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Assessing the Scalability of Green Hydrogen Innovations for Net Zero

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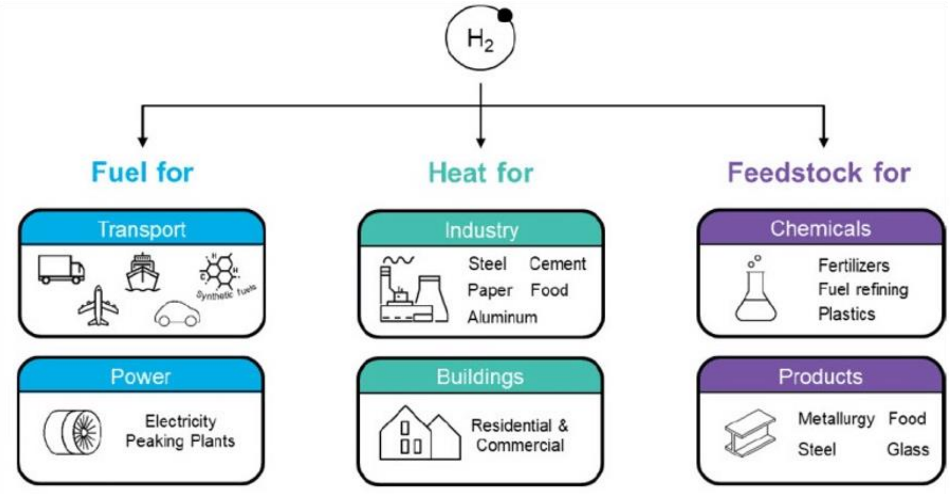
1. Background

Global warming is becoming a well-acknowledged challenge in recent years due to greenhouse gas emission. Severe consequences, including double rate of sea-level rise and fifteen times higher mortality rate from disasters in highly vulnerable regions, drive the United Nation to set climate action as one of the seventeen sustainable development goals (“The Sustainable Development Goals Report 2023: Special Edition”). To limit the temperature increase to 1.5 degree Celsius, which is signed by 195 nations in Paris Agreement in 2015(“What’s in a Number? The Meaning of the 1.5-C Climate Threshold”), above pre-industrial level, a lot of policies are published by governments, including UK government’s six-caron-budget which sets restrictions on total amount of greenhouse gas emissions during fix-year period (“Carbon Budgets”). This budget is used to quantify the mitigation requirement and keep the cumulative carbon dioxide reducing to net zero (Masson-Delmotte et al.) and is a key rationale for countries and districts to set their own target while achieving net zero (Dickau et al.).



