H_2 beyond CO_2

VOLUME 2: References and workings

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Contents

Meta analysis summary – environmental factors by H_2 production technology

	metric	PEM		Alkaline		SMR+CCS	
		Current	Future-R*	Current	Future-R*	Current	Future
Technology Readiness Level		Early Commercial		Mature		Early Commercial (SMR mature, CCS early commercial)	
Electricity Required	*kWh/ kgH₂*	**~55**	**~48**	**~54**	**~50**	**~1-1.3** At capture rates of 56%-90% (greater capture rates mean marginally higher electricity requirements)	Limited study evidence
Emissions Intensity - Global Warming Potential (GWP)	*kg CO₂- e/kg H₂*	**11.6 – 29.5** (grid mix of refs available)	**3.3** (100% renewable*)	**7.52 – 23.8** (grid mix of refs available)	**data gap** Likely to be similar to PEM although no 100% renewables* studies found.	**2.3-5.8** at capture rates of estimated 90%-54% The higher the capture rate, the lower the GWP.	**<2.3** Will depend on capture rates of CO2 w/ future potential 99%; as well as potential for mitigation of emissions in NG extraction.
Dynamic Response		Faster than alkaline start-up and shutdown faster and ramp up/down		Slower than PEM start-up and shutdown and ramp up / down		NA – SMR is not considered complementary with renewable energy given low electricity load and lack of dynamic response.	
Water Requirements	*liters/ kgH₂*	**9-10**	Limited study evidence	**9-10**	Limited study evidence	**18.4-21.6**	Limited study evidence
Resource Usage/ Depletion		Platinum group metals Depletion not an issue in the short term.	Potential issues with depletion of platinum and iridium should technological advancements not materialise.	Nickel Depletion not an issue in the short term.	Potential issues with depletion of nickel beyond 2050 should technological advancements and maximum recycling rates not materialise.	Natural gas, nickel, zinc, iron, copper. Depletion not an issue in the short term.	Potential issues with depletion of nickel beyond 2050 should technological advancements and maximum recycling rates not materialise.
Pollution from inputs (materials)		Primarily from mining but largely manageable. Key pollutants from heavy reliance on coal for energy include sulfur dioxide.	Potential for cleaner, greener mining and extraction.	Primarily from mining but largely manageable. Key pollutants include sulfur dioxide from the processing of sulfidic ores like nickel.	Potential for cleaner, greener mining and extraction.	Primarily from mining but largely manageable. Key pollutants include sulfur dioxide resulting from the processing of sulfidic ores like zinc, copper and nickel.	Potential for cleaner, greener mining and extraction.

Source: Regnan estimates using various sources – see following sections for full details.

Notable gaps in the literature

From our comprehensive review, we identify the following key matters in need of a more extensive evidence base:

- Volume of high quality water required for SMR+CCS – we found only two sources that provided water requirements per kg of hydrogen.

- Future water requirements for PEM, alkaline and SMR+CCS – we found no studies which discussed future outlook for water needs.

- Precise amount of raw materials needed for SMR, particularly nickel, zinc, copper, was difficult to find.

- Comparable life cycle metrics related to acidification, eutrophication, human toxicity (amongst others) were difficult to find for each technology beyond the single study referenced on these indicators.

Detail - environmental factors

Climate change

Electricity required to produce hydrogen

Current technology (kWh/kgH_2)

PEM (current)	Alkaline (current)	SMR+CCS
54.6[1]	53[2]	1.3 – 90% CC rate[3]
51-61[4]	57[5]	1.1 – 90% CC rate[6]
54.3[7]	52.6[8]	1.0 – 56% CC rate[9]
47-73[5]	53.6[5]	
54[2]		
54[5]		
Average: 55.15	Average: 54.05	

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Future technology (kWh/kgH_2)*

PEM-R (future-2030)	Alkaline-R (future-2030)
48[4]	46-51[10]
50.3[7,11]	47[5]
43[12]	48[2]
45[13]	50[14]
49-52[10]	52[15]
48[2]	53.9[16,17]
52[5]	
Average: 48.11	**Average: 49.9**

*No material difference foreseen for SMR+CCS

Note on future alkaline-R

"[..] there is a modest potential for increases in the efficiency of conversion of electricity to hydrogen for alkaline technology"[2].

