H_2 beyond CO_2

Filling the gaps in the environmental case for **hydrogen**

Regnan thematic research insights
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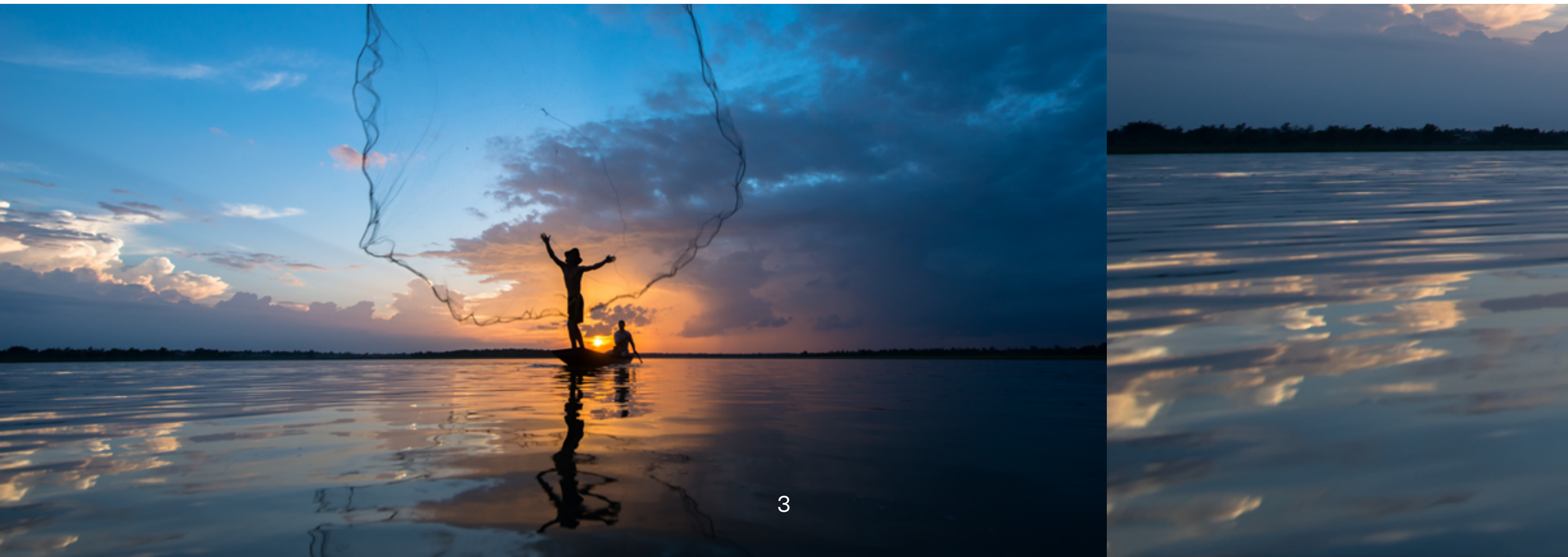

Purpose of this research

Our report evaluates the broader environmental case for hydrogen production technologies, providing a more holistic approach to integrating environmental considerations in the investment case for the hydrogen economy. It is designed to help investors better assess the relative sustainability of hydrogen technologies and projects.

Current excitement about the possibility of hydrogen (H_2) becoming a major energy source in the future is predominantly based on its potential contribution to global decarbonization goals.

Most ESG analysis of H_2 focuses solely on the potential greenhouse gas emissions savings that could be achieved. But what about the other environmental impacts of H_2?

Will pursuit of a H_2 economy lead to fresh environmental problems?

Should other decarbonization approaches be preferred as more sustainable overall?

Given expected cost convergence of H_2 production technologies, could environmental factors be key to determining the winners and losers?

Such questions are central for Regnan, and necessitated this research to fill the gaps in the environmental case for hydrogen.

Our findings have implications no matter the investment approach, whether as risks, constraints, or sources of competitive advantage.

