WHITE PAPER

De-Risking Low-Carbon Hydrogen

A Guide for Machinery Makers to Navigate the Global Dynamics of Hydrogen

October 2024
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1. Low-carbon hydrogen is pivotal to fueling Europe's energy independence

Hydrogen from renewable sources plays a crucial role in securing Europe's energy independence and fortify its position as a global hub for green technology innovation. Hydrogen's significance is evident not only in the continent's ambitions to decarbonize, but also from geopolitical and economic standpoints.

- From a **geopolitical perspective**, Europe is facing unprecedented challenges in its energy landscape. The geopolitical consequences of Russia's invasion of Ukraine, including the ban on gas imports from Russia, as well as Germany's exit from nuclear power, have catalysed a radical transformation of Europe's energy mix. To prevent the rise of new dependencies in its energy supply, Europe must prioritize the development of a resilient and self-sufficient green energy infrastructure. In this equation, low-carbon hydrogen, produced via electrolysis, is pivotal. It offers a pathway not only to diversifying energy sources but also to efficiently balancing the grid, considering growing renewable capacity and resulting fluctuations of energy supply.

- From an **economic perspective**, the development of a hydrogen ecosystem from large-scale production presents a significant opportunity for Europe's industrial sector along the entire value chain—from production of hydrogen via renewables (including wind turbines, solar parks and hydropower), electrolysis (such as gas conditioning and balance of plant), storage (including tanks, carriers and compressors), and transport and use (including engines, fuel cells and reformers). This potential exceeds €25 billion in economic opportunity to 2030 for suppliers, machinery- and equipment manufacturers alone.

But the ramp-up of low-carbon hydrogen in Europe—and globally—has recently encountered several setbacks. BCG projects global demand for low-carbon hydrogen to reach around 14 million tonnes per annum (mtpa) by 2030, a figure that is 30% to 40% lower than normative 2°C demand models suggest is necessary. This shortfall is driven primarily by rising capital costs and the resurgence of fossil alternatives, as well as by delays and budget overruns in hydrogen-related projects. These factors are combining to stall progress and complicate the path toward developing a green hydrogen industry.

As a result, industrial companies—including machinery and component suppliers, plant developers, and equipment manufacturers—are facing an erosion of their hydrogen-related business cases. The decreasing commercial viability of hydrogen investments has put pressure on the entire value chain, raising questions about the feasibility of widespread adoption without more robust support and cost-efficiency measures.

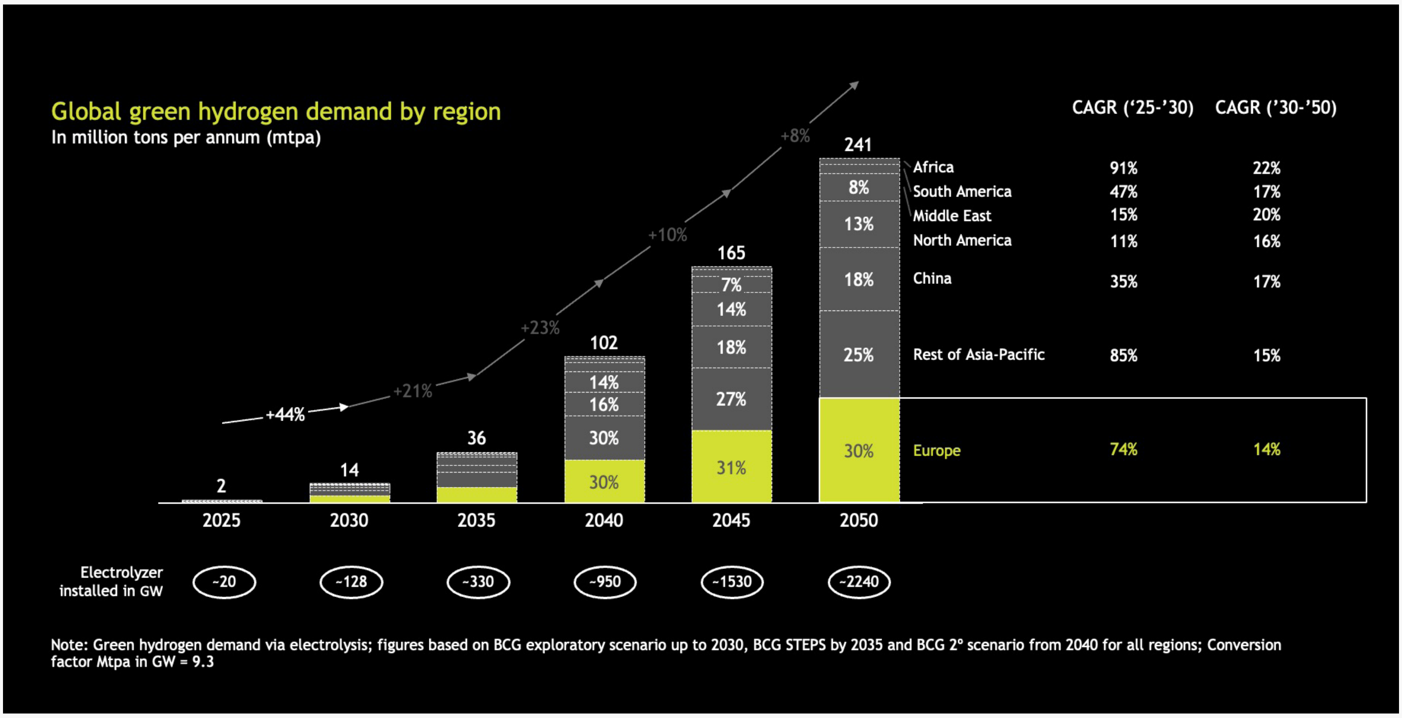
This publication aims to serve as a guide for industrial companies and regulators alike, helping them to de-risk their investments in hydrogen, master the delayed ramp-up, and improve competitiveness amid growing competition in a yet-to-develop market.

