CLEAN AIR
TASK FORCE

Hydrogen Production via Electrolysis

The Limits of Potential Cost Declines

Author: Ghassan Wakim, Hydrogen Technology Director

Summary

Cost forecasts for 'clean' hydrogen—where clean hydrogen is generally understood to mean hydrogen produced using electrolysis powered by low-carbon electricity—are an important consideration for many industries as they seek to develop strategies for decarbonizing their operations in the future. Currently, some optimistic outlooks predict that production costs for clean hydrogen will fall below $1 per kilogram (kg). These forecasts are incomplete, however, because they focus (incorrectly) on reductions in electrolyzer capital costs as the main driver of future production cost declines. This paper summarizes the results of a recent Clean Air Task Force (CATF) analysis showing that even with projected improvements in electrolyzer efficiencies and reductions in capital costs, average production costs for clean hydrogen are highly unlikely to fall below $3/kg (Real 2022 USD) in the foreseeable future.[1] In fact, CATF's analysis indicates that, among the factors that influence production costs for electrolytic hydrogen, the most important is the cost of electricity. This factor alone accounts for 50%–75% of the overall cost of hydrogen produced via electrolysis.[2]

Electrolysis: A history

'Electrolysis' refers to the use of an electrical current to split molecules into their constituent elements. The process of electrolyzing water to produce hydrogen has been understood for over two centuries and has been implemented on an industrial scale since the early 20th century, primarily to produce hydrogen and ammonia using hydroelectric power. At present, however, other methods for producing hydrogen—such as steam methane reforming—are much less expensive. In 2022, only 0.1% of global hydrogen production originated from water electrolysis, mainly due to the prohibitive economics of this production pathway. The idea of producing hydrogen on a large scale via water

1 There will be significant variation in production costs between different projects and geographies owing to many factors including capital costs of renewables, cost of capital, and operations and maintenance costs.

2 It is important to note that the key determinant of hydrogen's economic competitiveness as a decarbonization solution is its *delivered* cost, which includes the costs of compression, storage, transmission, and distribution in addition to the production cost.

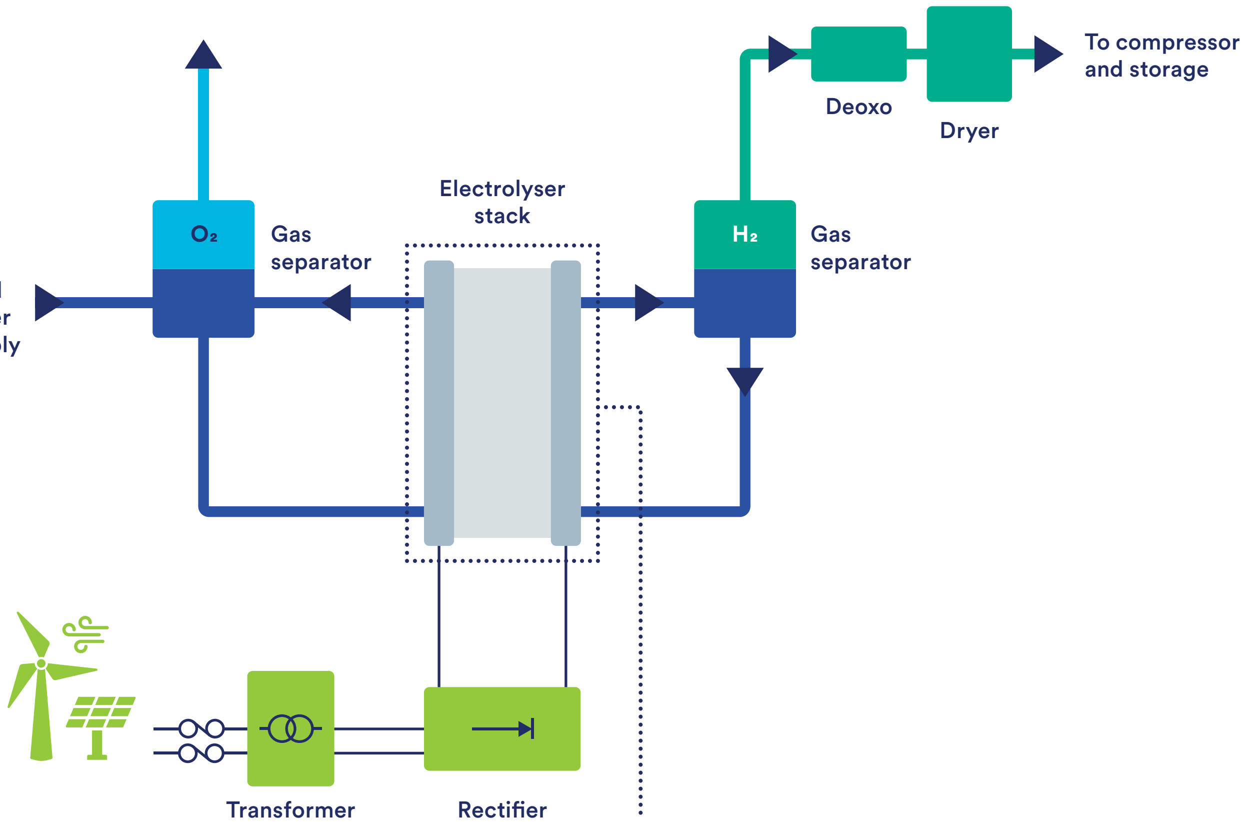
electrolysis has recently drawn renewed attention because it offers the potential to generate hydrogen with near zero emissions if the electricity used is generated from low-carbon sources. Dramatic price reductions[3] for solar and wind generation over the last decade have fueled hopes that 'cheap' clean electricity can be used to propel the production of clean hydrogen as an economic option for sectors such as fertilizer and steel production.