In this report, Regnan:

- **Presents investment relevant insights from our comparison of three key production technologies,** considering performance today as well as how the positioning of each will evolve over time.
- **Provides current and future estimates across all key environmental factors,** via a meta analysis of scientific studies for our focus technologies:
  - Water electrolyzers - **alkaline** and polymer electrolyte membrane electrolysis (**PEM**); and
  - Steam methane reforming with carbon capture and storage (**SMR+CCS**).
- **Identifies management practices that responsible investors should look for** to minimize risks and maximize positive impact.

New to H_2?

Some resources to get you started:

https://www.iea.org/fuels-and-technologies/hydrogen#our-work-on-hydrogen

Key Findings

Potential environmental risks associated with the hydrogen economy are highly nuanced. The most sustainable options will be dependent on site specific features and applications.

These environmental risks require careful management if the hydrogen economy is to truly deliver on its environment promises. Consideration of these factors will help investors better assess the relative sustainability of hydrogen technologies and projects.

These considerations are especially important given our finding that all the studied technologies can provide strong carbon benefits with potential to achieve close to zero direct emissions H2 production.

For water electrolyzers this is achieved by utilizing renewable energy (green hydrogen), and for SMR, by coupling with carbon capture and storage (CCS) (blue hydrogen). However, CCS entails greater uncertainty given the few storage facilities developed to date.

Green H_2

Green H_2 from water electrolysis will be preferred where the benefits of combining H_2 production and renewable energy can be achieved.

Coupling electrolyzers with intermittent renewables like wind and solar can help manage output peaks and avoid the need for forced shutdown of renewables where supply outstrips demand (curtailment). This supports growth in renewables while also improving the economics of H_2 production. PEM wins out for such applications as its rapid response times help it to work in sync with intermittent electricity sources. We also expect PEM to emerge as the environmentally preferable electrolyzer technology over time.

For electrolyzers, the energy source drives the climate outcomes as well as the majority of other environmental impacts and we see potential for PEM systems to become more energy efficient than alkaline[1].

Blue H_2

We see blue H_2 emerging as the preferred H_2 production technology in regions with local natural gas resources, existing pipeline and transport infrastructure, and adequate water resources to support H_2 production growth.

Despite being derived from a fossil fuel, current best practice blue H_2 can achieve a carbon footprint comparable to green H_2. We expect blue H_2 to maintain this positioning into the future. Further initiatives to reduce fugitive emissions in natural gas production and increases in carbon capture rates in H_2 production (99% is technically feasible now) would enable SMR+CCS to maintain its comparable position with electrolyzer technology even when using 100% renewables and with projected improvements in electrolyzer technology[2].

To promote acceptance of blue hydrogen as a sustainable solution, uncertainties about effective long term storage of captured carbon and the extent of climate impact from natural gas production must be addressed. Efforts are also required to continue to bring down the value chain emissions footprint of production and to manage pollution impacts associated with inputs used in blue H_2 production.

Water access provides competitive advantage

Water is a key input to all focus technologies with SMR+CCS being the most water intensive overall (around double the requirements of electrolyzers). High water requirements will continue long into the future. So, more climate change resilient locations will be advantaged, given that climate change is projected to exacerbate water scarcity even if decarbonization is rapidly pursued globally.

Desalination cannot level the playing field on water when environmental impacts are considered as it adds substantially to energy consumption and other environmental impacts, undermining H_2 sustainability.

While some of blue H_2's additional water requirements can be from lower quality sources, all H_2 production technologies studied need large amounts of high purity. Regions with high quality water will have a marginal cost advantage.

[1] by ~2030 PEM 48 v alkaline 50 kWh/kg.
[2] PEM-R100% at 2030: 3.3 kg CO_2-e/kg H_2 versus best current practice of SMR with CCS ~2.3 kg CO_2-e/kg H_2

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Key inputs could be a constraint to H_2 growth and present impacts to be managed

For PEM, platinum and iridium availability could become a concern as demand grows. Geopolitical risks will be key given significant concentration (over 90%) of global reserves in South Africa - production requires power and water, both of which are constrained in the region.