2. Europe is in a leading position for green hydrogen, but has recently lost its punch

Europe has long aimed to position itself as a global leader in hydrogen infrastructure and technology, setting ambitious targets to produce and import 10 million tons of renewable hydrogen each by 2030. With significant policy frameworks such as the Fit-for-55 initiative (2021), the IPCEI Hy2Tech/Use project support (2022), and the broader European Green Deal 2050, the continent has launched substantial efforts to drive the transition to green hydrogen.

BCG expects that Europe will account for approximately 30% of global green hydrogen demand by 2050, which translates to around 73 mtpa. This would place Europe ahead of other major regions such as China (18%) and North America (13%). With current production levels below 0.3 mtpa, however, this ambition signals a tremendous stretch for Europe as it aims to become the largest global consumer and adopter of green hydrogen technologies. (See Exhibit 1.)

Exhibit 1 | Europe is Expected to Account for Around 30% of Global Green Hydrogen Demand by 2050



Source: BCG Hydrogen demand model; Global Data; Expert interviews; BCG analysis.

The key to Europe's success so far is its history of successful projects and leading position in the technology behind the hydrogen electrolyzers and other equipment made there. The unsurpassed reliability and efficiency of European equipment is due largely to the region's extensive landscape of leading machinery makers and hydrogen-related technology startups, and its broad ecosystem of chemical and industrial off-takers, ready to integrate low-carbon hydrogen in their operations. Today, Europe is home to six of the top ten global electrolyzer manufacturers, including notable names such as Nel, Siemens Energy, Haldor Topsoe, Nucera, ITM and John Cockerill. Together, these companies are set to deliver a combined production capacity of around 125 GW by 2030, showcasing Europe's industrial strength in the hydrogen space.

However, despite these promising fundamentals, Europe's hydrogen ramp-up is falling short of ambitions. The region has built-up less than 0.5 GW of green electrolyzer capacity, which is significantly below its 6 GW target for 2024. Less than 3% of green hydrogen projects are currently in execution, cost projections for Europe are as much as 2 times the once-calculated production cost for 2030, and the overall supply ramp-up has now been delayed by three to four years vs. originally projected capacity.

In short, despite its technological and commercial edge, the business case for Europe's hydrogen equipment makers is coming under increasing pressure, the result of weak demand, higher capital costs, project delays and bureaucratic hurdles.

3. The US and China are upping their game in low-carbon hydrogen—yet neither has found the "silver bullet"

China and the US are surpassing Europe in both ambition and execution. The US is leveraging strong federal support and significant incentives to accelerate its hydrogen economy. China is surpassing with a flourishing scene of new market entrants and significant time-to-market advantages vs. European projects. However, neither China nor the US has yet unlocked the economic key to making green hydrogen scalable and commercially viable.

The US: strong federal hydrogen initiatives, but in a "wait-and-see" mode

The US is significantly advancing its green hydrogen agenda, primarily driven by federal initiatives such as the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA). These policies have provided the most substantial incentives for hydrogen in the world, particularly in established sectors like chemicals and refineries. The new incentive legislation's section 45V stands out by offering a tax credit of up to $3 per kilogram, depending on the carbon intensity of its production. Unlike European schemes, which often focus on upfront investment, the incentives support the "produced molecule," making it attractive for opex-heavy off-take.

In addition, the IIJA allocated $62 billion to the Department of Energy (DOE), with $10 billion dedicated to clean hydrogen. The DOE's establishment of regional clean hydrogen hubs across the US is an important component of the US strategy, aimed at developing local ecosystems of producers, consumers, and infrastructure.

Despite these strong initiatives, the US is facing significant hurdles in making green hydrogen economically viable. While the new incentives have improved hydrogen production costs "on paper," they remain high. And without binding demand mandates, there is limited incentive for consumers to pay a premium of blue or green hydrogen vs. its grey alternative. The higher willingness to pay for low-carbon hydrogen only exists in overseas markets like Europe or Japan.

Moreover, most of the low-carbon hydrogen produced in the US by 2030 will be for export via hydrogen derivatives, and two thirds of that will be blue, not green. Therefore, of the dozens of electrolyzer manufacturing plants that had been announced in the US, only a handful have been built and even those are not at full capacity. The only projects that are moving forward today are blue hydrogen/ammonia projects which rely on a well-established 45Q tax credit for carbon capture—and because the 45Q credit is of equal or greater value than 45V, it is cannibalizing its green counterpart subsidy.

Without addressing these economic challenges, the US will struggle to achieve competitive hydrogen pricing at the scale necessary, and several market players, such as Plug Power, are coming increasingly under pressure.

China: mainly district-level H2 initiatives, but rapidly evolving landscape

China's commitment to green hydrogen has been gaining traction, but much of its progress is currently driven at the provincial, not national level. The 14th Five-Year Plan, issued in 2021 by the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA), encouraged pilot programs for the production and utilization of hydrogen from renewable energy sources. More than 30 administrative divisions have set mid-term hydrogen ambitions, aiming to create a market valued in the billions of renminbi. Policy support covers the full value chain, from feedstock and production to storage, transport, and utilization. Much of the national focus remains in the transport sector (including fuel cell electric vehicles) and select pilot projects for peak shaving, frequency regulation, and hydrogen derivative production. Today, China remains largely dependent on grey hydrogen, and is mainly limited to alkaline technology dominating low-carbon hydrogen production.