Electrolysis takes center stage

The electrolyzer is the device where electricity passes through water to produce hydrogen and oxygen. Electrolyzers come in all shapes and forms. Figure 1 depicts the basic elements of an electrolyzer, showing the stack in which electrolysis takes place, the water circulation system, the gas processing system, and the power supply.

Figure 1. System-level schematic of an electrolyzer.

Source: IRENA 2020

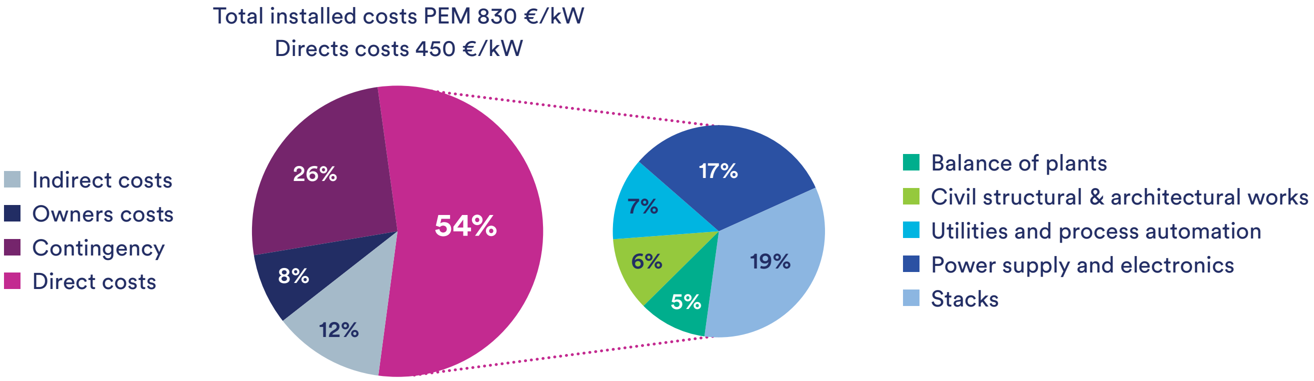


[3] Prices for renewably generated electricity, as reflected in purchase power agreements (PPAs), have benefited from a low-interest rate environment over the past decade and generally include subsidies. As such, the decline in prices shown in the figure may not reflect a parallel reduction in solar and wind manufacturing costs. PPA contract prices consider the levelized cost of electricity (LCOE), capacity factors, rates for ancillary grid services such as frequency control, and the value of renewable energy certificates (RECs) that are awarded to renewable generators to validate their environmental attributes in the context of policies such as renewable portfolio standards.