For SMR and alkaline, we flag nickel as the input to watch. We see potential for availability to become a problem in the event of increased demand for vehicle batteries, on top of sustained demand for use in steel making. Potential for nickel substitutes and efficient recycling of nickel will be essential if demand forecasts come to fruition.

Raw material inputs are also a key source of pollution in all of the examined technologies. While these impacts are manageable in our view, it is unclear that they are being given the attention required currently.

> **Sulfur dioxide (SO_2) emissions in particular warrant greater attention to minimize impacts of expanded H_2 production via alkaline electrolyzers and SMR. Materials efficiency and responsible sourcing initiatives are key responses.**

Conclusion

Overall, our analysis confirms that, while there are issues to be managed, H_2 production can be environmentally sustainable. We have identified the key environmental factors that influence winners and losers (such as water access) and the issues that responsible investors should attend to (such as SO_2 and methane emissions in supply chains) to ensure net positive impact from their hydrogen investments.

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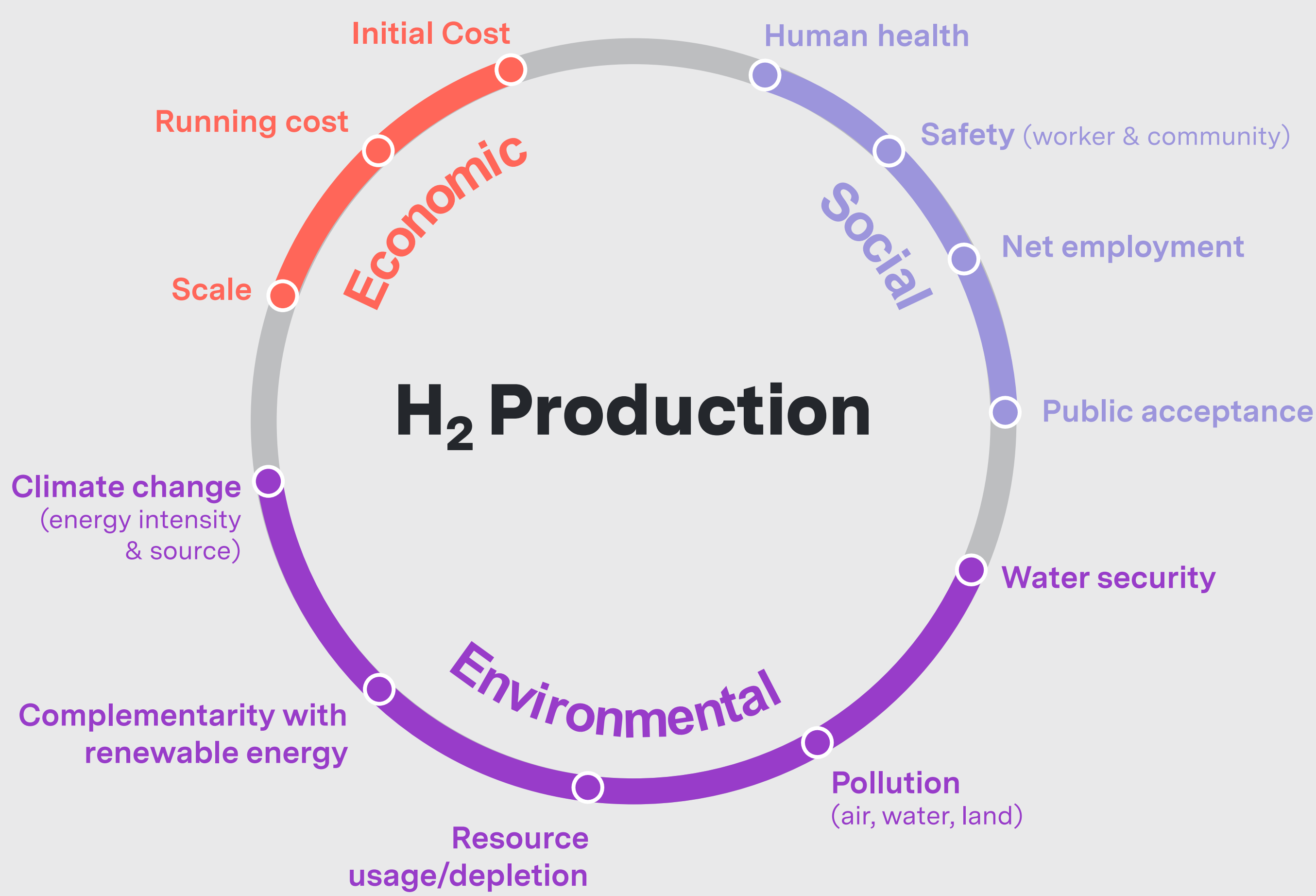
Scope of this report