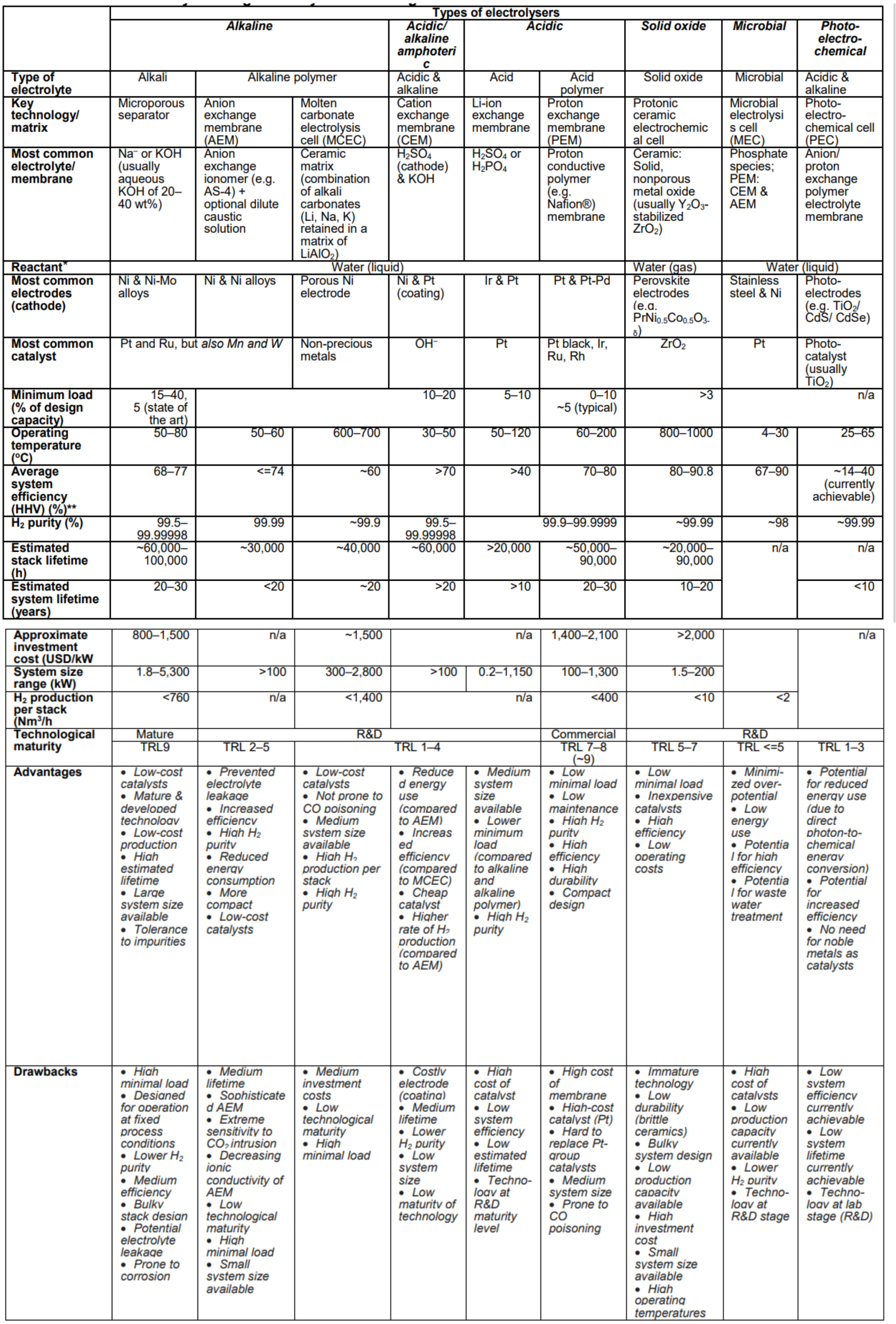
Source: BloombergNEF

Figure 1 Application of Green Hydrogen

To attain net zero by 2050, various of technology solutions are developed to complete global energy transition (Maestre et al.). According to the statement of International Energy Agency (IEA), renewable energy including solar, wind, hydropower and others contributes about 30% of electricity in 2022 (Tian et al.). However, the end-appliance is usually far away from the location where renewable energy is effectively produced (Plappally and Lienhard). As the world looks to get rid of the reliance on fossil fuels, hydrogen meets the demand of clean energy carrier which can promise large scale of storage (Plappally and Lienhard). Moreover, hydrogen has wide application on transportation fuel, industrial and domestic heating, chemical feedstocks and so on, indicating its potential as supplementary energy sources [Figure1].

Hydrogen can be produced by several ways: gray hydrogen is produced from natural gas and still emit carbon dioxide; but, with carbon capture to reduce emission, it can be categorised as blue hydrogen ("Investment Tax Credits for Hydrogen Storage"). Importantly, the most environmental-friendly fuel with zero carbon emission is green hydrogen, also referred as clean hydrogen, which produced by electrolysis of water using renewable energy (Bianco and Blanco). Although mechanism for electrolysers to produce green hydrogen is the same, their components, including electrodes, electrolyte, catalyst, operating temperature and so on, are various, indicating that they have different recommended application condition and drawbacks; below[graph2] is the general overview from the Oxford Institute for energy studies (Patonia and Poudineh).

However, due to its uncompetitive cost and immature manufacture method, its current production amount is much lower than the demand for net zero in 2050 (*Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*). Thus, we are going to explore what's the barrier for green hydrogen to achieve its target production and how can we compensate the gaps between them.