Two electrolyzer parameters are of particular interest from a cost standpoint:

- **System Specific Electricity Consumption (kWh/kg H_2)**[4] is a measure of how efficiently the electrolyzer converts energy input (electricity) into chemical energy (hydrogen). It is typically expressed in kilowatt-hours (kWh) per kg of hydrogen (H_2) produced.
- **Total Installed Cost ($/kW)** includes the direct costs of the project and other costs associated with project development, such as indirect costs (project management, administration etc.), owner's costs (permitting, engineering fees, insurance etc.), and contingency costs to cover risks and deviations from the project budget. All too often, forecasts of electrolyzer cost focus only on the direct costs of a project, which make up only a portion of the total cost, as shown in Figure 2. Gigawatt-scale electrolysis facilities are large infrastructure projects and capital cost reductions will be driven mainly by developer experience. Aside from the electrolysis units themselves, other components of a hydrogen production facility (e.g., piping, vessels, compressors, substations, etc.) are technologically mature and will see limited reductions in cost.

Figure 2. Estimated 2030 total installed cost for a proton exchange membrane (PEM) water electrolysis facility.
Source: Institute for Sustainable Process Technologies (ISPT) 2022



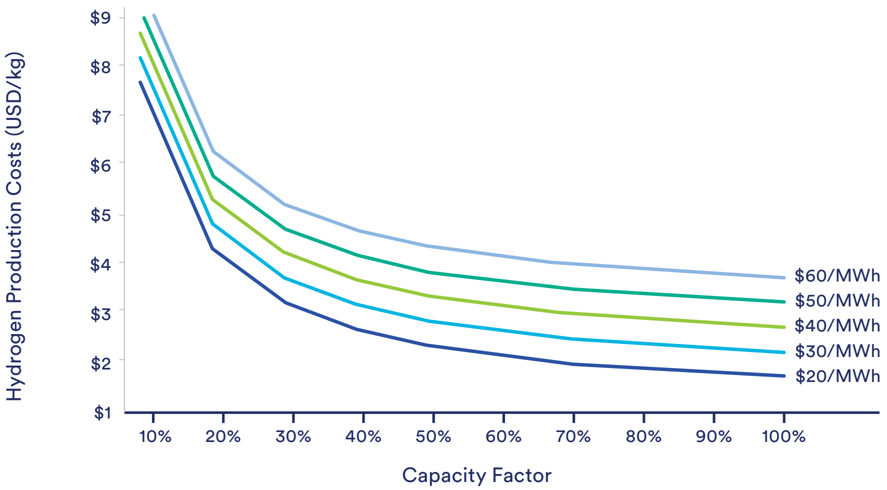
[4] The performance of the stacks that form the core of water electrolyzers will degrade over time due to the wear and tear of normal operations. The rate of degradation might also increase if hydrogen production ramps up and down regularly. As a result, the electricity consumption per unit of hydrogen produced will increase the longer the electrolyzer has been in operation until the stacks are replaced.

The variable renewable energy challenge[5]

Although electricity prices have been falling for over a decade, prices for solar photovoltaic (PV) and wind energy, as reflected in power purchase agreements (PPAs) for these sources, increased in 2022 due to higher material, interest, and capital costs.[6] In fact, prices for electricity from a system powered predominantly by variable renewables may be approaching a lower limit due to costs related to maintaining system reliability and resiliency, which can increase the costs of electricity by double or more compared to busbar costs. Low solar and wind prices come with a catch in that electricity output from these generators is weather-dependent. In the context of electrolysis-based hydrogen production, this variability is important because it means that electrolyzers will not be running constantly if they rely exclusively on power from renewable resources such as wind and solar. This in turn means that capital costs will need to be amortized over a smaller quantity of hydrogen, increasing the per-kg cost of hydrogen produced. The effect of electrolyzer utilization can be seen in Figure 3, which shows hydrogen production cost declining as electrolyzer capacity factor increases (capacity factor is a measure of how much the unit runs relative to its theoretical maximum utilization). Alternatively, electricity storage (e.g., batteries) can be added to enable continued operation during periods of low wind or solar availability, thereby increasing electrolyzer utilization. However, this addition increases costs by approximately $100/MWh in the case of a 4-hour lithium-ion battery storage system.[7]