Emissions intensity - global warming potential (GWP)

Current technology ($kg CO_2$-e/kg H_2)

PEM (current)	Alkaline (current)	SMR+CCS
11.6 (Energy scenario: natural gas 40%, wind energy 39%, photovoltaic 21%)[18]	**7.52** (Energy Scenario: Austrian grid mix)[17]	**5.8**[19] (54% capture rate)
29.5 (Energy Scenario: Hard coal 15%, Lignite 24%, Nuclear 12%, Natural gas 14%, oil 1%, wind 17%, photovoltaic 6%, biomass 8%, hydro power 3%)[18]	**13.08** (Energy Scenario: Spanish grid mix)[17]	**3.4**[20] (capture rate not disclosed*)
	23.8 (Energy Scenario: German grid mix)[17]	**3.07**[21] (capture rate not disclosed*)
		3.3[22] (capture rate not disclosed*)
		2.3 (90% capture rate with British Columbia average upstream emissions)[23]
		4.1 (80% capture rate with Canada average upstream emissions)[23]

*These are all studies which reference blue H_2, other sources state blue H_2 typically implies a 80-90% capture.[23] For comparison, SMR without CCS results in estimates in the range of **11.3-12.13**, substantially higher than with CCS[1]

Future technology (*kg CO$_2$-e/kg H$_2$*)

PEM-R (future)	Alkaline-R (future)	SMR+CCS
Given electricity mix is the primary driver of GHG emissions we investigated GHG emissions for electricity production where electricity is produced via renewable means. A meta review of 153 life cycle studies[24] show: For wind energy: • Low of 0.4 g CO$_2$-e/kWh to a high of 364.8 g CO$_2$-e/kWh • Mean of 34.11 g CO$_2$-e/kWh For solar photo voltaic: • Low of 1 g CO2-e/kWh to a high of 218 g CO2-e/kWh • Mean value of 49.91 g CO2-e/kWh Offshore wind production has a marginally higher GHG emissions profile than onshore, owing to the more GHG intense installation process off shore (transporting the platform and installation)[25].		Estimated potential to be <2.3 at potential 99% capture rates.

3.3 where electricity generation
mix is 65% wind and 35% PV[18]

Complementarity with renewable energy

PEM exhibits superior characteristics for intermittent operation. The majority of experts surveyed expect a shift from incumbent alkaline to PEM systems from 2020 to 2030 as the preferred technology for electrolysis coupled to renewable generators[26].

State of the art PEM electrolysers are able to operate with much greater flexibility compared to current alkaline electrolysers, offering a significant advantage to PEM electrolysers to work with renewable energy, owing to its wider operating range, shorter response time, minimal power consumption in standby mode, ability to operate for shorter time periods at higher capacity beyond nominal load (over 100% to 200%). Operators of PEM electrolysers are able to supply hydrogen to clients, while providing ancillary services to the grid, with low additional capital and operational expenditure, provided that sufficient hydrogen storage is readily available[15].

Systems response: alkaline is seconds and PEM is milliseconds[27]; cold start up time alkaline is <60 mins and PEM is <20 mins[5]; lower dynamic range alkaline is 10-40% and PEM is 0-10%[28].

Water requirements (*litres/kgH$_2$*)

PEM	Alkaline	SMR+CCS
9-10[2]	9-10[2]	19.8[29] SMR only
9[13]	9[13]	18.37 (5.66 cooling, 12.71 demineralised)[30]
		1.8 litres/kg additional for CCS[1]

Water requirements for electrolysers

Numerous other studies reviewed are generally in line with the numbers presented in the table.

High Purity Water

Electrolysers require high purity water to inhibit side reactions caused by ions (salts) found in naturally occurring water. Commercial electrolysers tend to have an integrated deioniser which allows for use of fairly low grade potable water as an input[13]. Water purification is generally not a significant additional cost, although this depends on local circumstances[31].

Desalinisation

While desalinisation would only add a modest cost of US$0.01-0.02 per kg of H_2, it adds substantially to energy consumption and other environmental impacts, such as seawater temperature rise, increased salinity, fish migration, shifting population balance of algae, nematodes and molluscs[32], undermining H_2 sustainability[2].