Recently, however, we are observing significant uplift in hydrogen-related technology innovation and support that will boost China's position towards becoming a leading hub for low-carbon hydrogen:

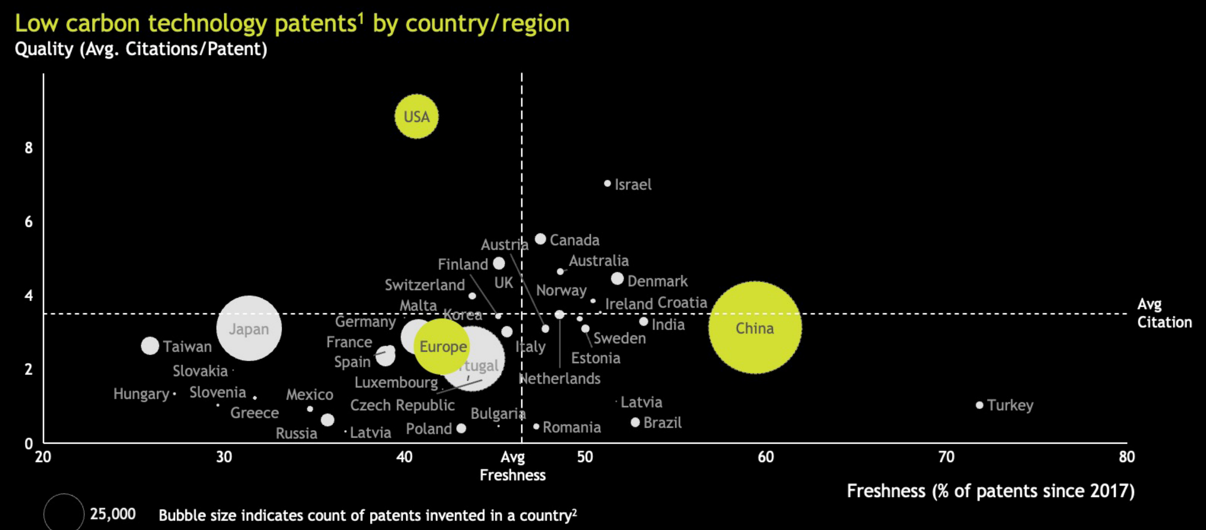
- **Green patent activity:** In the past three years, China has seen annual growth of around 30% in hydrogen-related patents, with more than 1,000 new patent families filed for green hydrogen production and fuel cells, and an increasing share of high-quality patents. This activity is a multiple of Europe's and the US's combined, underscoring China's determination to lead the global hydrogen race (see Exhibit 2).

- **Market entrants:** We observe more than 100 new system-level entrants along the hydrogen value chain, spanning electrolysis, compression, fuel cells and storage solutions. The increasing number of players is not only the result of state-level support, but also increasingly driven by growth- and capital markets-pressure in the private sector for solar, automotive, semiconductors, and energy storage.

- **Hydrogen cost:** China's rapid expansion of solar and wind capacity allows it to produce green hydrogen at prices as low as 12 RMB/kg, equal to around 1.50 EUR/kg in few regions like Inner Mongolia today. At the same time, an abundance of renewable energy has led to an increased need for efficient energy storage solutions, with hydrogen—particularly Proton Exchange Membrane (PEM) technology—emerging as a key technology for China to balance the grid.

- **Electrolyzer pricing:** Recent bids for national hydrogen projects in China have shown electrolyzer prices of up to 60% for PEM electrolyzers and 80% for alkaline electrolyzers (ALK) compared to Western equipment. While only parts of this price advantage stem from lower labor and materials costs, state support and increasingly intensified local competition among Chinese electrolyzer providers is pushing hydrogen products to significantly lower prices.

Exhibit 2 | China is Outcompeting the US and Europe in Low-Carbon Patent Activity



1. incl. green energy solutions, alternative fuels, H2-based solutions & derivatives, CCU, etc.; 2. Patent source is identified by using inventor's address; only country-specific patent publications have been considered; Analysis based on climate related patents filed since 2010 identified using a combination of keyword based strategies and patent tech codes
Sources: Patentsight, Derwent Innovation, Center of Growth & Innovation Analytics, BCG Green Tech Portal, BCG Analysis

Despite this momentum, China is short of domestic off-take for green hydrogen production projects. As a result, Chinese electrolyzer manufacturers have been expanding internationally, securing significant projects in regions such as the Middle East, South America, and parts of Europe. Companies like LONGi, PERIC, Sungrow, SinoHy, and SPIC have recently entered these markets, focusing on countries in the Asia-Pacific and MENA regions. This international expansion is also driven by fierce competition in the Chinese domestic market, prompting Chinese players to seek growth opportunities abroad.

