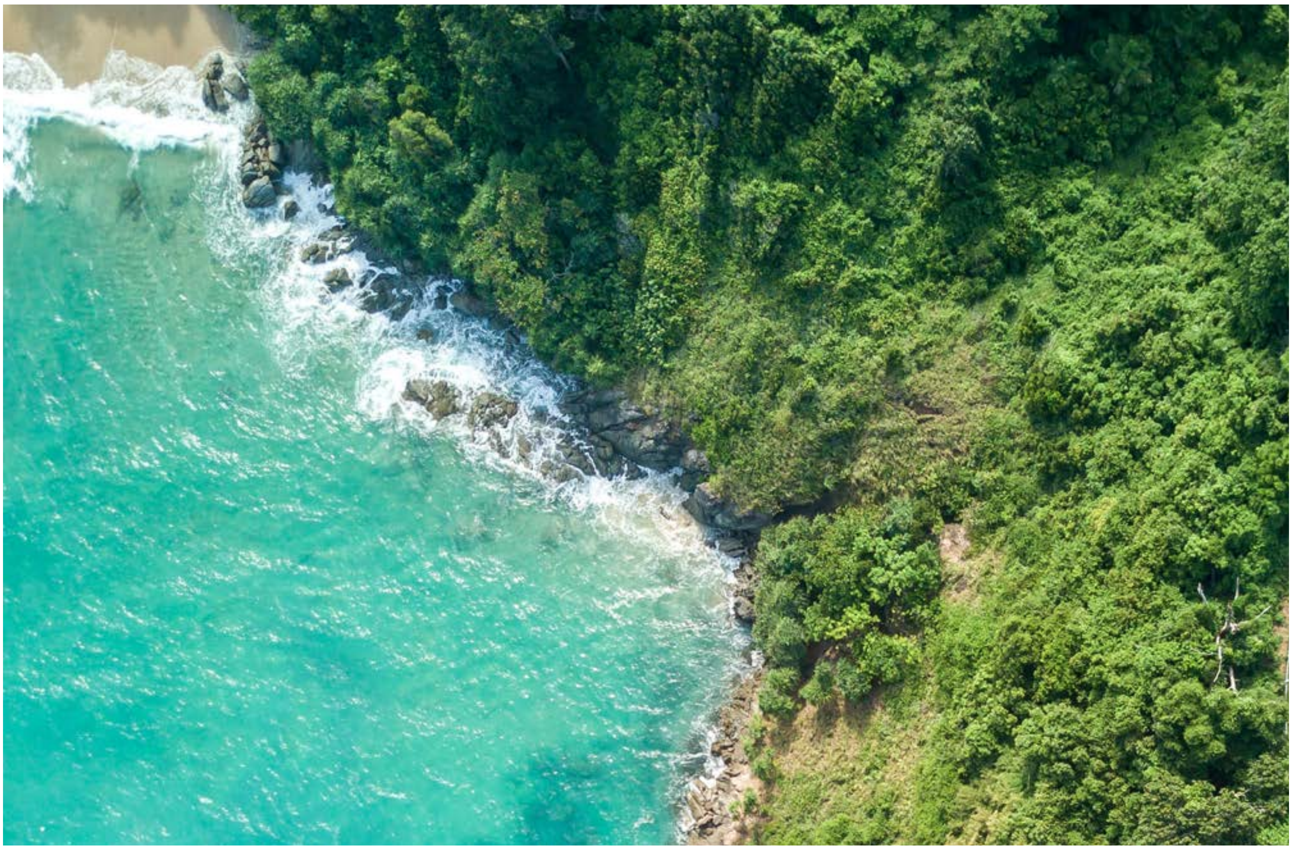