Figure 3. Levelized production costs for low-carbon hydrogen[8] from electrolysis.

Source: CATF internal modeling



5 This analysis focuses on the costs of dedicated electrolytic hydrogen production as opposed to electrolytic hydrogen produced from curtailed renewable electricity which can potentially be used as a form of long duration energy storage (LDES).

6 There are regional variations in PPA prices, which can be attributed to how these power arrangements are structured and to the effects of subsidies and tax incentives for developers.

7 Lazard (2023) shows that the additional cost to source 'firm' electricity from renewable generators significantly increases the LCOE from these sources. Firming costs are not necessarily indicative of long-term total electricity costs in that these are not the costs to deliver energy every hour of every day (24/7).

8 To calculate simple levelized cost of hydrogen for this analysis we assume a hydrogen production level that is constant throughout the life of the project. The real weighted average cost of capital (WACC) is assumed to be 8%, We further assume a total installed cost (TIC) of $950/kW for PEM electrolyzers, with system-specific energy consumption of 48.1 kWhAC/kg hydrogen, where this energy consumption increases linearly up to 10% higher than start-of-run conditions after 60,000 hours of stack operation. Stack replacement is calculated at 10% of TIC. Annual operating expenditures are assumed to be 3% of TIC. We assume that hydrogen is delivered at 30 barg at the battery limit of the electrolysis facility.

Hydrogen production cost outlook

If an electrolysis facility is powered by solar PV only, the capacity factor of the electrolysis facility will be in the 20%–30% range depending on the quality of the solar resource.[9] If a facility is powered by wind only, the expected capacity factor is on the order of 40%.

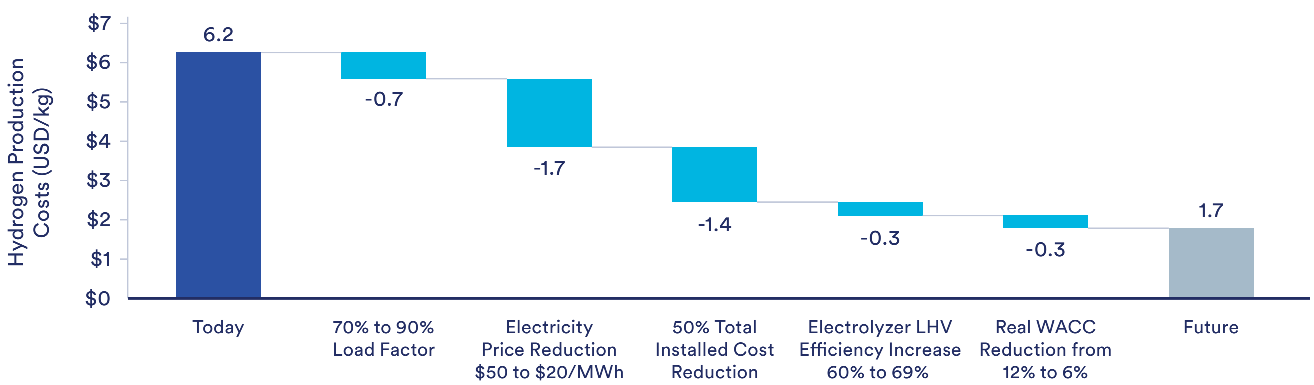
Reasonable future price floors for renewably generated electricity range from $10/MWh for solar PV to $20/MWh for wind.[10] These translate to unsubsidized hydrogen production costs of $3.2 and $2.7 per kg, respectively if we assume estimated performance figures for PEM electrolyzers in 2030 together with projected reductions in electrolyzer costs by 2030 (Figure 2). It is worth noting that dedicated clean hydrogen production will invariably be coupled to downstream processes that require a constant supply of hydrogen. As such, variable renewable electricity will need to be firmed up [higher electricity costs] and hydrogen storage will be required to consistently deliver hydrogen to users.