The purpose of this report is to fill gaps in the case for H_2 and enable us to comprehensively assess the impact of H_2 solutions.

We focus on H_2 *production* as it accounts for the majority of impacts for any H_2 *application* (solution), and will be needed to extend this work into comprehensive views of the impacts for H_2 applications of interest.

Informed by both desktop and primary research, Regnan generated the following schema of key economic, environmental and social issues associated with H_2 production. While social and economic factors are considered in public and policy discussions on H_2 production, environmental impacts beyond energy and carbon are generally absent from existing analysis. Hence, our focus on these in this research.

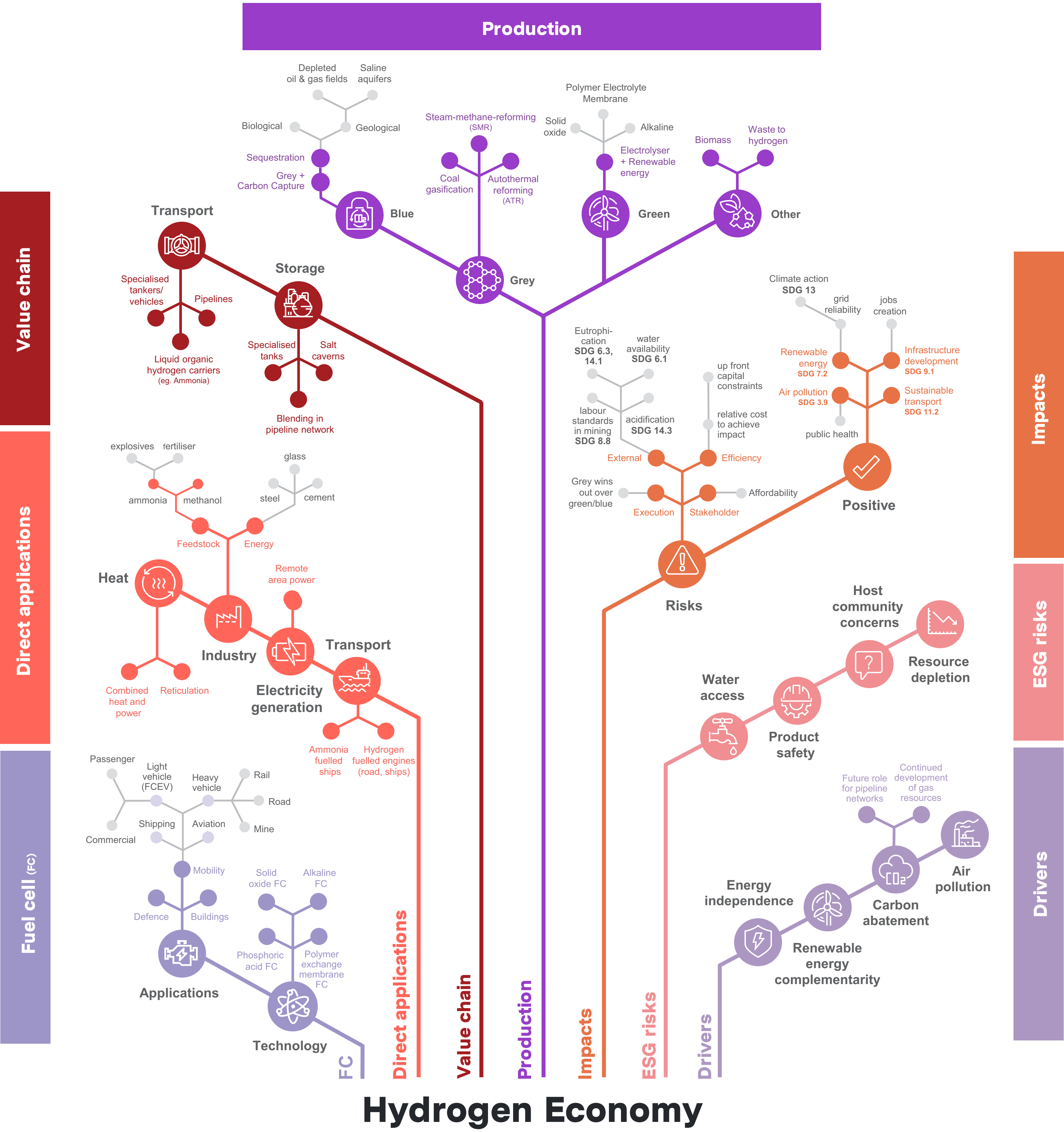
Sustainability of H_2 production technology



