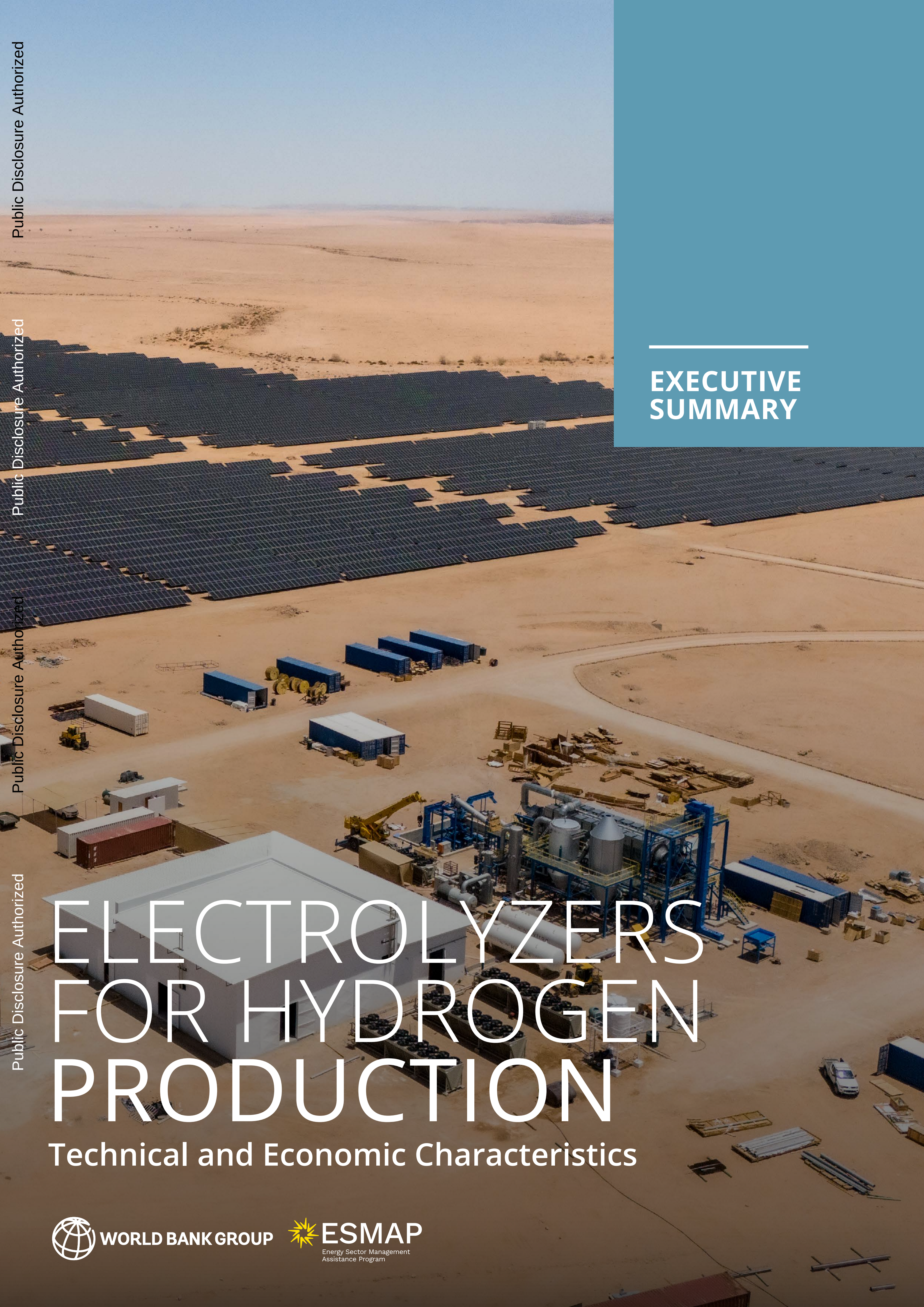

EXECUTIVE SUMMARY

ELECTROLYZERS FOR HYDROGEN PRODUCTION

Technical and Economic Characteristics

WORLD BANK GROUP
ESMAP
Energy Sector Management
Assistance Program

Key Take Aways

Study Context and Market Dynamics

This report is **a state-of-the-art overview of electrolyzer technologies for hydrogen production and their supply.** Prepared under the 10 GW Lighthouse Initiative in support of the United Nations Framework Convention on Climate Change's Breakthrough Agenda, the analysis draws on interviews with more than 50 original equipment manufacturers (OEMs) and project developers.