Some hydrogen project developers intend to sign PPAs for clean firm power, which in theory would allow them to operate electrolysis facilities at capacity factors over 90%. This would translate to hydrogen production costs of $3.3 per kg at electricity prices of $50/MWh.

Figure 4 presents an optimistic cost reduction pathway for gigawatt-scale hydrogen production from electrolysis using PEM electrolyzers.

Figure 4. Potential cost reduction pathway for hydrogen production.[12]

Source: CATF internal modeling



9 The global weighted average capacity factor for utility-scale PV systems for 2022 stood at 20.5%.

10 The lowest-cost utility-scale solar PV PPA was signed for $10.4/MWh for a 600-MW solar PV plant, and a $19.9/MWh price point was achieved for a 400-MW onshore windfarm in Saudi Arabia. IRENA shows the 2022 global utility-scale solar PV project LCOE at $49/MWh and that for utility-scale wind at $33/MWh.

11 In the case of NEOM, hydrogen production is coupled to an ammonia production which needs to run at relatively constant production levels. Therefore, the plant design also includes hydrogen storage and is configured to minimize the cost of ammonia production.

12 Other potential drivers for cost reduction include improved electrolyzer durability and reduced operations and maintenance costs owing to a maturing and competitive supply chain.

Future cost reductions for 'clean' hydrogen will depend on a significant ramp-up of electrolysis projects to support the development of a mature supply chain. This will allow for improvement in several key parameters, among them:

Electrolyzer load

Electrolyzer capacity factors can be increased today, but this approach depends on the availability of clean electricity. In general, developers will seek to maximize the operational load of electrolyzers to recuperate the significant capital costs of the electrolysis facility. While variable renewable sources should become more abundant, driving hydrogen costs down will require very high-capacity factor clean electricity and/or more cost-effective electricity storage options.

Electricity price

There is currently no clear path for prices for clean, firm electricity to reach the $20/MWh level, which is significantly low compared to current typical wholesale electricity prices. While $10–$15/MWh has been achieved for numerous solar PV projects in the Middle East, these projects do not deliver electricity around the clock, which limits achievable electrolyzer capacity factors. Furthermore, these rates generally exclude transmission and network access fees which can add $10–$20 per MWh.[13]

Total installed cost

Our estimate of the potential reduction in total installed cost is sourced from the ISPT report, which provides the capital cost breakdown for a gigawatt-scale plant built in 2030 shown in Figure 2. Smaller installations will have higher specific installed costs on a per-kW basis.

Efficiency

The potential for electrolyzer efficiency improvements by 2030 was estimated by Fraunhofer in a study commissioned by CATF in 2021. These improvements are dependent on sustained electrolyzer demand and rapid progress in research and development.