Source: Regnan

Our map of the H_2 economy

The mind map below presents how we think about the different elements of the H_2 economy, including linkages to Sustainable Development Goal achievement, both positive and negative. This is an evolving picture that we use and update with developments.



Source: Regnan

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Focus technologies

In this report we focus on the H_2 production methods currently receiving the most attention globally as viable technologies anticipated to 'scale up', which also have potential to be environmentally sustainable based on our analysis.

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 electrolyzers 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).

An overview of each of these technologies is provided below, with more detail in volume 2 on these and some emerging alternative technologies.

Alkaline electrolysis

Alkaline electrolyzers are the most mature technology in H_2 production. Compared to PEM, alkaline incurs lower operational expenditure as well as lower capital expenditure given its use of steel and nickel, as opposed to PEM's use of platinum group elements.

Improvements, including efficiency gains, are expected to be modest in the future and the system is also disadvantaged given slow start-up times.

Polymer electrolyte membrane (PEM) electrolysis

A low temperature system (operating temp ~80°C), PEM technology is more flexible (start up/down and ramp up/down time) and smaller in size compared to alkaline.

Currently more expensive than alkaline, primarily as a result of the use of platinum and iridium, the technology is also more sensitive to impurities in water.

Despite having been around since the 1950s, PEM shows good promise for efficiency improvements, specifically increasing electrolyzer lifetime and decreasing the membrane thickness, which are expected to reduce costs and make the technology cost competitive.

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

The majority of the H_2 produced today is via SMR with methane as a feedstock, but only a tiny fraction (0.6% of global H_2 production) uses SMR *with CCS*. CCS is critical to limiting greenhouse emissions.

The pre-combustion phase of SMR is responsible for 60% of emissions from the process, with the remaining 40% attributable to combustion processes in the plant (post combustion phase).

Pre-combustion capture is considered the most economical option and available technologies enable the majority of pre-combustion CO_2 emissions 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, particularly given greenhouse emissions are not only associated with the SMR process but also during natural gas extraction, in particular, due to fugitive methane emissions – adding substantially to life cycle emissions of blue H_2.

Captured CO_2 is dried and compressed (to dense liquid form), transported, and then injected back into the ground to be either used for enhanced oil recovery or stored permanently (often both) in geological formations, including spent oil and gas fields and saline formations.