Electrolyzer demand - Experience with electrolyzers for renewable hydrogen production is growing, but from a low baseline. As of mid2025, approximately 2.15 gigawatts (GW) of electrolyzer capacity was operational worldwide — equivalent to meeting only about 0.2 percent of current global hydrogen demand. A further 16 GW of capacity is under construction, and an additional 3.5 GW has reached FID.

The market is dominated by two technologies: alkaline (ALK) and proton exchange membrane (PEM). In terms of installed capacity, ALK holds a 64 percent share versus PEM's 36 percent. ALK's dominance is more pronounced in the pipeline of projects, where it constitutes 84 percent of projects under construction. PEM represents 11 percent of the capacity to be built. Solid oxide electrolyzer cell (SOEC) and anion exchange membrane (AEM) technologies account for the remaining 5 percent under construction and are emerging as new pathways.

Electrolyzer supply - Global annual electrolyzer manufacturing capacity stands at 61 GW; an additional 16 GW is under construction. Of the existing manufacturing capacity, 43 GW per year (70 percent) is for ALK, while 13 GW (21 percent) is for PEM. The remainder (9 percent) is for other technologies.

A supply-demand imbalance has led to notable manufacturing overcapacity, and many plants are operating below utilization levels. This imbalance has contributed to sectoral consolidation, reflected in recent bankruptcies, restructuring efforts, and merger activity among electrolyzer manufacturers.

Electrolyzer Technologies, Costs, and the Impact on Hydrogen Economics

Several technical factors influence electrolyzer selection and deployment—including system lifetime, compatibility with variable renewable electricity, electrical efficiency, and equipment size. These performance parameters remain dynamic as technologies mature. A clear industry trend across all electrolyzer types is modularization. This design approach improves scalability, reduces installation and balance of plant (BoP) costs, and simplifies maintenance.

However, **integrating electrolyzers with variable renewable energy remains a challenge.** Although PEM systems are technically better suited to handle rapid fluctuations in renewable output, large projects often continue to favor ALK technologies due to their lower cost and greater commercial availability. To manage variability—particularly in off-grid configurations—developers are adopting strategies such as hybrid solar-wind systems and battery storage to smooth power supply and improve electrolyzer utilization.

Electrolyzer CAPEX structure. The capital expenditure (CAPEX) of an installed electrolyzer system consists of direct CAPEX (stack, balance of stack (BoS), and BoP) and indirect CAPEX (engineering, procurement, construction (EPC); installation; and other associated costs). Both components play an equally important role in determining total project cost.

Current cost ranges vary by technology and manufacturing origin. Lowest quoted systems cost in EMDCs range from $800/kilowatt (kW) to $1,000/kW for ALK and from $1,000/kW to $1,200/kW for PEM. However, cost vary widely, with smaller systems often costing substantially more on a perkilowatt basis. SOEC and AEM technologies are currently the most capital-intensive options due to earlier-stage commercialization and lower manufacturing scale. Cost and price information is of limited value as the scope of what is included varies. For example, in-house engineering skills may eliminate the need for an EPC contractor. Also, the after-sales service and technology bankability can be important aspects. As global manufacturing capacity expands and improvements come to materials use, design optimization, and component standardization, **further reductions are expected in installed electrolyzer costs.**

Key drivers of the levelized cost of hydrogen (LCOH). The best projects today can produce hydrogen at around $3 per kilogram (kg), but most projects face higher hydrogen production costs. A robust analysis of the LCOH is essential for any evaluation of technology options. Such an analysis must account for total CAPEX and operational expenditure (OPEX), including costs associated with managing renewable variability.

Electricity is the most significant OPEX and a key driver of project economics. Meanwhile, electricity supply cost and prices are highly dependent on location. The operational flexibility of electrolyzers can enable efficient utilization of low-cost power, which reinforces the need to align technology selection and system design with local energy profiles. Developers are adapting hybrid designs and battery storage. Grid-connected projects that rely on power purchase agreements may face a different situation in terms of electrolyzer choice than projects operating with their own renewable energy assets.

The greatest CAPEX cost reduction opportunities lie not in the electrolyzer stack itself, but in the BoP, construction, and system integration. Indirect CAPEX—especially EPC and building costs—often presents more room for savings than the stack, where most research and development is now concentrated. Cost data for installed electrolyzer systems suggests notable economies of scale. Less established electrolyzer technologies present a higher technology risk and may therefore face higher financing costs unless the risk can be mitigated through warranties, guarantees, or other means.