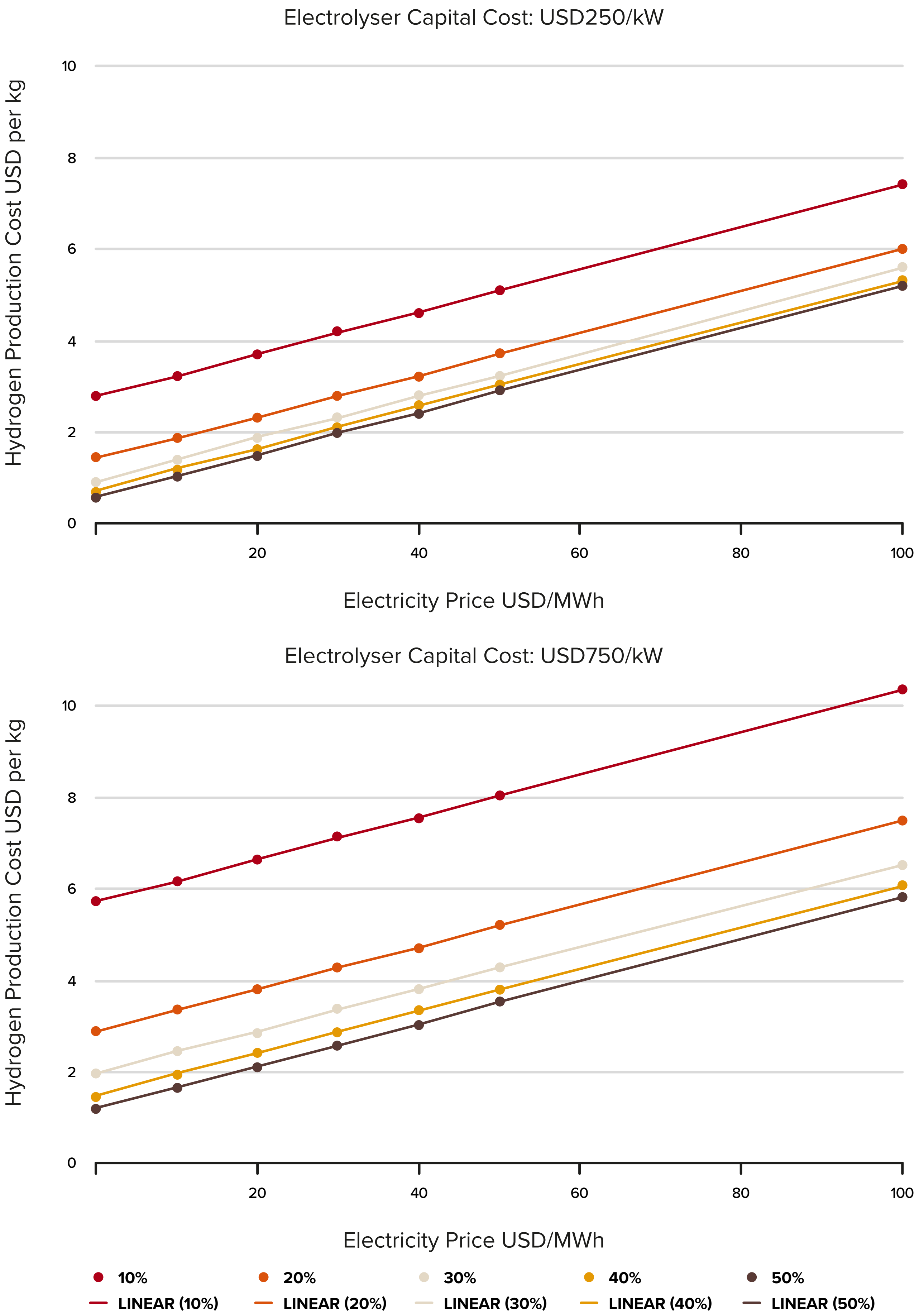