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Comparing impacts across production technologies

This section presents the results of our meta analysis of environmental impact studies for our focus technologies. Full details of the studies reviewed and how we reached our summary conclusions are presented in Volume 2: References and workings.

Contributing to carbon emissions abatement

Climate change benefits can be achieved with all the focus technologies, for electrolyzers – by utilizing renewable energy, and for SMR - by coupling with CCS. However, CCS entails greater uncertainty.

- H_2 production has the potential to be close to zero direct (and very low life cycle) emissions. This offers potential for strong carbon benefits in a range of applications, although the extent of climate benefit will vary with application and needs to be judged against the alternatives.

For electrolyzers, the energy source drives these climate outcomes as well as the majority of other environmental impacts.

- Life cycle energy efficiency was chosen as a key metric of environmental impact to remove the influence of electricity grid mix assumptions, given these vary from market to market and are expected to evolve. We have focused on green H_2 (electricity sourced via 100% renewables) to demonstrate the maximum environmental benefits achievable.
- Coupling the water electrolysis system with wind energy attains the most climate efficient result, outperforming solar photovoltaic (PV) energy. PV is more carbon intensive over whole of life (from production to disposal at ~50g CO_2-e/kWh for PV) than wind energy (34g CO_2-e/kWh).
- We see potential for PEM systems to become more energy efficient than alkaline (by ~2030 PEM 48 v alkaline 50 kWh/kg). Currently, alkaline systems are modestly more energy efficient compared to PEM systems (kWh of electricity required to produce H_2). However, future projections anticipate only small efficiency gains in the mature alkaline systems, while less mature PEM systems have greater potential for improvement.

Coupling electrolyzers with intermittent renewables like wind and solar can help manage output peaks and avoid generator curtailment, supporting growth in renewables while also improving economics of H_2 production, with PEM best placed.

- PEM systems can start up/down and ramp up/down more flexibly and reactively than alkaline. This makes PEM better suited to be coupled with intermittent renewable energy compared to current alkaline electrolyzers.
- This coupling helps the economics of PEM – H_2 is produced when excess renewable energy results in low energy prices – and can result in network cost savings and even payments for helping to stabilize the electricity grid.

SMR with successful CCS has potential to be one of the more sustainable and economic options for H_2 production particularly in regions with local natural gas resources, existing pipeline and transport infrastructure and reliable CO_2 storage.

- Best current practice of SMR with CCS equates to around 2.3-3 kgCO_2-e/kg H_2, far lower than either electrolyzer technology at current grid mix (lowest from studies reviewed for alkaline was 7.52 based on the Austrian grid and PEM 11.6 with gas/wind/solar - 40/39/21).
- Further savings can be achieved by increasing capture rates and with further initiatives in natural gas production, especially for fugitive emissions given that methane is an especially potent greenhouse gas. There is consensus that it is technically feasible to increase CO_2 capture rates within the H_2 production process from current practice of 60-90% to closer to 99%. However, this is not yet economically viable without subsidies or a carbon price.
- Such improvements would enable SMR+CCS to maintain its comparable position with electrolyzer technology using 100% renewables, even with projected improvements in electrolyzer technology (PEM-R100% at 2030: 3.3 kg CO_2-e/kg H_2).
- However, environmental risks and impacts must be managed, including concerns around the uncertainties of carbon storage, upstream methane emissions, pollution potential within the supply chain, and a relatively large water consumption footprint.

Sustainable SMR relies on capture and storage, which must be maintained for long periods to be climate effective.

- CO_2 leakage rates of <.01% are generally considered best practice, where 99% of CO_2 will have been retained at the 100 year mark. Based on monitoring of the leakage rates for current facilities and expert views, this appears achievable provided choices for storage are well researched and considered, and accountability mechanisms (agreements, regulations, etc.) to guarantee ongoing and long term monitoring of storage sites are robust.
- Successful permanent storage in depleted oil and gas field locations is stated by experts with a high degree of confidence given existing exploration and research. Oil and gas fields alone provide enough capacity to meet future CO_2 storage requirement estimates.
- CCS in areas without local oil and gas fields will be faced with transport and infrastructure costs. While saline aquifer formations are more commonly found throughout the world – also 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.
- Despite global storage potential, given few CO_2 storage facilities developed to date (28 globally including enhanced oil recovery and storage), there remains uncertainty whether effective storage of CO_2 can be *consistently* reliable.