Financing costs

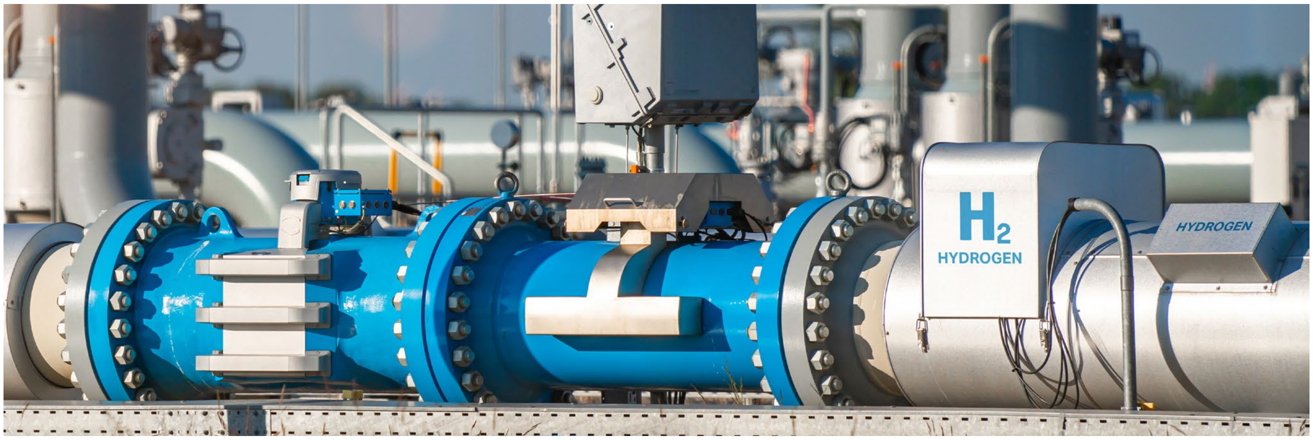
Building and operating numerous electrolysis facilities will improve developer experience, reduce technology risk, and drive down the cost of capital.[14] Government policies can further reduce the cost of capital by guaranteeing low-cost financing, but this becomes more challenging and costly in an environment of 'high' interest rates (at least, relative to the interest rates of the last decade). Further complications in terms of project financing can arise in developing markets due to geopolitical, regulatory and currency risks.[15]

---

13 This paper assumes that the electricity price procured by the electrolysis facility is inclusive of all charges such as network access fees and transmission charges.

14 The weighted average cost of capital (WACC), also known as the discount factor, is assumed to decrease from 12% to 6%.

15 If renewable electricity generators are installed as part of the hydrogen production project—as opposed to procuring electricity externally—hydrogen production costs will be particularly sensitive, due to the front-loaded nature of capital spending, to the allocation of project costs, cost of equity, and interest on debt.



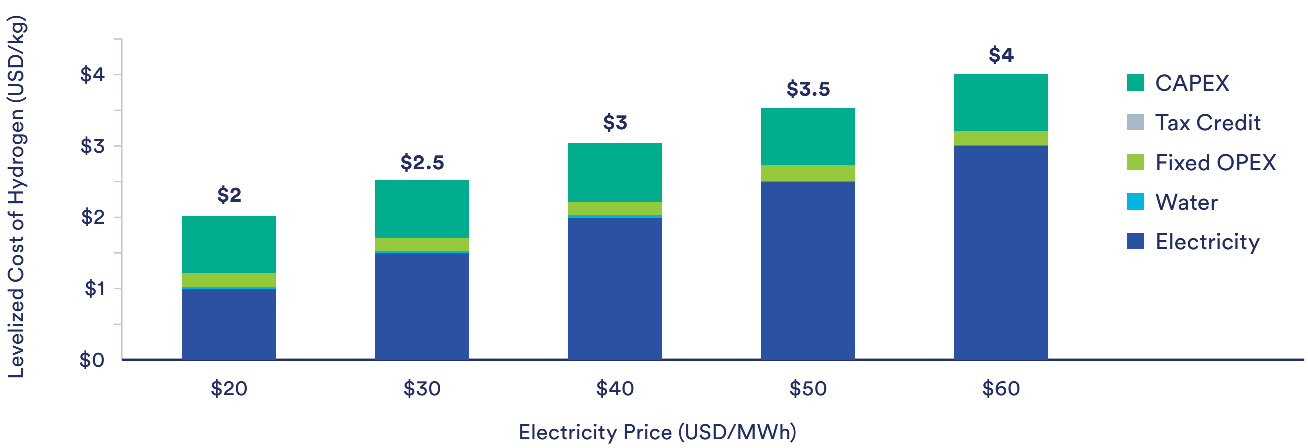
In summary, this analysis suggests that the most optimistic cost reduction pathway for clean electrolytic hydrogen, assuming gigawatt-scale PEM electrolysis facilities, yields a production cost of $1.7 per kg (the right-most gray bar in Figure 4). Results for other types of electrolyzers, such as alkaline and solid oxide electrolyzers, are similar.