Figure 7. Cost of clean hydrogen production from electrolysis as a function of electricity price, utilization of the electrolyser (percentage figures) and capital cost.(Hydrogen Council 2020)



6.0 REDUCING THE COST OF CLEAN HYDROGEN PRODUCTION

The cost of producing blue and green hydrogen is reducing. Examples of cost reduction drivers for green hydrogen include reduced capital cost of electrolysers with increased scale and through technology innovations, and the ongoing reduction in the cost of renewable electricity. A thorough discussion of opportunities to reduce the cost of production of green hydrogen is contained in another report in this series, on Green Hydrogen, produced by the Center for Global Energy Policy at Columbia University SIPA(Fan et al. 2021) .

At a high level, the same principles are reducing the cost of production of blue hydrogen. Larger facilities which form part of CCS hubs will benefit from economies of scale in hydrogen production and in CO_2 transport and storage that reduce the total unit cost of production. Industrial CCS hubs, where multiple facilities utilise common CO_2 transport and storage infrastructure, create business ecosystems, reducing counterparty risk and the cost of capital. Given the capital intensity of blue hydrogen production, reducing the cost of capital by several percent can provide material reductions in the unit cost of production.

Better integration of hydrogen production and CO_2 capture components of the blue hydrogen production chain also offers significant opportunities for cost reduction. For example, rather than designing the steam methane reformer and CO_2 capture and compression plants separately, and then connecting them together, designing an integrated plant where the overall performance of the entire process is optimised will deliver cost savings. Those savings will arise from better heat integration which involves using sources of heat in the reformer or gasifier to provide some of the heating required for the capture plant. Finding the optimal steam supply method, minimising the inefficiency of the steam extraction at nominal and partial loads, and recovering waste heat from the capture system for use in the plant steam cycle (where applicable) are now being widely applied to the development of new generation carbon capture plant. Incremental improvements in engineering design – "learning by doing" – such as better heat integration described above, and more efficient physical plant design to reduce the use of higher cost materials (e.g. stainless steel), will continue to drive incremental reductions in the cost of production of blue hydrogen.

New CO_2 capture technologies are in development that offer the promise of step change reductions in the cost of CO_2 capture. These technologies include chemical looping processes, new adsorption processes and new physical and chemical solvents for use in absorption processes as well as new membranes for the separation of CO_2 from other gases.

Finally, a completely new cycle for the production of electricity, hydrogen and ammonia with inherent CO_2 capture is in development based on the Allam Cycle which utilises the CO_2 from gas combustion to drive a turbine. The fully integrated plant, currently progressing through feasibility studies, may produce hydrogen with 100% CO_2 capture at significantly less cost that current blue hydrogen production facilities.

These cost reduction opportunities are explored and described in another report in this series on Technology Readiness and Costs of CCS.

7.0 RESOURCE REQUIREMENTS FOR CLEAN H_2 PRODUCTION

The availability of land, water, electricity, coal, gas and pore space for CO_2 storage will determine the best clean hydrogen production method in any specific location.

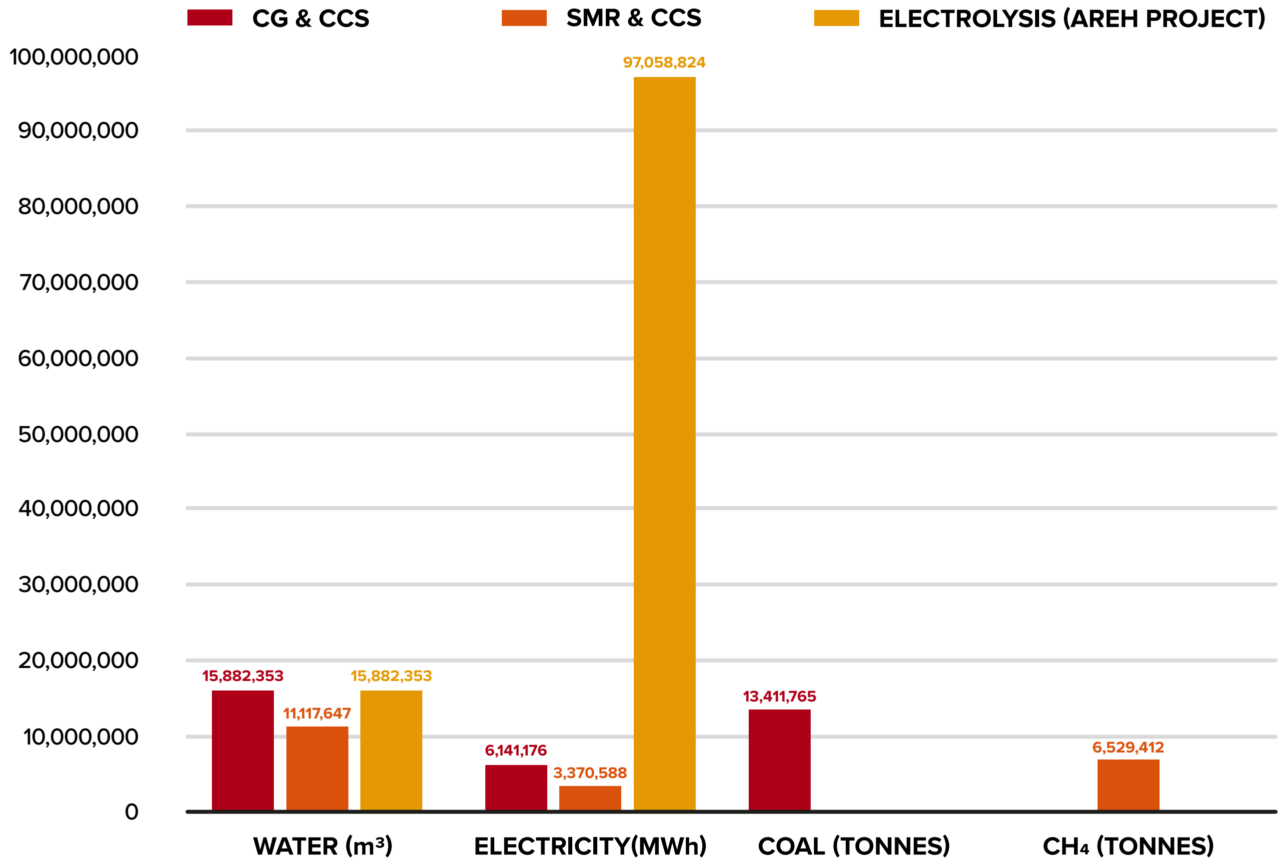
The production of clean hydrogen using electrolysers or coal or gas with CCS require similar amounts of water, around 6kg/kgH_2 for gas plus CCS and 9kg/kgH_2 for coal plus CCS or electrolysis (Bruce et al. 2018; Naterer, Jaber & Dincer 2010). Electrolysis has extremely high electricity demand of 55kWh/kgH_2 (IEA 2019) compared to 1.91kWh/kgH_2 for gas plus CCS and 3.48kWh/kgH_2 for coal plus CCS (including the electricity required to produce the gas or coal) (IEA 2019; Mehmeti et al. 2018). Hydrogen produced by electrolysis will only be clean if it is powered by renewable energy or nuclear power (see figure 2.). Renewable hydrogen requires sufficient land to host the wind and/or solar PV generation capacity whilst fossil hydrogen with CCS requires land for CO_2 pipelines and injection infrastructure. Fossil hydrogen with CCS also requires coal or gas and pore space for the geological storage of CO_2.