		PEM		Alkaline		SMR + CCS	
	metric	Current	Future-R*	Current	Future-R*	Current	Future
Electricity Required	*kWh/kgH$_2$*	**~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 CO_2-e/kg H_2*	**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 CO_2 w/ future potential 99%; as well as mitigation of emissions in gas 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.	

Source: Regnan estimates using various sources, see Volume 2: References and workings for full details

Water

We see two key implications related to water:

1) **water secure regions will be best placed to host H_2 production and**

2) **regions with high quality water will have a marginal cost advantage.**

SMR+CCS requires more water than electrolyzers (around double). While the cooling component can be lower quality (e.g. sea or groundwater) and can be recycled, **electrolyzers still appear (based on evidence from two studies) to have an advantage on consumption of *high purity* water.**

There is no material difference between water volumes required for different electrolysis technologies.

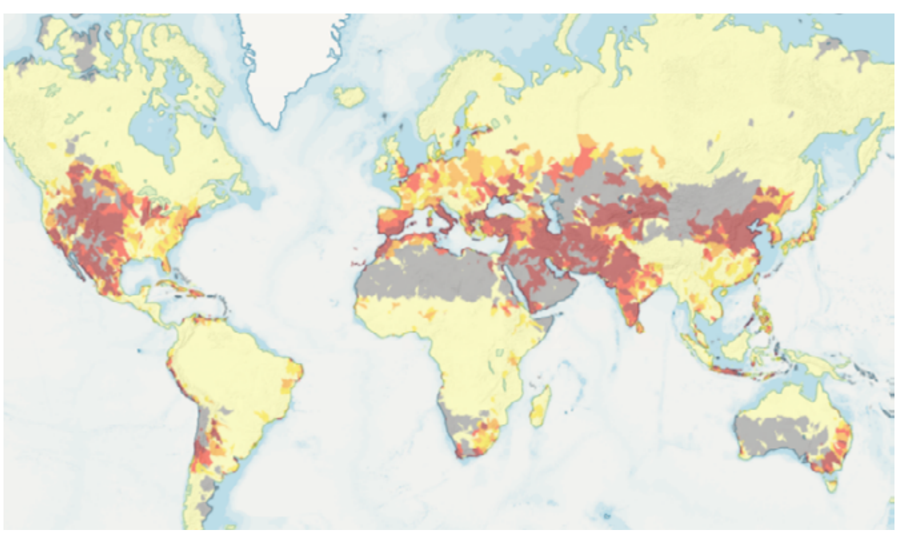
Climate change is projected to exacerbate water scarcity even if transition is actively pursued. This may pose constraints to large scale H_2 production in certain regions without desalination. While desalinization would only add a modest cost of US$0.01-0.02 per kg of H_2, it adds substantially to energy consumption and other environmental impacts, such as seawater temperature rise, increased salinity, fish migration, shifting population balance of algae, nematodes and mollusks.

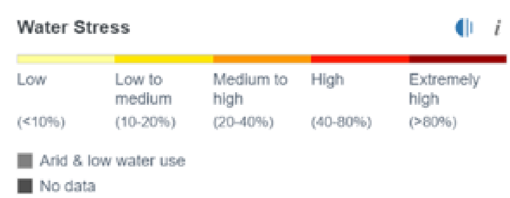
High purity water is required for all focus technologies. In regions with low quality water, a purifier is required, resulting in context specific cost implications. For example purified water in China costs US$4/tonne compared to US$0.4/tonne in the US (per kg of H_2: $0.04 in China compared to US$0.004 in the US).