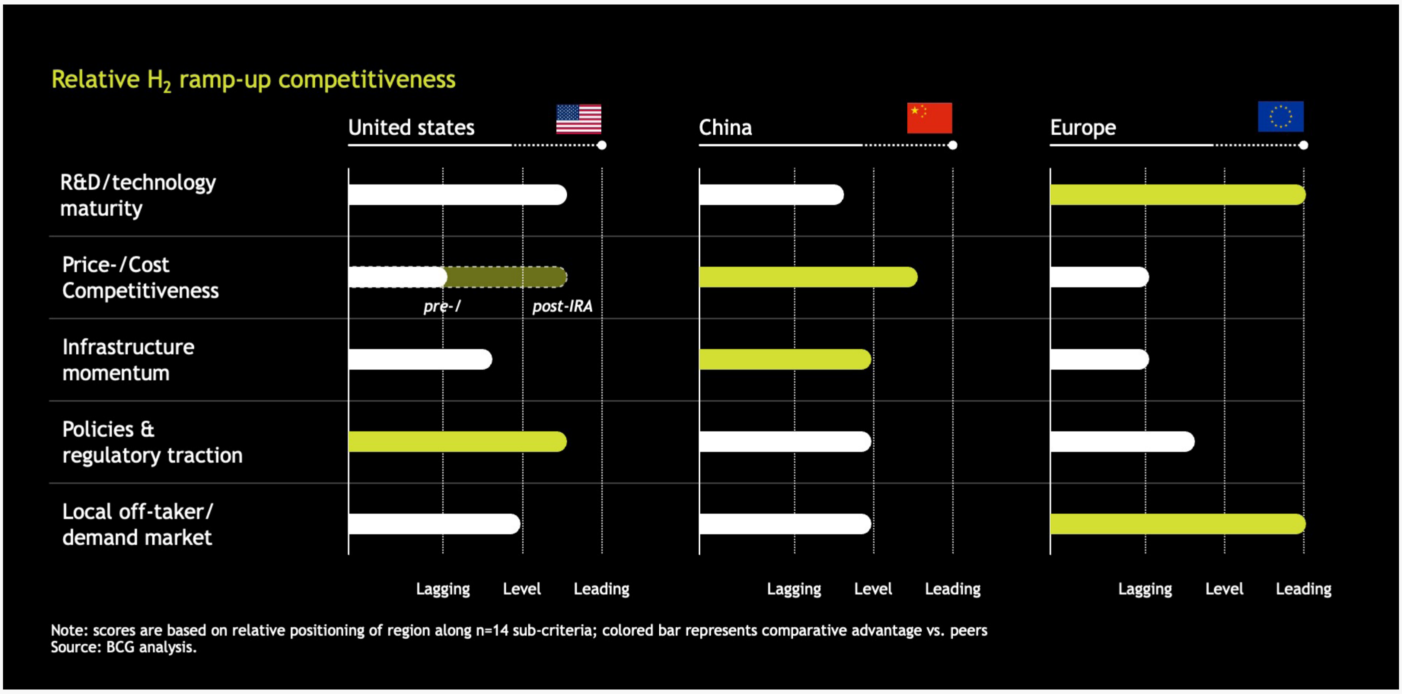
BCG anticipates that China will incorporate district-level targets and standards in national-level plans by 2025. And next year, as China enters its 15th Five-Year Plan, we expect the government to intensify its commitment to hydrogen-related projects. Increased cost competitiveness, new national targets, and growing local competition will likely drive a substantial expansion of China's hydrogen market in the transport, energy, and industrial sectors. Current technology and capability gaps, especially areas such as PEM-related technology and system integration, are likely to be bridged in the next three to five years through a combination of targeted support, domestic and foreign off-take projects, and cross-country technology partnerships.

4. Imperatives for action: What industrial goods companies can do to ramp up and de-risk their hydrogen activities

In summary, no region has yet found the silver bullet for making the economics of green hydrogen fully viable. Challenges related to costs, infrastructure, and market dynamics continue to hinder the large-scale economic viability of green hydrogen.

Exhibit 3 provides a simplified overview of the relative strengths of each of the key regions in promoting a green hydrogen industry. Europe leads in the industrial equipment and technology behind green hydrogen production and applications, and in the demand for decarbonizing an existing ecosystem of industrial, transport and energy sectors. China's advantage lies in its relative cost position, its pragmatic piloting and significantly faster time-to-market for required plant and infrastructure build-out (three to five years vs. five to seven years in Europe and the US). The US's favorable new energy policies will likely make the continent a leading exporter for low-carbon hydrogen globally.

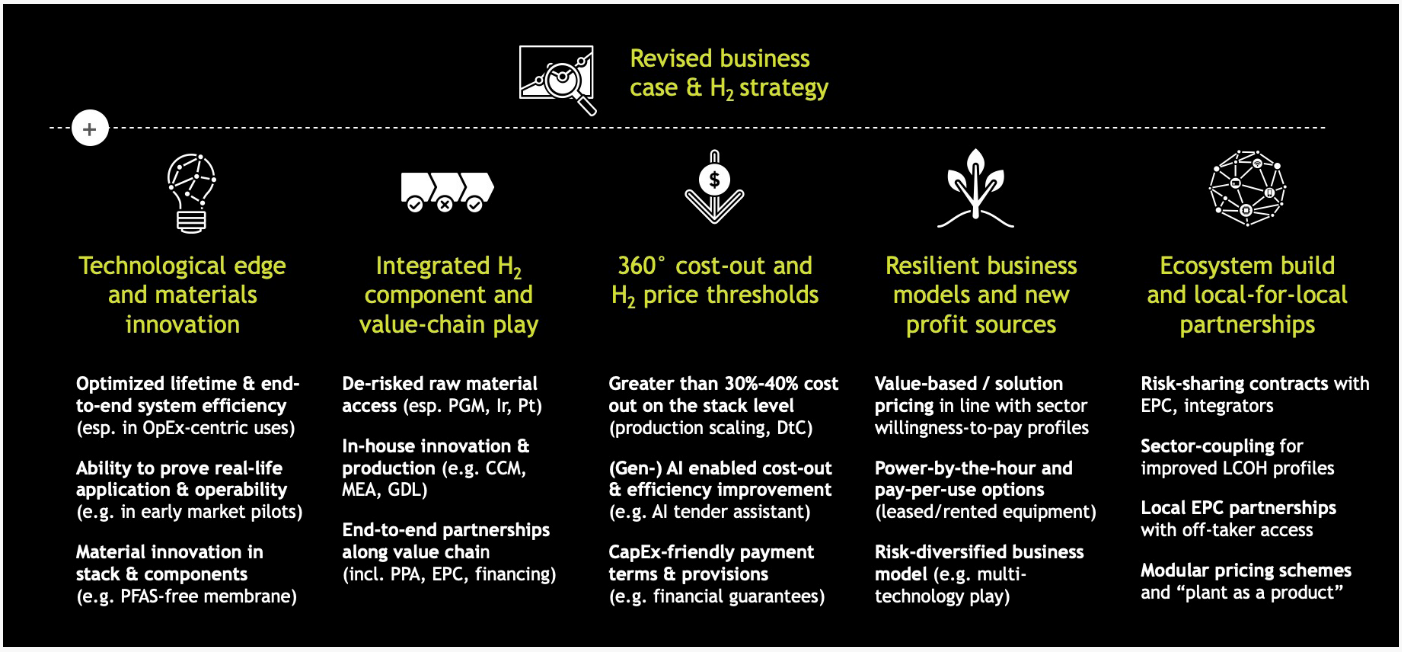
Exhibit 3 | Europe, China and the US all have Distinct Advantages Enabling the Low-Carbon Hydrogen Ramp-Up