	Types of electrolysers								
	Alkaline			***Acidic/ alkaline amphoteric***	***Acidic***		***Solid oxide***	***Microbial***	***Photo-electro-chemical***
Type of electrolyte	Alkali	Alkaline polymer		Acidic & alkaline	Acid	Acid polymer	Solid oxide	Microbial	Acidic & alkaline
Key technology/ matrix	Microporous separator	Anion exchange membrane (AEM)	Molten carbonate electrolysis cell (MCEC)	Cation exchange membrane (CEM)	Li-ion exchange membrane	Proton exchange membrane (PEM)	Protonic ceramic electrochemical cell	Microbial electrolysis cell (MEC)	Photo-electro-chemical cell (PEC)
Most common electrolyte/ membrane	Na^- or KOH (usually aqueous KOH of 20–40 wt%)	Anion exchange ionomer (e.g. AS-4) + optional dilute caustic solution	Ceramic matrix (combination of alkali carbonates (Li, Na, K) retained in a matrix of $LiAlO_2$)	H_2SO_4 (cathode) & KOH	H_2SO_4 or H_2PO_4	Proton conductive polymer (e.g. Nafion®) membrane	Ceramic: Solid, nonporous metal oxide (usually Y_2O_3-stabilized ZrO_2)	Phosphate species; PEM: CEM & AEM	Anion/ proton exchange polymer electrolyte membrane
Reactant*	Water (liquid)						Water (gas)	Water (liquid)	
Most common electrodes (cathode)	Ni & Ni-Mo alloys	Ni & Ni alloys	Porous Ni electrode	Ni & Pt (coating)	Ir & Pt	Pt & Pt-Pd	Perovskite electrodes (e.g. $PrNi_{0.5}Co_{0.5}O_{3-\delta}$)	Stainless steel & Ni	Photo-electrodes (e.g. TiO_2/ CdS/ CdSe)
Most common catalyst	Pt and Ru, but *also Mn and W*		Non-precious metals	OH^-	Pt	Pt black, Ir, Ru, Rh	ZrO_2	Pt	Photo-catalyst (usually TiO_2)
Minimum load (% of design capacity)	15–40, 5 (state of the art)	10–20			5–10	0–10 ~5 (typical)	>3	n/a	
Operating temperature (°C)	50–80	50–60	600–700	30–50	50–120	60–200	800–1000	4–30	25–65
Average system efficiency (HHV) (%)**	68–77	<=74	~60	>70	>40	70–80	80–90.8	67–90	~14–40 (currently achievable)
H_2 purity (%)	99.5–99.99998	99.99	~99.9	99.5–99.99998	99.9–99.9999		~99.99	~98	~99.99
Estimated stack lifetime (h)	~60,000–100,000	~30,000	~40,000	~60,000	>20,000	~50,000–90,000	~20,000–90,000	n/a	n/a
Estimated system lifetime (years)	20–30	<20	~20	>20	>10	20–30	10–20		<10
Approximate investment cost (USD/kW	800–1,500	n/a	~1,500	n/a		1,400–2,100	>2,000		n/a
System size range (kW)	1.8–5,300	>100	300–2,800	>100	0.2–1,150	100–1,300	1.5–200		
H_2 production per stack (Nm^3/h	<760	n/a	<1,400	n/a		<400	<10	<2	
Technological maturity	Mature	R&D				Commercial	R&D		
	TRL9	TRL 2–5	TRL 1–4			TRL 7–8 (~9)	TRL 5–7	TRL <=5	TRL 1–3
Advantages	• *Low-cost catalysts* • *Mature & developed technology* • *Low-cost production* • *High estimated lifetime* • *Large system size available* • *Tolerance to impurities*	• *Prevented electrolyte leakage* • *Increased efficiency* • *High H_2 purity* • *Reduced energy consumption* • *More compact* • *Low-cost catalysts*	• *Low-cost catalysts* • *Not prone to CO poisoning* • *Medium system size available* • *High H_2 production per stack* • *High H_2 purity*	• *Reduced energy use (compared to AEM)* • *Increased efficiency (compared to MCEC)* • *Cheap catalyst* • *Higher rate of H_2 production (compared to AEM)*	• *Medium system size available* • *Lower minimum load (compared to alkaline and alkaline polymer)* • *High H_2 purity*	• *Low minimal load* • *Low maintenance* • *High H_2 purity* • *High efficiency* • *High durability* • *Compact design*	• *Low minimal load* • *Inexpensive catalysts* • *High efficiency* • *Low operating costs*	• *Minimi-zed over-potential* • *Low energy use* • *Potential for high efficiency* • *Potential for waste water treatment*	• *Potential for reduced energy use (due to direct photon-to-chemical energy conversion)* • *Potential for increased efficiency* • *No need for noble metals as catalysts*
Drawbacks	• *High minimal load* • *Designed for operation at fixed process conditions* • *Lower H_2 purity* • *Medium efficiency* • *Bulky stack design* • *Potential electrolyte leakage* • *Prone to corrosion*	• *Medium lifetime* • *Sophisticated AEM* • *Extreme sensitivity to CO_2 intrusion* • *Decreasing ionic conductivity of AEM* • *Low technological maturity* • *High minimal load* • *Small system size available*	• *Medium investment costs* • *Low technological maturity* • *High minimal load*	• *Costly electrode (coating)* • *Medium lifetime* • *Lower H_2 purity* • *Low system size* • *Low maturity of technology*	• *High cost of catalyst* • *Low system efficiency* • *Low estimated lifetime* • *Techno-logy at R&D maturity level*	• *High cost of membrane* • *High-cost catalyst (Pt)* • *Hard to replace Pt-group catalysts* • *Medium system size* • *Prone to CO poisoning*	• *Immature technology* • *Low durability (brittle ceramics)* • *Bulky system design* • *Low production capacity available* • *High investment cost* • *Small system size available* • *High operating temperatures*	• *High cost of catalysts* • *Low production capacity currently available* • *Lower H_2 purity* • *Techno-logy at R&D stage*	• *Low system efficiency currently achievable* • *Low system lifetime currently achievable* • *Techno-logy at lab stage (R&D)*