		PEM		Alkaline		SMR + CCS	
	metric	Current	Future-R	Current	Future-R	Current	Future
Water Requirements	*liters/kgH$_2$*	**9-10**	Limited study evidence	**9-10**	Limited study evidence	**18.4-21.6**	Limited study evidence

Source: Regnan estimates using various sources, see Volume 2: References and workings for full details

Water stress by 2030





Source: World Resource Institute Aqueduct, 'Business as Usual' scenario

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Value chain environmental footprint

Other environmental impacts are manageable – with attention and effort:

- Other environmental impacts result from the mining and production of raw materials like nickel, zinc, platinum, iridium and copper. While these are manageable in our view, it is unclear that they are being given the attention required currently.
- Sulfur dioxide (SO_2) emissions in particular warrant greater attention to minimize impacts of expanded H_2 production via alkaline electrolyzers and SMR.
- SO_2 emissions are a key implication of refining processes for sulfidic ore bodies (relevant to nickel, copper, zinc).
- Unmitigated SO_2 emissions result in toxic acidification of terrestrial and aquatic habitats via runoff and acid rain. SO_2 also has human health implications including increased risk of stroke, heart disease, asthma and lung cancer.
- Impacts can be mitigated through SO_2 capture systems at smelting facilities. Current variations in capture rates for SO_2 relate primarily to local regulations to which industry practices respond. That is, the issue is manageable where there is the will to regulate it.
- Current good practice achieves SO_2 capture rates of 85-90% [e.g. Vale, BHP]. For instance, BHP has plans for its Nickel West operations to increase its capture rate to 99% SO_2 emissions from its smelting processes. Captured SO_2 can be used as sulfuric acid for the processing of other non-sulfidic ores, partly offsetting the costs.
- Given limits on visibility through the supply chain for raw material purchases in spot markets, resource efficiency is a key response, as is engagement and advocacy for higher standards globally. Where possible, direct sourcing, either in regions with high clean air standards or from producers that are members of responsible mining groups requiring best practice standards, can also be pursued.

		PEM		Alkaline		SMR + CCS	
	metric	Current	Future-R	Current	Future-R	Current	Future
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 Volume 2: References and workings for full details

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Input constraints to growth (resource depletion)

Raw material availability may become a problem longer term (beyond 2050):

- Nickel (required for SMR and alkaline) availability may become a problem due to increased demand for vehicle batteries, on top of sustained demand for use in steel making. Potential for nickel substitutes and efficient recycling of nickel will be essential if demand forecasts come to fruition.
- While availability of platinum and iridium is unlikely to impede the deployment of PEM in the short term, medium to long term risks depend on how scenarios unfold. Key factors include:
  - Technological advancements of PEM, specifically in decreasing the platinum and iridium requirements - projections estimate potential improvements of 10x in iridium and 4x in platinum. Pursuit of such improvements would have both cost and environmental benefits.
  - Decline in numbers of internal combustion engine vehicles (which use platinum in catalytic converters), for example, due to take up of electric vehicles, which don't currently use any platinum.
  - Improvement in recycling rates of platinum and iridium.
  - Geopolitical risks given significant concentration of global reserves in South Africa (over 90%). Production requires power and water, both of which are constrained in the region. We note power outages in South Africa are common, during which mining becomes unsafe. Water is also scarce in the country, with projections showing increased scarcity as climate change progresses, which may inhibit mining capacity.

		PEM		Alkaline		SMR + CCS	
	metric	Current	Future-R	Current	Future-R	Current	Future
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 materialize.	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 materialize.	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 materialize.

Source: Regnan estimates using various sources, see Volume 2: References and workings for full details

Next Steps

The role H_2 can play in decarbonization is an ongoing area of interest for Regnan. We will maintain the core elements of this report and extend upon it, for example:

- to develop comprehensive environmental assessments of end use applications of H_2.
- to assess the potential role of gas networks in a H_2 economy.

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