While each region's systems provide different frameworks, it is important not to view these differences in terms of regional competition for supremacy. In fact, in a market that is not yet developed, competition is limited. Moreover, across regions, stakeholders along the hydrogen value chain share an interest in maintaining the spirit of "co-opetition" (to cooperate and compete) to advance the hydrogen ramp-up and develop the industry.

To that end, we offer specific courses of action for industrial goods companies engaged in making and advancing the electrolyzers, fuel cells, infrastructure, and other hydrogen-related equipment to de-risk their current business models and master the ramp-up. Exhibit 4 summarizes key levers to de-risk the hydrogen ramp-up and improve competitiveness in an increasingly challenging market.

Exhibit 4 | The Hydrogen De-Risking Toolbox Spans Six Dimensions



Source: BCG analysis.

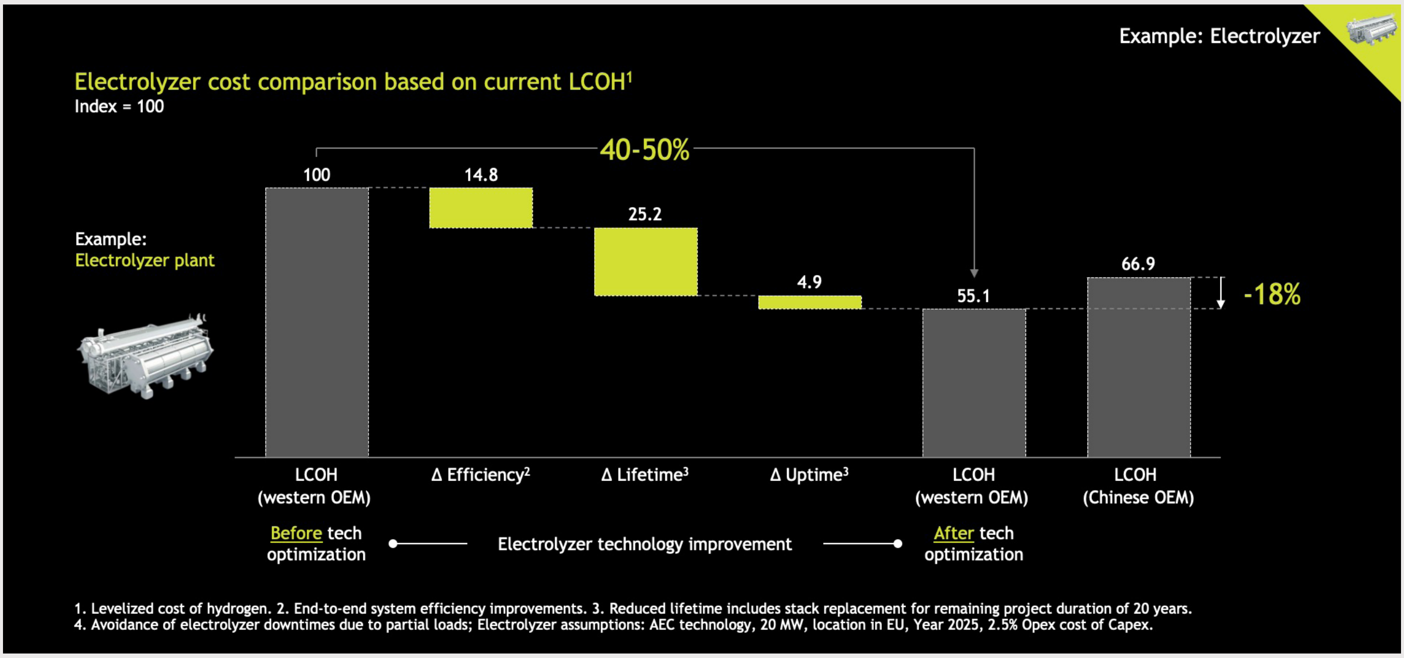
- **Revised hydrogen-related business cases:** Many hydrogen-focused companies—such as fuel cell suppliers, stack providers, and electrolyzer manufacturers—are increasingly struggling to meet their business targets, including budget, revenue, and profit expectations. Delays of three to five years in anticipated revenue uplift have led to increasing diversification of companies to overcompensate for insufficient volumes. Companies must re-evaluate their business models with a focus on technological and economic viability, and market realities. This requires a targeted focus on specific, early demand pockets, customer segments, and regions. Customer-specific willingness-to-pay and key purchasing criteria, as well as close monitoring of regulatory changes in policies and energy market (de-)regulation, is crucial to safely navigating the evolving hydrogen market.

- **Technological edge and materials innovation:** Most hydrogen applications, from production (such as electrolysis) to use (such as fuel cells and H2 engines), are opex-intensive. These applications benefit from reduced consumption, increased efficiency, longer equipment lifetimes, and lower maintenance costs. Electrolyzer stack suppliers and system OEMs offering proven technological advantages can command premium pricing in the coming years. (See sidebar. "Electrolyzer Stack Efficiency and Material Innovation.")