Future water requirements

We found no studies which discussed future outlook for water needs.

Resource usage and depletion

Having surveyed the three technologies we view the following as critical inputs for each technology, which also each have resource depletion implications, addressed below. PEM technology currently requires platinum group elements (PGE) which are used in PEM processes. For alkaline, cathodes are reliant on nickel, which is likewise used as a catalyst in SMR+CCS.

Platinum group elements (PGE)

Resource availability

PGEs are among the rarest metals; the earth's upper crust contains only about 0.0005 part per million (ppm) platinum. Future demand for PGEs depend on demand for electrolysers, fuel cells and new vehicles in developing countries (with catalytic converters) and uptake of electrical vehicles replacing internal combustion engine vehicles[33].

Expert estimation from UBS does not foresee a platinum shortage for loadings for the EU target of 40GW of PEM electrolysers by 2030, however iridium is noted as a potential bottleneck in the longer term, beyond 2030[34]. US Geological Survey anticipates supply of PGEs are sufficient to meet demand until 2040, assuming consumption increase of 2% annually and projected recycling of platinum[35].

<u>**World Mine Production and Reserves:**</u>

	Mine production				PGM Reserves[9]
	Palladium		Platinum		
	2018	**2019e**	**2018**	**2019e**	
United States	14,300	12,000	4,160	3,600	900,000
Canada	20,000	20,000	7,400	7,400	310,000
Russia	90,000	86,000	22,000	22,000	3,900,000
South Africa	80,600	80,000	137,000	130,000	63,000,000
Zimbabwe	12,000	12,000	15,000	15,000	1,200,000
Other countries	2,920	3,000	4,470	4,300	NA
World total (rounded)	220,000	210,000	190,000	180,000	69,000,000

Source: Platinum Group Metals Data Sheet, US Geological Survey[35]

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Geopolitical risks to platinum production a higher risk in the short term

Given high resource concentration in South Africa, risks are high[36]. US Geological Survey highlights supply risks from social, environmental, political and economic factors in South Africa. Production of PGEs require power and water, both of which are in short supply in the country. In 2008 the South African mining industry experienced shut downs as a result of unpredictable power supply, which made mining unsafe[35]. Water supply is also an issue, and we highlight physical impacts of climate change are likely to further exacerbate water scarcity in the country, we see these as risks in the short-medium term even if carbon transition is pursued.

Resource demand

Platinum loading reduction from 2 to 0.2 mg/cm^2 and iridium loading reduction from .2 to 0.05 mg/cm^2 is estimated in the near future[18].

Platinum loadings can be reduced by a factor of 8 from 0.2 $mgPt/cm^2$ to 0.025 $mgPt/cm^2$ without significantly reducing cell performance[37].

Estimations project iridium reductions by 90% and platinum reductions by 75% by 2050.

For PEM power between 7-20GW in Germany, assuming a stack lifetime of 7 years, 0.8-2.1 tonnes of iridium will be required per year for Germany. Global iridium production currently is between 3.5-4 tonnes per year. Highlighting the need for loading reduction for the successful implementation of PEM[18].

Platinum recycling

In 2017 in North America, Europe and Japan, platinum recycling rates were above 50%[38].

The high technical recyclability of PGEs mean that 95% recovery can be achieved at a state-of-the-art facility. Challenges lie in collection of scrap, and capacity and technical capability of the recycling chain globally[39].

> *"PGMs can be recycled from a variety of end-of-life products (such as spent autocatalysts) and even from residues created during primary production. Secondary production processes can vary widely depending on the specific material or combination of materials treated. Some secondary producers of PGMs use a dissolving process to create a PGM-rich solution for refining, while others may use a smelting process to create a matte. In both cases, the final PGM products are identical in quality and purity to those refined from mined material"[40].*

Nickel

Resource availability

Some electrochemical processes use nickel as a core material for cathodes, including in alkaline and solid oxide electrolysis. Nickel is also used as a cost effective catalyst in the SMR process, where support from various other metals enhances the performance and durability of the nickel catalyst.