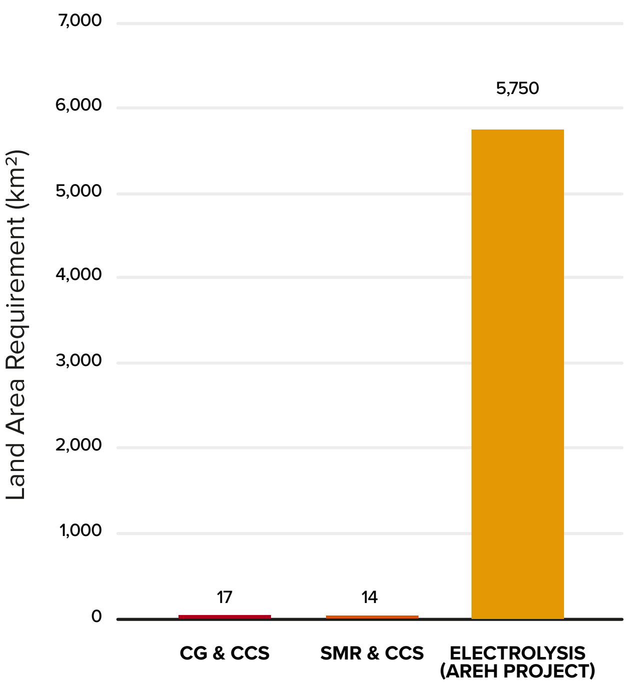
The AREH project in Australia's remote north-west plans to produce 10 million tonnes per year of ammonia. This requires approximately 1.76Mtpa of hydrogen which will be produced by the electrolysis of water powered by a combined 23GW of solar PV and wind capacity, located on 5750km² of land ('The Asian Renewable Energy Hub' 2020b). AREH benefits from excellent solar and wind resources that together will achieve an expected capacity factor of approximately 48%. AREH also benefits from the availability of abundant land with very low opportunity cost. This combination of resources, together with scale, could deliver near-zero emissions hydrogen, towards the lower end of costs for renewable hydrogen (see Figure 4.).