Table 1 Summary of Different Types of Electrolysers

2. Supply and Demand

The clean hydrogen innovations for industrial decarbonisation have two main technological applications: one is using green hydrogen as fuel; the other is using it as feedstock. To meet the demand of those applications, we need to consider two points —- supply side, how much hydrogen can be produced, and demand side, how much hydrogen is required. To be specific, some top manufacturers are listed below with the technologies they used and their ambition on green hydrogen production and some consumers are listed with their product.

Manufacturer	**Electrolysis Technology**	**GH2 Progress**
Linde	PEM	• 35MW PEM electrolyser to be built in Niagara Falls in the US by 2050 • Building 24MW PEM electrolyser in Germany • 24MW PEM electrolyser for Yara in Norway for ammonia production • 156 tons of green hydrogen will be produced in Brazil ("Electrolysis for Green Hydrogen Production")
Air Liquide	PEM	• Normandy project in France with a 200MW capacity industrial scale electrolyser system • Co-operating with Siemens Energy for Trailblazer Project with 20MW Elyzer P-300 in 2022(Liquide)
Siemens Energy	PEM	• Co-operating with Air Liquide for Trailblazer Project with 20MW Elyzer P-300 in 2022

		• Scheduling a 70 MW electrolyser for CO2 neutral e-methanol for marine use in Sweden in 2025(*Green Hydrogen Production*)
Plug Power	PEM	• 120MW PEM electrolyser is going to be powered by zero-carbon solar farm with water provided by self-built tertiary water treatment plant by 2025(Saathoff and Saathoff)
Uniper	PEM and ALK	• Establishing power-to-gas pilot plants using PEM electrolyser from 2015-2022 in Hamburg with the power of 1.5 MW • Establishing pilot plant using Alkaline Electrolyser from 2018-2023 with the power of 2 MW(“Hydrogen”)

Table 2 Manufacturer of Green Hydrogen

Consumer	**Application**	**Product**
Yara International	Chemical Feedstock	Fertilisers
OCI Global	Chemical Feedstock	Methanol
Airbus	Fuel	Fuel cell
Nikola	Fuel	Hydrogen-electric Semi Truck

Table 3 Consumer of Greem Hydrogen

From the table of manufacturer above, we can summarise that the commercialisation of green hydrogen has been promoted, and the large-scale industrial manufacture of hydrogen has started all over the world with co-operations from leading companies like Siemens Energy and Air Liquide. These constructing pilot plants are expected to boost the total amount of production of green hydrogen in 2025.

For consumers' table, an obvious trend is that the current commercial usage of green hydrogen focused on feedstock and fuel fields; some of them are performing as both consumer and manufacturer. For instance, Yara collaborates with Linde for the 24 MW electrolyser project in Norway ("Electrolysis for Green Hydrogen Production"). Another key point in application is the lack of widespread heating application like domestic heating. This situation is mainly due to the high investment required for capital expenditure and danger of high concentration of pure hydrogen; in places like house or gym, electric heat pump is a more efficient and cheaper heating method (Carnevali). Besides these companies mentioned in the table above, there are also other consumers such as Maersk, who used the e-methanol made from green hydrogen for shipping.