Nickel is currently promoted as a metal of the future given its role in electric vehicle batteries, driving an increase in demand. Combined with steady demand from the steel industry, it is likely the nickel industry will need to substantially ramp up production, adding cost pressures and constraints on the supply available to meet demand in the medium term (2023-2025), and potential constraints on reserves in the long term (beyond 2050). Globally there are a reported 89Mt of nickel reserves, which given an estimated 2.5Mtpa demand driven by various industries by 2025 means that there could be implications for meeting demand beyond 2050.

Managing nickel depletion risks will depend on technological advancements as well as maximum recycling rates. The IEA Greenhouse Gas R&D programme (IEAGHG) points out the nickel in the steam

reformer and pre reformer's catalyst can usually be recovered, however this depends on solid waste handling policies and guidelines undertaken by reforming plant producers or the catalyst vendors[41].

Pollution

Raw material inputs are a key source of pollution in all of the examined technologies. Our analysis showed that the use of PGEs in PEM technology, nickel in alkaline[26] and SMR+CCS, as well as other metal inputs in SMR+CCS, contribute to the environmental footprint of hydrogen production either via their production and processing methods, energy consumption associated with mining, or both.

Environmental impacts of PGE mining

Primary impacts are from power consumption during mining and ore beneficiation. Impacts emerge from South Africa's heavy reliance on coal for electricity production, where PGE mining is concentrated (hard coal which has a sulfur content).

High concentration of PGEs in South Africa will restrict electrolyser producers from sourcing PGEs from a jurisdiction with a more renewable grid. Thus, we see limited potential for mining companies to influence the grid mix to more renewable sources, which is dependent on South Africa's decarbonisation policies. Accordingly, we see good practice response as focussing on increasing the efficiency of PGE use in electrolysers and source recycled PGEs to minimise environmental impacts[40].

Environmental impacts of sulfidic ore extraction (i.e. Ni, Cu, Zn)

While alkaline electrolysis requires a nickel cathode, the SMR design also requires various raw material inputs:

- Nickel for catalysts, which is supported by other metals to enhance the performance and durability of the catalyst including, for example, copper, iron, chromium.

- A zinc oxide (ZnO) bed is used in the desulfurisation process.

- The water gas shift reaction also requires amounts of copper, iron and chromium.

Extraction of many of these materials, particularly metals that have come from sulfidic ore, can contribute to substantial levels of pollution which has implications for acidification and human health. While pollution associated with mineral extraction contributes to the overall environmental impact of hydrogen production, with technological enhancements and sound management, these appear to be manageable risks.

Mining and processing of sulfidic ores has the potential to produce various environmental impacts which contribute to the overall life cycle impact of hydrogen, of which acidification potential is a particular concern. Sulfidic ore, when smelted, produces sulfur dioxide (SO_2) emissions that can result in terrestrial and aquatic acidification either via runoff or as a result of acid rain, and also has human health implications including increased risk of stroke, heart disease, asthma and lung cancer[42]. Globally smelting contributes to an estimated 10% of SO_2 emissions (~17.5% anthropogenic SO_2 emissions) to which the smelting of sulfidic ores like nickel, copper, and zinc are substantial contributors[43].

SO_2 emissions in the processing of ore bodies are largely preventable. Current good practice show SO_2 capture rates at smelters of 85-90% (e.g. Vale, BHP), where BHP has plans for its Nickel West operation to increase its capture rate to 99% SO_2 emissions[52] [53]. Given captured SO_2 can be used as sulfuric acid for the processing of other non-sulfidic ore, there is an added economic benefit to SO_2 capture. Despite this, capture rates of SO_2 often reach only the minimum required to comply with local regulatory standards. For instance, a lack of policy around SO_2 emissions in the Norilsk region of Russia meant that the nickel producing region was the largest anthropogenic SO_2 emission source worldwide, contributing

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1,833kt of SO_2 emissions in 2018, over 6% of the global total anthropogenic emissions that year[43]. In large part due to environmental pressures from multiple stakeholders the owner, Nornickel, began the closure of the plant in Dec 2020 which should reduce SO_2 emissions for its subsidiary company, Kola MMC, 85% by 2021[44].

Whether it be as a result of enhanced regulation, stakeholder scrutiny, adherence to rules of responsible mining associations, or a general aim for industry best practice, we see improvements in the industry by major players. However, electrolyser and SMR manufacturers may still find it challenging to ensure the procurement of responsibly sourced raw materials through spot markets. To mitigate this issue, as has been noted in the EV battery market, some manufacturers are initiating contracts direct with responsible miners for the supply of raw materials in order to ensure transparency in the supply chain.