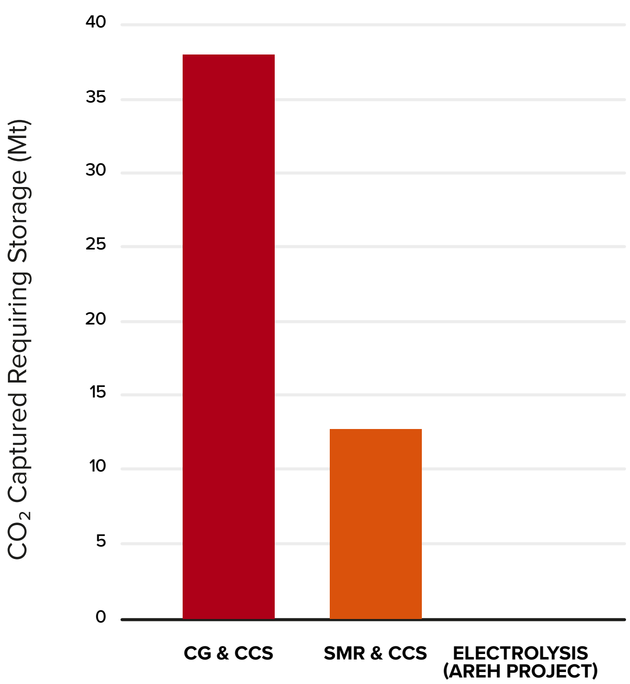
Where abundant low-cost land or excellent renewable resources are not available, but coal or gas and pore space for geological storage of CO_2 is, clean hydrogen from gas or coal with CCS will be the best option. Compared to renewable hydrogen, clean hydrogen produced from gas or coal with CCS requires very modest amounts of land and electricity. For example, production of 1.76Mt of hydrogen (equivalent to one AREH project) from steam methane reformation with CCS would require approximately 14km² of land, assuming a 500km CO_2 pipeline in a 20m wide corridor, 2km² for the plant, and four CO_2 injection wells situated over a 2km² area. Figure 8. compares resource requirements for renewable hydrogen based on the AREH project to the same quantity of hydrogen produced from gas or coal with CCS.

[6] Total project area is 6,500km², including an additional 3GW of wind and solar PV capacity which will be dedicated to electricity production for export.

Figure 8. Resources required for the production of 1.76Mt of H_2 from coal or gas with CCS and electrolysis powered by renewable electricity. Land requirements for electrolysis pathway is taken from the AREH Project website. Assumes combined 48% capacity factor for wind and solar PV and 55kWh/kg of H_2 via electrolysis (IEA 2019). 9kg water required per kg of H_2 for electrolysis (IEA 2019). Electricity requirement for CG+CCS (3.48kWh/kgH_2) and SMR+CCS (1.91kWh/kgH_2) includes electricity used in the production of the coal or gas (Mehmeti et al. 2018). 6.3kg of water required per kg of H_2 for SMR with CCS (Naterer, Jaber & Dincer 2010). 9kg water required per kg of H_2 for coal gasification with CCS (Bruce et al. 2018). Land requirement for CG+CCS and SMR+CCS assumes 500km CO_2 pipeline in a 20m wide corridor, 2km² for the plant and 10 injection wells over 5km² for CG+CCS, and 4 injection wells over 2km² for SMR+CCS. CO_2 captured requiring geological storage per kg of H_2 is 21.5kg for CG+CCS and 7.2kg for SMR+CCS.







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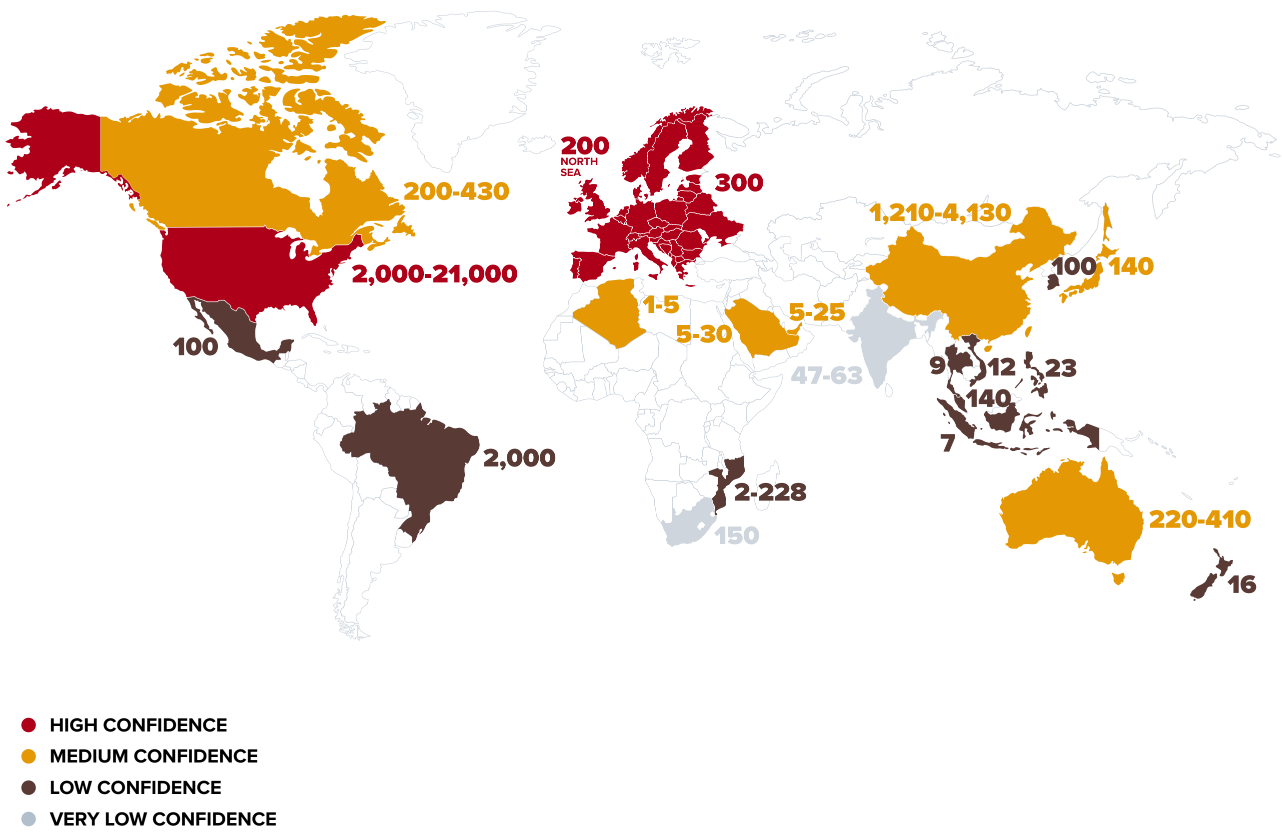
As noted previously, the production of blue hydrogen requires access to coal or gas and access to pore space for the geological storage of CO_2. Both the coal and gas industries are mature with well-established supply chains. Accessing sufficient supplies of coal or gas to support blue hydrogen production in any prospective location will be a routine process that needs no discussion in this report. Accessing pore space for geological storage of CO_2 however is not yet routine. This raises the question as to whether the availability of geological storage resources is a significant constraint on the production of blue hydrogen.