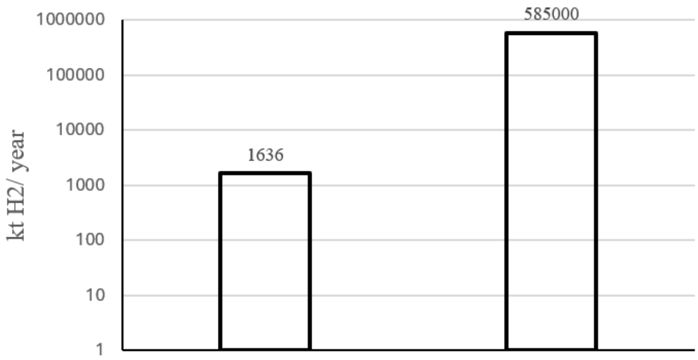
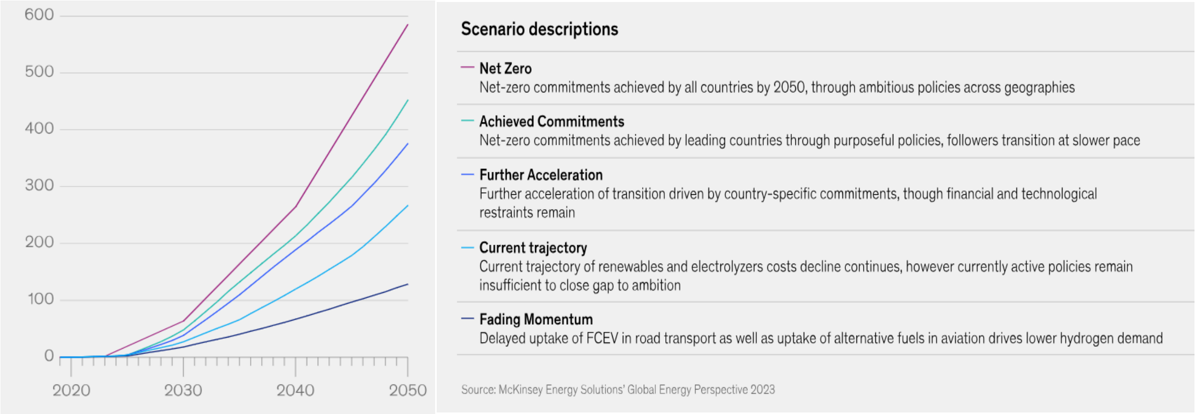


Figure 2 Green Hydrogen Production in 2023 VS Demand in 2050

However, the current annual production for green hydrogen is much less than the requirement to achieve Net Zero target in 2050. From the data published by International Energy Agency, the total Green Hydrogen production amount in operational projects in 2023 is around 1636 kilo tonnes per year, which is almost 500 times less than the 585 million tonnes per year objective (Gulli et al.); in another word, current production does not reach 0.5% of the future goal.

With the line chart, which label in vertical axis should be million tonnes per year, from Mckinesy's Energy Solutions Global Energy Perspective 2023, the planned trend is better illustrated: a rapid increase in two decades, 2030-2040 and 2040-2050, in annual production from both leading countries and the followers is a must to meet the Net Zero demand. In this solution, around 70 Mt of annual output should be accomplished by near 2030, and then estimated 260Mt of green hydrogen should be attained by 2040.



Scenario descriptions

— Net Zero
Net-zero commitments achieved by all countries by 2050, through ambitious policies across geographies

— Achieved Commitments
Net-zero commitments achieved by leading countries through purposeful policies, followers transition at slower pace

— Further Acceleration
Further acceleration of transition driven by country-specific commitments, though financial and technological restraints remain

— Current trajectory
Current trajectory of renewables and electrolyzers costs decline continues, however currently active policies remain insufficient to close gap to ambition

— Fading Momentum
Delayed uptake of FCEV in road transport as well as uptake of alternative fuels in aviation drives lower hydrogen demand

Source: McKinsey Energy Solutions' Global Energy Perspective 2023

Figure 3 Scaling the Green Hydrogen to 2050 Target

3. Cost in Green Hydrogen Production

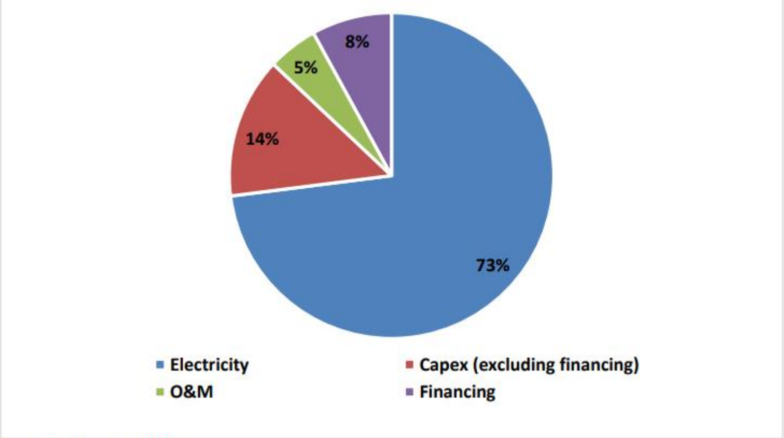
3.1 Challenges on scaling up green hydrogen