Further cost reductions to achieve $1/kg production costs would require unrealistic leaps such as reducing total project costs to $100/kW (down from approximately $2000/kW today), increasing electrolyzer operating efficiency to nearly 90% (from 65% today on an LHV basis), and securing access to clean firm electricity at $20/MWh.

Realistically, we conclude that average production costs for clean hydrogen are unlikely to fall below the $3/kg (Real 2022 USD) threshold for the foreseeable future, mainly because there is no realistic expectation that prices for delivered clean firm electricity will fall below $40/MWh.[16]

Figure 5. Contribution of electricity costs to total hydrogen production costs.[17]

Source: CATF internal modeling



16 Other costs that have been excluded from this analysis include costs generally associated with the business activities of companies that are operating electrolysis facilities, where these business costs generally include overhead, insurance, management, marketing, and taxes. While these costs are not substantial, they add to the general cost of hydrogen production. In addition, this analysis excludes the effects of clean hydrogen incentives such as subsidies and production tax credits.

17 2030 TIC at $950/kW, PEM 69% LHV Efficiency, 70% load factor, real WACC 8%, 25-year project lifetime

Conclusion/Implications

A multi-billion-dollar expansion of GW-scale electrolytic hydrogen production facilities will be needed in the near term for supply chains to mature and development costs to decrease.[18] This buildout will need to be preceded by an even more pronounced expansion of clean electricity production, which, according to our analysis, can be expected to continue to account for 50%–75% of the total cost of electrolytic hydrogen production. As such, our findings further underscore the significant decarbonization efforts needed to ensure that a reliable, clean, and affordable electricity system is in place to enable the scale-up of electrolytic hydrogen production.[19]

Policy makers should be properly informed about the realistic outlook for electrolytic hydrogen production costs and availability. We conclude that production costs for clean hydrogen will remain above $3/kg, which is equivalent to $\$22/MMBTU_{HHV}$ or €70/MWh_{HHV} at the plant gate. The delivered cost to end-users, which can be expected to include the costs of compression, storage, transmission, and distribution, will be even higher. Even if the much-touted production cost goal of $1/kg were to be achieved, it would still be hard to describe electrolytic hydrogen—at a production cost equivalent to $\$7.4/\ MMBTU_{HHV}$ or €24/ MWh_{HHV}—as a fuel that is 'cheap' as well as clean.

These conclusions have several implications for policies that aim to expand the use of clean hydrogen:

1. Realistic price projections that accurately reflect the cost of produced and delivered hydrogen are essential to better guide hydrogen-related policy decisions and better reflect the true monetary cost of these decisions.

2. Hydrogen use should be prioritized for end-use sectors where an evidence-based analysis shows that other technically and economically viable decarbonization alternatives are lacking. Practically, this means focusing on the decarbonization of existing hydrogen production, which largely serves the chemical and refining sectors, and prioritizing the use of clean hydrogen in feedstock applications such as steel manufacturing. A complete evidence-based analysis should consider a suite of technology options including direct electrification, carbon capture and storage, clean hydrogen, and other novel methods that can provide low-cost decarbonization pathways.

3. Policy makers and investors should focus on decarbonizing the power grid and providing clean firm power to enable the scale-up of clean hydrogen production from water electrolysis. An approach that clusters renewable electricity projects with electrolyzer facilities can deliver low-cost clean hydrogen in certain geographies but is not a pathway to delivering low-cost 'green' hydrogen at scale.

---

18 This paper focuses on the limits of production cost declines, but there are other factors that might limit the expansion and availability of electrolytic hydrogen including land-use constraints.

19 The US DOE report *Pathways to Commercial Liftoff: Clean Hydrogen* emphasizes this point: *"Low-cost clean hydrogen via electrolysis will also depend on ample availability of low-cost clean electricity (<$20/MWh) that will need to scale in parallel with market demand for clean hydrogen."*