Another report in this series (on CCS Hubs and Clusters) addresses this question for CCS in any industry. A conclusion from that analysis is that global resources for the geological storage of CO_2 are more than sufficient for CCS to play its full role under any climate mitigation scenario. The opportunity lies in identifying locations where all the requisites of blue hydrogen production are available. For example, locations with access to coal or gas as well as pore space for CO_2 storage. The Hubs and Clusters Report identifies many such locations around the world. Figure 9 below provides a summary of an estimate of global geological storage resources for CO_2. It is clear that pore space for the geological storage of CO_2 is not a constraint on blue hydrogen production, although locating production centres relatively close to storage resources will minimise CO_2 transport costs.

Figure 9. Estimate of Global CO_2 Geological Storage Capacity in Billions of Tonnes. Confidence is a measure of the maturity of storage resource appraisal.



8.0 EMISSIONS ABATEMENT OPPORTUNITY COST OF RENEWABLE HYDROGEN

As shown previously, low-emissions hydrogen provides an opportunity to deliver emissions abatement at the multi-gigatonne scale if sufficient volumes are utilised in place of unabated fossil fuels. However, as the objective is to reduce all anthropogenic emissions to net-zero, it is appropriate to examine how the production of low emission hydrogen would impact upon the broader emissions abatement challenge.

Producing hydrogen using electrolysers requires large amounts of electricity. To illustrate, producing 530Mt of clean hydrogen, the amount the Hydrogen Council projected could be utilised in 2050, would require 29,000TWh of near-zero emissions electricity. This is more than the total global generation of electricity by all sources in 2018 (International Energy Agency (IEA) 2020). That quantity of near zero emissions electricity could theoretically completely replace all fossil generation capacity resulting in a global zero emissions (at point of generation) electricity system. A legitimate question is whether there is an emissions abatement opportunity cost associated with using renewable electricity (or nuclear generation) to produce hydrogen instead of displacing unabated coal or gas electricity generation. Assuming that the clean hydrogen displaces the combustion of natural gas, that emissions abatement opportunity cost can be very significant because:

- 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 or gas fired power stations have a thermal efficiency of around 30 – 50%. Displacing one GJ of electricity production from a coal or gas power plant prevents emissions from the combustion of 2-3GJ of coal or gas.