Although the urgent demand for scaling up the green hydrogen is presented on the previous chapter, the growth of green hydrogen is still facing obstructions to make a real impact on industrial-scale manufacture. The obstructions comprise lack of dedicated infrastructure and electrolysis technology barriers: the number of both transport infrastructure including pipelines and storage infrastructure such as hydrogen refilling stations is not capable of aimed usage in 2050 (Bianco and Blanco, “Green Hydrogen: A Guide to Policy Making”). These constructions can be made up by government’s policy and investments from stakeholders. In the meantime, technological challenges have an emphasize on high production cost and energy losses.

3.2 Cost breakdown of green hydrogen

Despite active support of research and development into electrolysis, a more basic cost reduction is needed for green hydrogen to be a competitor with other hydrogen has higher carbon footprint (Patonia and Poudineh). To achieve a decline on cost, the breakdown of the cost should be discussed.

According to the data from Wood Mackenzie, renewable electricity is the paramount factor among all components, which contributes 73% to the total amount. Capital expenditure, including purchase and instalment of electrolysers, is the second largest proportion in the cost, which highly depends on the size and type of electrolysers. The margin of production companies, also known as financing factor, also plays a vital role in the price. Last but not least, the operational and maintenance fee combined with water charge is also a nonnegligible part of the cost components.



Source: Wood Mackenzie (2019)

Figure 4 Main Cost Drivers for Green Hydrogen in 2019

If we focus more on the electrolysers and the pilot plant, the cost breakdown will be different and highly depends on the type of electrolysis technology. For the relatively mature commercialised electrolysers, which occurs in the table above including Alkaline and PEM electrolysers, the cost of stacks is the main expenditure; for those developing high-efficient electrolysers, price of constructing the balance of the plant is more expensive.