Electrolyzer Stack Efficiency and Material Innovation

Data from public bids for large green hydrogen production plants indicate that Chinese electrolyzer OEMs such as LONGi, PERIC and Sungrow can offer their equipment at prices up to 60% less (for PEM electrolysis) and even 80% less (for alkaline electrolyzers) than established prices in international markets. Our research shows that only around 15% to 20% of this cost differential is explainable by lower labor rates and materials cost. The remainder is competitive pricing for early market testing. From a total cost of ownership (TCO) perspective, however, OEMs with a technological edge—state-of-the-art electrolyzer stack efficiency, longer lifetime and equipment uptime even at partial loads—can reduce the levelized cost of hydrogen by up to 40% to 50%, realizing TCO advantages of an average 18% for their operators (see Exhibit A).

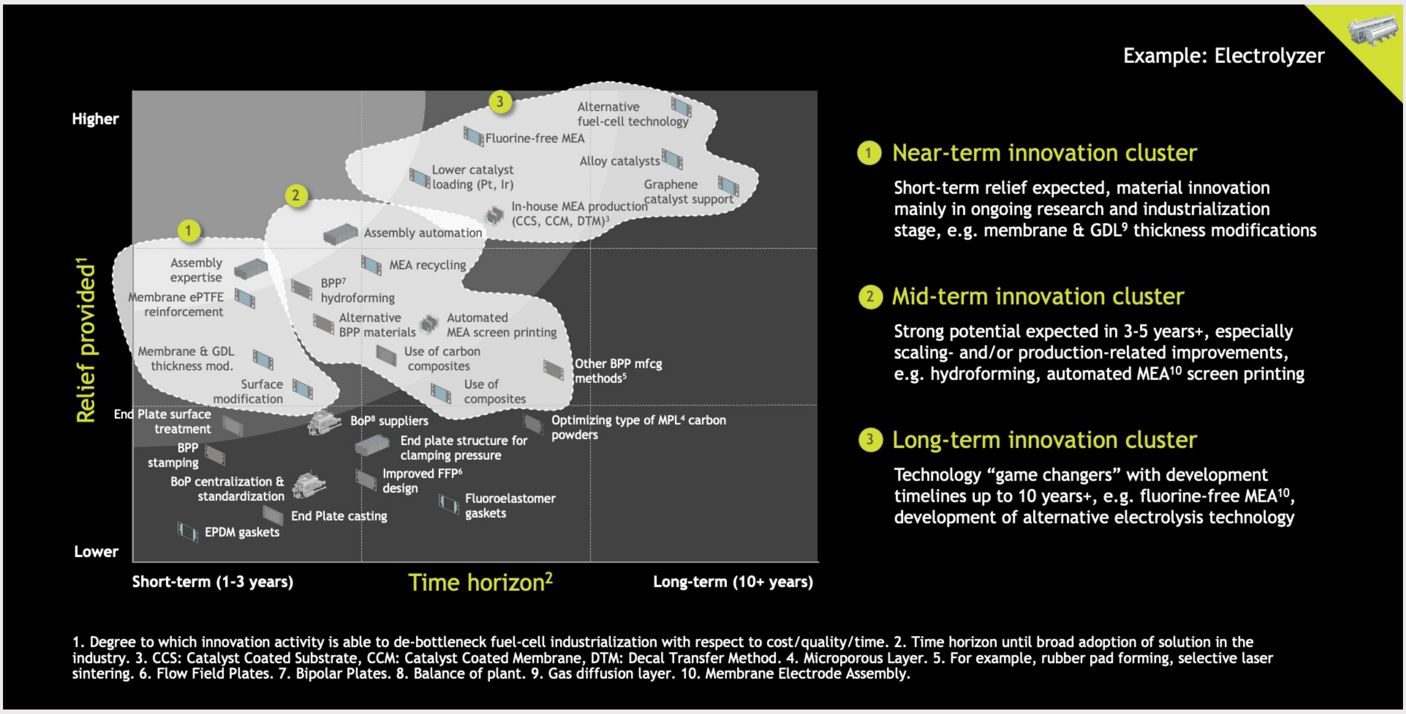
Exhibit A | Advances in Electrolysis Technology can Reduce the Levelized Cost of Hydrogen (LCOH) by up to 40% to 50%



Source: Technical spec sheets; BCG analysis

Material innovation offers another opportunity for differentiation, particularly at the stack level for electrolyzers and fuel cells. Key innovations include reducing the use of platinum-group metals (PGMs), such as iridium and platinum, used as catalysts in PEM electrolyzers. Given that PGMs are often mined as by-products, and the iridium supply may face bottlenecks in the 2030s, lowering PGM content can mitigate supply risks and reduce costs. While eliminating PGMs or industrializing alternatives is a long-term challenge due to the link between catalyst loading and efficiency, progress continues. Additionally, membranes free of PFAS (Per- and Polyfluoroalkyl substances) and gas diffusion layers such as hydrocarbon membranes are being explored, driven by the EU's plans to ban PFAS materials, which could create a competitive edge for those who master material innovation in this space. Exhibit B highlights opportunities for short-, mid-, and long-term differentiation through material innovation in electrolyzers.