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

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

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

Where:

Er = Energy value of the renewable electricity in GJ

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

[7] Assuming 55kWh of electricity is required to produce 1kg of H_2

[8] Assuming there was sufficient dispatchable near zero emissions generating capacity such as nuclear and hydroelectric plus renewable generation and energy storage to ensure supply

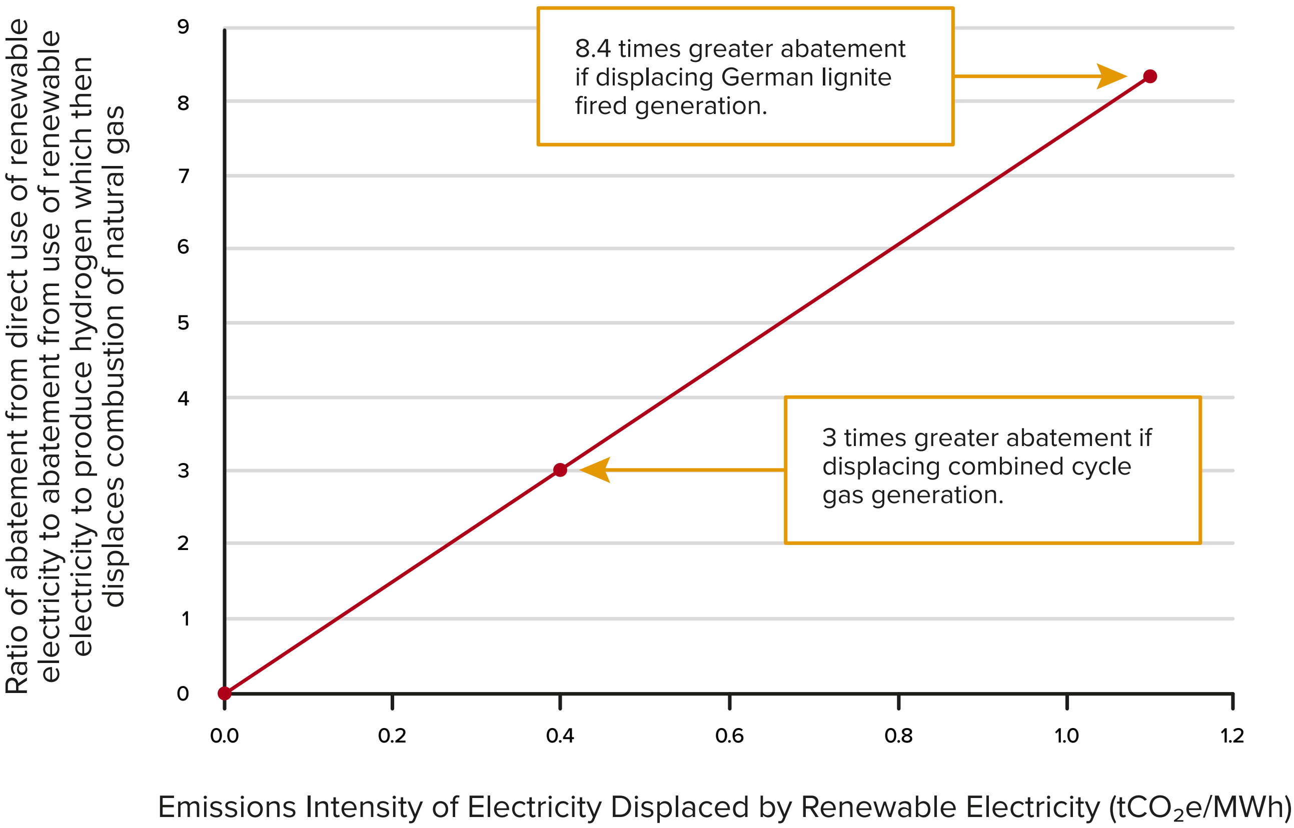
Ag	=	emission abatement if renewable electricity is used to produce hydrogen which then displaces combustion of natural gas in tonnes CO2e
PEMeff	=	efficiency of conversion of electrical energy to hydrogen by electrolysers: assume 0.71 (converted from 55kWh/kgH2 – Higher Heating Value)
EFc	=	Emissions intensity of grid generation which would be displaced in kg CO2e/GJ of electricity
EFg	=	Emission factor for natural gas combustion: 51.53kgCO2e/GJ

Substituting for variables:

$$Ac = \left(\frac{EFc}{36.6}\right) * Ag$$

This relationship is graphed in Figure 10 for electricity production with emissions intensity up to 1.1tCO_2/MWh (305kgCO_2/GJ), which is equivalent to German lignite fired generation.

Figure 10. Ratio of Emissions Abatement from Renewable Electricity that Displaces Fossil Generation in a Grid to emissions abatement from Renewable Electricity used to produce Hydrogen which then Displaces the Combustion of Natural Gas.