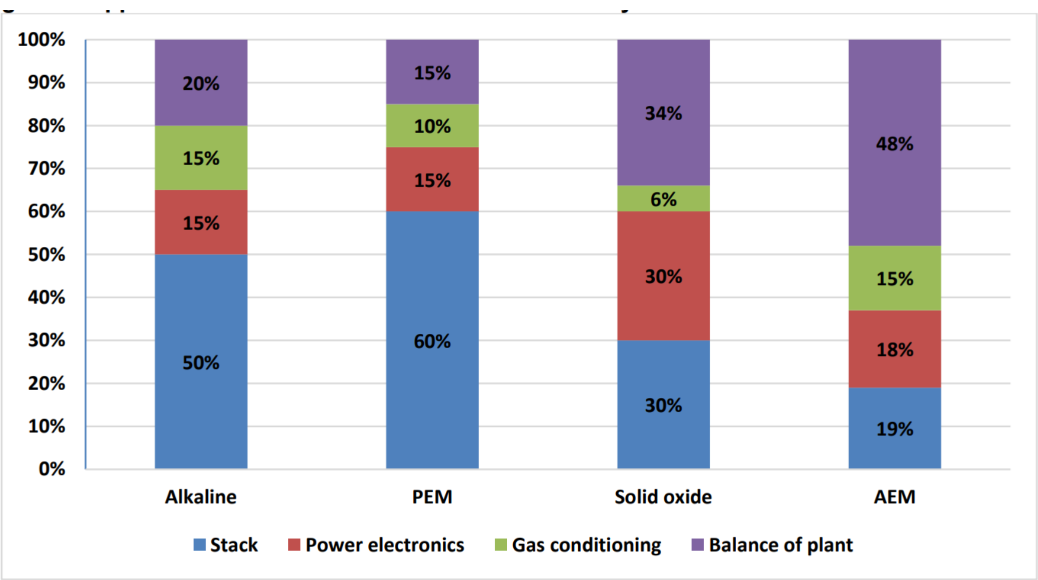


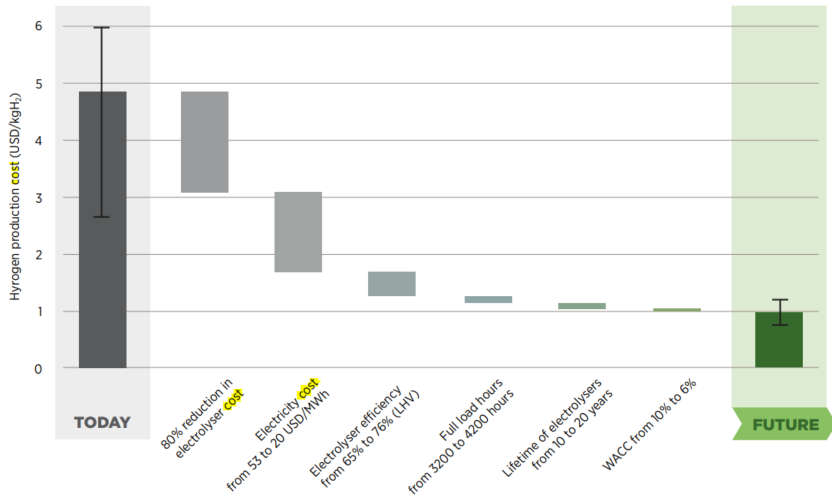
Figure 5 Approximate Cost Breakdown for 1MW Electrolysers

Source: from Patonia, Aliaksei, and Rahmatallah Poudineh

3.3 How to reduce cost

According to IRENA's report in 2021, cheaper electricity and lower electrolyser capital costs, along with increased efficiency and optimised electrolyser operation are key factors to reduce the production cost of green hydrogen for up to 80%. The detailed strategies are the following:

1. Using free surplus green energy
2. Improving the efficiency and durability of electrolyser, using simpler design
3. Mass-manufacture of the electrolyser core (stacks).
4. Increasing the electrolyser size and reducing the cost contribution from the balance of plant and auxiliary equipment.
5. Standardising the design, optimising the supply chain, replicating installation, and learning from best practices in deployment are all promising methods of reducing cost.



Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3 200 (onshore wind) and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4 200 (onshore wind) and a WACC of 6% (similar to renewable electricity today).

Based on IRENA analysis

Figure 6 Electricity and Electrolysers: Potential to Cut Hydrogen Cost by 80%

Although electricity from renewable energy contributes the largest proportion to the green hydrogen cost, its market price is relatively fixed. This factor can be released by policies made from government. For example, government can provide an allowance to the manufacturer of green hydrogen. In addition, production factories can use free surplus green energy; but this may cause the restriction on the production of green hydrogen.

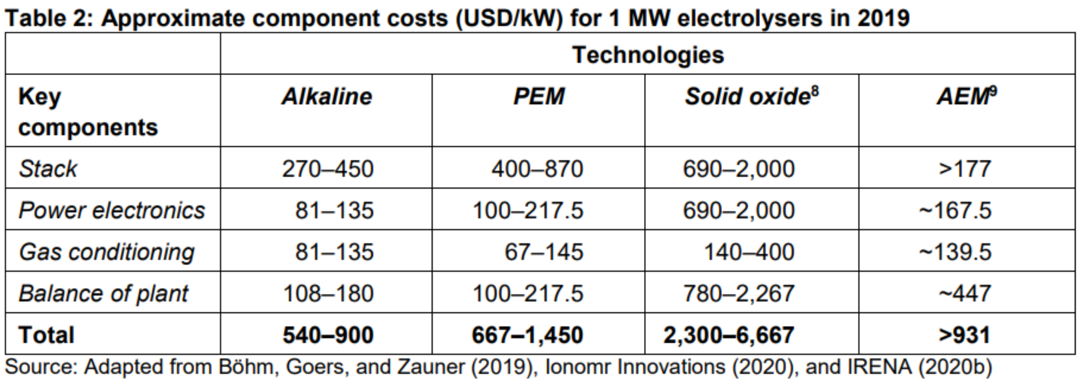


Table 2: Approximate component costs (USD/kW) for 1 MW electrolysers in 2019

	Technologies			
Key components	***Alkaline***	***PEM***	***Solid oxide***[8]	***AEM***[9]
Stack	270–450	400–870	690–2,000	>177
Power electronics	81–135	100–217.5	690–2,000	~167.5
Gas conditioning	81–135	67–145	140–400	~139.5
Balance of plant	108–180	100–217.5	780–2,267	~447
Total	**540–900**	**667–1,450**	**2,300–6,667**	**>931**

Source: Adapted from Böhm, Goers, and Zauner (2019), Ionomr Innovations (2020), and IRENA (2020b)

Figure 7 Approximate Component Costs (USD/kW) for 1MW Electrolysers in 2019

Cost reduction can begin with stacks. From the figure above [Figure 8], we can see that stacks contribute 30%-50% to the total component cost for a 1MW electrolyser. To decrease that expense, cheaper catalyst and materials can be used. For instance, alkaline electrolysers can use transition metal instead of expensive noble metal as a catalyst (Ferrero et al.). Generally, a decline on cost in 30% for solid oxide electrolyser and in 19% for AEM electrolyser can be attained (Patonia and Poudineh).