Better practice includes seeking mining companies that are either in regions with high clean air standards, or those that are signed onto responsible mining groups. For example, the Responsible Steel Association requires that any companies within the steel supply chain (nickel is a key material for stainless steel) must also adhere to the association's recommendations. Other groups with high standards should also be looked for, for instance the International Council on Mining & Minerals (ICMM) as it provides a variety of good practice guidance documents[45].

Further information on acidification

Acidification can cause plant poisoning in affected terrestrial environments, and in aquatic environments can kill fish and other aquatic life if there is no ability to move out of acidified areas. Even a slight rise in acidity levels has the ability to stunt growth and make plant and aquatic life weaker, paving the way for more invasive acid-tolerant species to become more prevalent. As an example, mosquitos have the ability to thrive in acidified wetlands[46].

In addition to smelting of sulfidic ores and the release of SO_2 into the atmosphere, acidification can also occur as a result of ground excavation. Exposure of acid sulphate soils, rich in iron sulphide pyrite, to oxygen to form sulfuric acid can cause other metals like iron and aluminium to become soluble which has implications when the disturbed soil is leached or flushed into waterways. Care must be taken by mining companies to avoid acid sulphate soil disturbance.

Technology overviews

We have studied two key pathways for hydrogen production:

- Water electrolysis – using electricity water is split into hydrogen and oxygen. We look at alkaline and PEM electrolysers coupled with renewable energy.

- Methane reforming where natural gas (CH_4) with water is converted into carbon dioxide and hydrogen. We look at steam-methane reforming with carbon capture and storage (CCS).

Alkaline electrolysis

The reaction occurs in a solution of water and liquid electrolyte (KOH/NaOH). When voltage is applied, hydrogen is produced at the cathode and water and oxygen at the anode.

Anode: $4OH^- \longleftrightarrow 2H_2O + 4e^- + O_2$ **Cathode:** $4H_2O + 4e^- \longleftrightarrow 4OH^- + 2H_2$

Polymer electrolyte membrane (PEM) electrolysis

In PEM systems the electrolyte is commonly a nafion polymer, with two noble metals (platinum and iridium):

Anode: $2H_2O <-> 4H+O_2+4e-$ **Cathode:** $4H++4e- <-> 2H_2$ electrodes

Steam methane reforming + carbon capture and storage (SMR+CCS)

1) Steam-methane reforming $CH_4 + H_2O --> CO + 3H_2$

2) Water-gas shift $CO + H_2O --> CO_2 + H_2$

1) For the SMR process, the feedstock (in this case natural gas) goes through a pre-treatment desulfurisation process, and is then pre reformed with steam, yielding methane and syngas. The primary reforming process converts methane and steam to hydrogen and carbon monoxide. The heat throughout the process comes from an external furnace.

2) In order to maximise hydrogen production, a further step is needed - the water gas shift reaction (WGS), occurring at low or high temperature (or both) depending on plant configuration, where hydrogen and carbon dioxide are produced via a reaction between carbon monoxide and water. The output is a hydrogen-rich syngas which requires further purifying via pressure swing adsorption (PSA), from which pure hydrogen is then compressed. Any excess steam in the process is used to further power the process via turbines integrated within the plant.

The majority of the hydrogen produced today is via SMR with NG as a feedstock, but only 0.6% of global hydrogen produced today is done so via SMR *with CCS*[47].

Carbon capture and storage (CCS)

Process

CCS must be integrated into SMR processes to limit greenhouse emissions.

CO_2 is produced during the pre-combustion phase of SMR, responsible for 60% of process emissions, with the remaining 40% attributed to the combustion processes in the plant.

- Pre combustion capture is considered the most economical option, which occurs via amine based absorption using methyl diethanolamine (MDEA) as a solvent, and via novel technologies like vacuum pressure swing adsorption (VPSA), which each allow for the majority of pre combustion associated CO_2 emissions (>95%) to be captured.

- Post combustion capture is more difficult given lower concentrations of CO_2 in the flue gas, and requires additional technology and costs.