Renewable electricity delivers three times more emissions abatement when used to displace NGCC generation and eight times more emissions abatement when used to displace lignite fired generation than when used to produce hydrogen which then displaces the combustion of natural gas.

Wherever possible, renewable electricity should be used to displace unabated fossil generation where it delivers significantly more emission abatement than it would if used to produce hydrogen which then displaces natural gas combustion.

Renewable hydrogen production should only be considered where there is no opportunity to feed renewable electricity into a grid to displace fossil generation, and where excellent renewable resources and abundant land with low opportunity cost exist.

9.0 IMPLICATIONS FOR POLICY

The utilisation of blue (and green) hydrogen in the global economy has the potential to support emissions abatement at the multi-giga tonne per year scale. However, ramping up both demand and investment in production of clean hydrogen requires strong and sustained policy. Under current policy settings the private sector will not deploy blue hydrogen production capacity at the scale required to meet climate change mitigation targets because there are several market failures and broader barriers to investment. These market failures directly affect the business case for investing in blue hydrogen by reducing the expected return from projects.

Fortunately, well established policy options, some of which have been used to support the establishment of other industries (eg, rail, electricity, telecommunications, internet, renewable energy) over the past century are available to correct these market failures and overcome the barriers to investment. These are described in detail in another report in this series on Policy and Regulatory Recommendations. Policy recommendations for national governments, as relevant to investments in blue hydrogen production from that report, are summarised here.

Recommendation 1. Based on rigorous analysis define the role of blue hydrogen in meeting national emission reduction targets and communicate this to industry and the public.

Recommendation 2. Create a certain, long term, high value on the storage of CO_2.

Recommendation 3. Support the identification and appraisal of geological storage resources – leverage any existing data collected for hydrocarbon exploration.

Recommendation 4. Develop and promulgate specific CCS laws and regulations that include transfer of long-term liability for geologically stored CO_2 to the Government subject to acceptable performance and behavior of the stored CO_2.

Recommendation 5. Identify opportunities for CCS hubs where blue hydrogen can be produced and facilitate their establishment. Consider being the first investor in CO_2 transport and storage infrastructure to service the first hubs.

Recommendation 6. Provide low cost finance and/or guarantees or take equity to reduce the cost of capital for blue hydrogen investments.

Recommendation 7. Where necessary, provide material capital grants to blue hydrogen projects/hubs to initiate private investment.

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10.0 CONCLUSION

Hydrogen produced from fossil fuels or biomass with carbon capture and storage, or by renewable energy powered electrolysers has the potential to deliver abatement at the multi-giga tonne per year scale. Blue or green hydrogen can Reduce CO_2 emissions by displacing fossil fuels such as natural gas in domestic and industrial applications and oil in transport. Although less mature than blue hydrogen, hydrogen produced from biomass (with CCS) can Remove approximately 15-20kg of CO_2 from the atmosphere for every kilogram of hydrogen produced.

The urgency attached to reducing global emissions to net-zero requires a rapid acceleration in the deployment of all emissions reducing technologies. Technologies that are mature and commercially available at large scale, such as blue hydrogen production that has been operating for decades, must be deployed now. In the majority of locations, blue hydrogen will be the lowest-cost clean hydrogen production option. Low production cost is critical to underpin rapid demand growth for clean hydrogen along with the production capacity to meet that demand. Consequently, blue hydrogen is well placed to kickstart the rapid increase in the utilisation of clean hydrogen for climate mitigation purposes.

Blue hydrogen has the added advantage of allowing renewable and nuclear power to displace unabated fossil fuel electricity generation in electricity grids, where it delivers between three and eight times as much abatement compared to using that same quantity of electricity to produce hydrogen using electrolysers, which then displaces the combustion of natural gas.

Green hydrogen, produced by electrolysers powered by renewable electricity, must also be deployed where there is a coincidence of excellent renewable resources, low cost land, and little opportunity to use the renewable electricity to displace unabated fossil generation. The significant opportunity and role of green hydrogen in achieving net zero emissions is described in another report in this series, produced by the Center for Global Energy Policy at Columbia University SIPA (Fan et al. 2021).

However, strong and sustained policy is required to incentivise investment in blue (and green) hydrogen production at the rate necessary to support the achievement of climate mitigation targets. Ultimately, policy must support the business case for investment by increasing expected returns and decreasing real and perceived risks. Considering blue hydrogen, there is a particular opportunity for government policy to support the establishment of essential infrastructure necessary to create CCS hubs. CCS hubs reduce the unit cost of production through economies of scale and create business ecosystems, reducing counterparty risk and the cost of capital.

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