In addition, increasing the size of stacks can also be an innovation. Mass-producing modular stacks improves total capacity and decreases the average cost of production; therefore, share of cost of balance of plant decreases. Surprisingly, if the capacity of plant increases to 20MW from 1 MW, according to Green Hydrogen Cost Reduction: Scaling Up Electrolysers To Meet The 1.5 Climate Goal from IRENA, over 33% cost can be saved.

Moreover, increasing the learning rate is also a good solution. Learning rate refers to the percentage by which the cost decreases when the production is doubled by means of standardising the electrolyser technologies, specialising production of specific parts of electrolysers in certain companies and simplifying the production process and instalment (Patonia and Poudineh). As a result, learning rate is an index to price reduction. Hydrogen Council in 2020 states that learning rate for Alkaline electrolyser is approximately 9% and for PEM electrolyser can reach 13%.

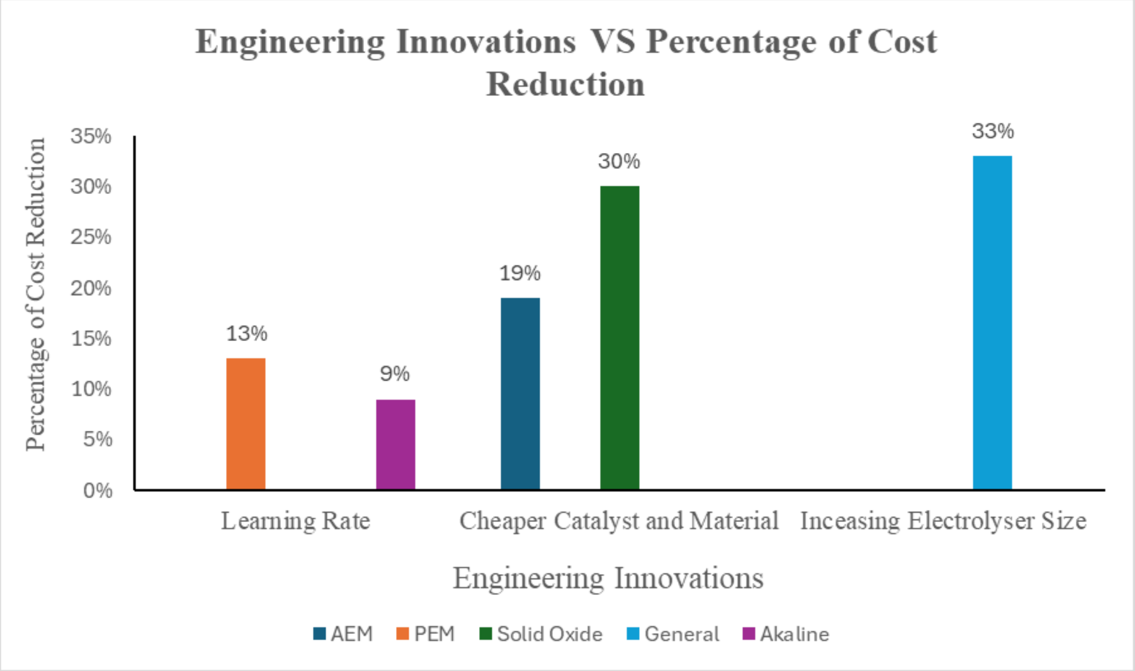


Figure 8 Engineering Innovations Effect

To sum up, increasing the electrolyser size is the most efficient method to reduce the cost, and a large number of enterprises is working on it. Combined with other engineering innovations, the cost in green hydrogen production can successfully be adjusted to an affordable range.

4. Conclusion

The current built green hydrogen plants are mostly in 1-2 MW. Meanwhile, a lot of projects are constructing electrolysers in over 20MW, which is a milestone during the journey. Some companies perform as both manufacturer and consumer at the same time, which is beneficial and boost the development in technology. However, the production currently is much lower than the requirement in the net zero plan due to a lot of challenges, including lack of recognition, deficient infrastructure, energy losses and so on. But the most important factor is the uncompetitive market price, so I highly recommend manufacturer to make an improvement through increasing learning rate with standardisation of all processes of instalment and production of electrolyser, decreasing average cost of stack by raising the capacity of company and replacing noble metal with cheaper catalyst. These methods can separately lessen the cost by around 9%-33%. Green hydrogen is an achievable innovation to attain decarbonisation.

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