Both pre combustion and post combustion carbon capture are required for maximum abatement[19].

CO_2 that is captured for storage purposes is then dried and compressed (to dense liquid form), transported, and then injected back into the ground to be stored permanently in geological formations including spent oil and gas fields, as well as saline formations.

Capture rates

Current practice in CCS have capture rates averaging 60-90%.

While we note positively an apparent consensus that it is technologically feasible to capture up to 99% of H_2 production emissions, there is also wide agreement that economic and legislative incentive is

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necessary to reach maximum possible emissions reductions. Critically, a key source of emissions in the life cycle is related to upstream emissions in the natural gas extraction processes. While high capture rates are feasible in the SMR process itself, without enhanced emissions control upstream, particularly of fugitive methane emissions, there are limits to decreasing greenhouse gases for SMR+CCS.

High captures rates mean little if CO_2 is not stored properly

While SMR+CCS is theoretically attractive, sustainable hydrogen will rely on adequate storage of CO_2. Global capacity of geological CO_2 storage will provide, even at conservative estimates, far beyond what is required. Oil and gas fields alone provide enough capacity to meet storage requirements, and given existing exploration and research on oil and gas fields, successful, permanent storage in these locations is stated by experts with a high degree of confidence[48]. However, CCS in areas without local oil and gas fields will be faced with transport and infrastructure costs, and while saline aquifer formations are more commonly found throughout the world - with vast storage potential - they remain under-researched given a lack of economic incentive to do so, and therefore higher uncertainty exists around saline aquifers for storage[47].

The IPCC states some of the risks to both ecosystems and humans arises from potential leakage caused by ineffective confining layers, compromised injection wells or abandoned wells. CO_2 leakage and consequent elevated CO_2 concentrations in the subsurface could cause lethal harm to plants and sub soil animals, or degradation to nearby groundwater. If released to the atmosphere, CO_2 could also have implications for human health and safety at the point of release[49].

Effective long term oversight of storage locations will be necessary, underpinned by regulation and long term monitoring programmes. Favouring high quality, well researched sites could greatly reduce risks - and perceived risks - for carbon storage[4950]. A recent study has found that when a suitable site is chosen the risks for leakage over 10,000 years is minimal[51].

The question remains whether storage can be consistently climate effective at the scale required. Globally only 28 commercial CCS facilities are in operation (including enhanced oil recovery (EOR) operations), with close to 40 in development stages. Only a handful of these relate specifically to hydrogen production and the majority of captured CO_2 is used for EOR, rather than solely for geological storage[47]. In 2020, according to the global CCS institute only 40Mtpa of CO_2 has been stored out of the 5635Mtpa (5.6Gt) needed by 2050 in the IEA's sustainable development scenario[47].

Emerging technologies

Of the many alternative and emerging H_2 technologies, we highlight below a few of particular interest. See also our mind map on page 8 of volume 1 for a full schema of production technologies.

Solid oxide electrolysis (SOE)

Currently at research and development stage, SOE is of interest as it holds promise to increase conversion efficiency over PEM and alkaline.

Auto Thermal reforming (ATR)

Autothermal reforming (ATR) is an alternative to steam methane reforming which also uses natural gas as a feedstock. While ATR is already commercialised, it is primarily used for other industrial applications (e.g. for synthetic fuels and chemicals production).

ATR is a process that uses pure oxygen, steam and CO_2 to react with NG to form raw syngas which is then put through the same water gas shift reaction and pressure swing absorber as SMR to retrieve high purity hydrogen.

ATR is notable because it offers benefits in carbon capture. While ATR's hydrogen output is less efficient than with SMR, carbon capture is easier (and more economical) given there is no flue gas carbon emissions associated with the ATR process. The same pre combustion methods of carbon capture used in SMR can be used in ATR, and are associated with higher capture rates at up to 98% resulting in a GWP of 2.6 kg CO_2-e/kgH_2, which is lower than SMR with CCS at est. 90% capture rates (~2.3 kg CO2-e/kg H_2)[19]. While ATR requires further enhancements to be economical for hydrogen production, the ability to capture CO_2 in a more cost effective way (when aiming for capture levels above 90-95%) makes ATR a potentially attractive blue hydrogen technology option in the future.

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