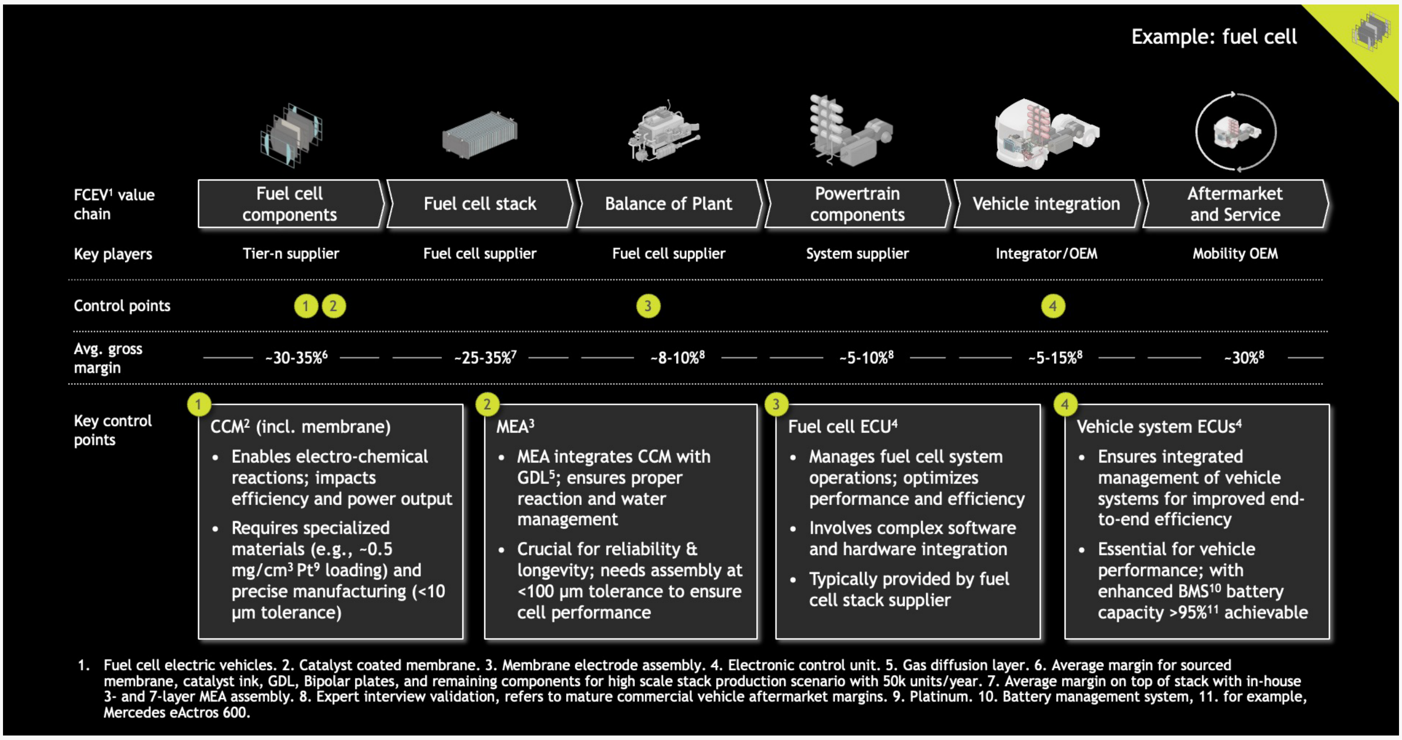
Exhibit B | Short-, Mid- and Long-Term Innovation Emerges to Steadily Improve Electrolyzer Technology



Source: BCG analysis.

- **Integrated hydrogen component and value chain play:** Companies must secure access to key raw materials and components (such as membranes, ionomers, and PGMs) critical to industrializing hydrogen solutions. This can be achieved through long-term yet flexible supply agreements, reduced material usage, recycling strategies, and avoiding single-source dependencies. Players that capture critical control points along the hydrogen value chain—such as in-house production of Catalyst-Coated Membranes (CCMs), Membrane Electrode Assemblies (MEAs), or Electronic Control Units (ECUs)— through in-house production, close partnerships or joint ventures, will be able to control the cost, quality and innovation parameters of their products. Exhibit 5 shows the critical control points for the example of mobility fuel-cells in truck and bus application.

Exhibit 5 | Four Key Control Points in the Mobile Fuel Cell Value Chain



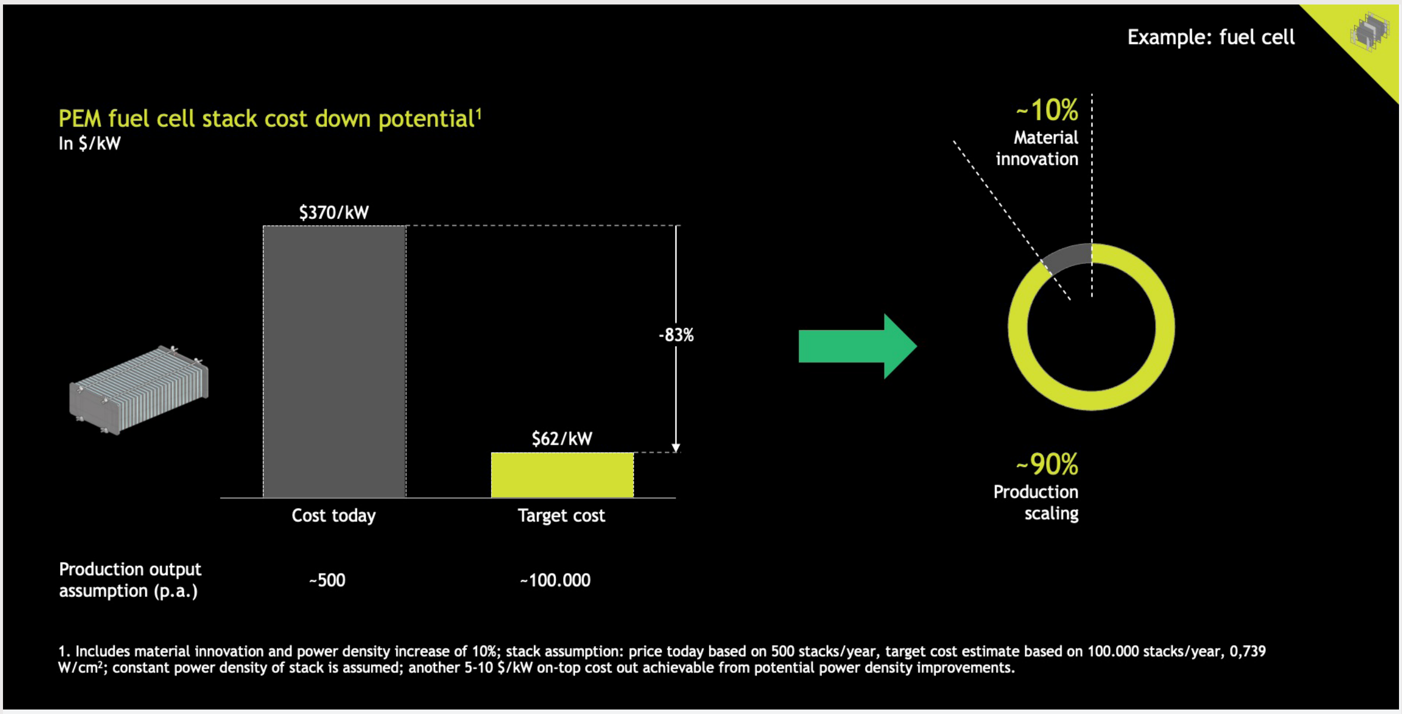
Source: technical spec sheets; BCG analysis

- **Drive 360° cost-out and meet hydrogen price thresholds:** As technology readiness, quality, and reliability mature, the focus must shift toward reducing costs for hydrogen-related equipment through scaled production, innovation, and improved technology readiness. While traditional efficiency and cost-reduction measures such as de-contenting, modularization, design-to-cost, and offshoring remain important, there is a growing focus on (gen-)AI-assisted efficiency improvements. AI-enabled tender assistants, digital spend analytics, and next-generation supplier scouting solutions, for example, can significantly accelerate time-to-market, improve win rates, and generally improve the cost position of companies. To meet willingness-to-pay targets for green hydrogen, companies can offer financial guarantees and deploy safety and redundancy solutions to ensure uptime for operators. (See sidebar "Stack-Level Fuel Cell Cost Reduction.")

Stack-Level Fuel Cell Cost Reduction

In fuel cells, for example, we estimate that around 90% of the total cost reduction potential comes from scaling (including increasing output to 50,000 to 100,000 stacks per year, improving cycle time, automating processes, and reducing scrap rates), while around 10% is innovation-driven. Overall, this could result in an 80% to 90% cost reduction at the PEM fuel cell stack level compared to today's baseline, or \$60-\$70/kW vs. about \$370/kW). While this is an optimistic scenario, a cost reduction of around 30% to 40% will be necessary to meet capex corridors of most fuel cell related applications (see Exhibit A).

Exhibit A | Fuel Cell Stacks with Cost-Down Potential of More than 80%



Source: BCG fuel cell cost model, Fraunhofer, DOE Hydrogen Program, NREL, Battelle Memorial Institute, Strategic Analysis Inc.; BCG analysis.

- **Resilient business model and new profit sources:** Companies that maintain flexibility in technology choices (such as PEM, AEC, AEM and SO), target applications for industrial, chemical and others, regions, and business models will be better positioned in a volatile market. Those offering both "stack+" solutions, individual components, and turnkey systems can adapt to various value chain dynamics. In addition, exploring new profit streams—such as value-based pricing, pay-per-use models, financing, leasing, and equipment rentals—can unlock opportunities in a market still hesitant to make capex investments.

- **Ecosystem build and local-for-local partnerships:** Partnerships between strategic suppliers, stack OEMs, EPCs/integrators, and off-takers under risk/benefit-sharing schemes have proved more successful in delivering projects on time, and within budget and quality targets. Companies should refine their ecosystem strategy to leverage collective strengths for mutual benefit. This can include modular pricing models to simplify the interface between OEMs and EPCs, "plant-as-a-product" solutions, and enhanced end-to-end system efficiencies, improving the LCOH profiles of operators.

5. Conclusion: De-risking and concerted micro- and macro-level efforts required

The global hydrogen market stands at a pivotal moment. Europe, the U.S., and China each bring its distinct strengths—but no region has yet cracked the economic code to make low-carbon hydrogen commercially viable. Despite the delays in the anticipated ramp-up, the long-term viability and need for hydrogen-enabled energy production, storage and distribution remains unchanged. Concerted efforts at both the micro-level (industry and company) and macro-level (regulator), driven by collaboration, innovation, and smart regulation, is the key to realizing hydrogen's full potential and securing a sustainable, economically viable solution for all regions. Industries and regulators will have to explore how co-opetition across systems and country borders would benefit their mutual economic interests and promote the low-carbon future.

For companies, it is critical to re-evaluate their business models in light of the recent dynamics explored in this whitepaper. This means focusing their investments on the most viable hydrogen configurations while de-risking their strategies. The levers we've suggested—including flexible technology choices, modular pricing, innovative financing models, and ecosystem partnerships—are essential to making hydrogen solutions commercially viable and competitive. By taking these steps, companies can position themselves for long-term success in a rapidly evolving hydrogen economy.

At the same time, policymakers must strike the right balance. Overregulation or blanket subsidies risk stifling innovation and misallocating resources. Instead, they should focus on creating streamlined, supportive environments that foster targeted technological development and early market adoption, allowing scalable solutions to be proven.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