Recommendations for equipment selection and due diligence

A holistic approach to electrolyzer procurement is essential. Buyers should evaluate systems not only on headline efficiency or stack specifications but also on the full set of technical, operational, and financial factors that determine longterm project value. Key considerations include **clear definition of electrolyze system boundaries; logistics and installation risks; warranty and service structures; feedwater and auxiliary infrastructure needs and finally the OEM performance track record.**

Technology selection should then focus on the attributes that most directly influence project economics and operational reliability: **electrical efficiency and operational flexibility; degradation and stack replacement; technology maturity and bankability and finally equipment reliability.** Project design is also shaped by external constraints. **Financing requirements can limit flexibility in system selection and raise overall project costs** — including the need to use established EPC contractors or proven OEM technologies. In addition, **policy frameworks can influence technology choices**, such as local content rules, manufacturing incentives, or eligibility criteria for public support, and procurement strategies. Continuous capacity building among financial institutions and public stakeholders remains essential to keep pace with rapid advances in electrolyzer technologies.


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Executive Summary

Electrolyzers are the cornerstone technology for renewable hydrogen production. They use electricity to split water into hydrogen and oxygen. When produced with renewable electricity sources such as wind, solar, and hydropower, they bring environmental benefits and opportunities for new economic development and job creation in emerging markets and developing countries (EMDCs).

Each year about 100 million tons (Mt) of hydrogen is produced globally, almost entirely from fossil fuels. Achieving a 10 percent renewable market share would require around 100 gigawatts (GW) of electrolyzer capacity. Demand for electrolyzers is expected to rise as new markets for hydrogen and hydrogen derivatives mature, particularly in ammonia and methanol synthesis, steelmaking, and shipping fuels.

World Bank and partner institutions have issued a report that concluded that installed cost of electrolyzer systems are critical for renewable hydrogen production cost. However better operational and commercial information is needed for electrolyzers (World Bank, 2024). This new report fills that gap.

This report is a state-of-the-art overview of electrolyzer technologies and suppliers. It is written with project developers, investors, and policy makers in mind, the very ones evaluating and facilitating progress toward the final investment decision (FID). The analysis suggests that no single best electrolyzer technology exists. Technology choice must consider end-use application and power supply characteristics, aspects that are further elaborated in this report.

Prepared under the 10 GW Lighthouse Initiative in support of the United Nations Framework Convention on Climate Change's Breakthrough Agenda, the analysis draws on interviews with more than 50 original equipment manufacturers (OEMs) and project developers. These interviews offer new insights that may diverge, at times, from conventional assumptions found in academic literature or social media. Much of this reporting divergence reflects the rapid innovation and lack of harmonized global data.

Electrolyzer Market Dynamics

Experience with electrolyzers for renewable hydrogen production is growing, but from a low baseline. As of mid-2025, about 2.15 GW of electrolyzer capacity was operational worldwide. This capacity has been sufficient to produce just 0.2 percent of global hydrogen consumption. China represents 56 percent of this capacity, while Europe accounts for 20 percent, with EMDCs responsible for smaller shares. Another 16 GW of capacity is under construction, and 3.5 GW has reached FID.

Project sizes are shifting from installations measured in tens of megawatts (MW) to facilities in the hundreds of megawatts range. This shift toward larger facilities is reshaping operational strategies. Utility-scale plants can optimize performance through stack-level cycling within a multi-unit configuration, allowing individual stacks to ramp up or down in response to power availability and maintenance requirements. Such operational flexibility is not feasible at the single-unit level, where system dynamics are inherently more constrained.

The market is now technologically bifurcated, which is to say largely dominated by two technologies: alkaline (ALK) and proton exchange membrane (PEM). In terms of installed capacity, ALK holds a 64 percent share versus PEM's 36 percent. ALK's dominance is more pronounced in the pipeline of projects, where it constitutes 84 percent of projects under construction. PEM represents 11 percent of the capacity to be built. Solid oxide electrolyzer cell (SOEC) and anion exchange membrane (AEM) technologies account for the remaining 5 percent under construction and are emerging as new pathways. Interesting new technologies, not yet deployed at a significant scale, are beyond the scope of this analysis.

Market projections for 2030 have been revised downward this past year. The latest estimates suggest that only 5–20 Mt of operational hydrogen production capacity would be in place by 2030. Considering both operational and pipeline projects—and factoring in the typical timeline from the FID to commissioning—global operational electrolyzer capacity is likely to remain below 100 GW by 2030—unless the sector receives a more streamlined and coordinated policy push.

Electrolyzer Manufacturing Capacity and Supply Chains

Global annual electrolyzer manufacturing capacity stands at 61 GW, with an additional 16 GW under construction. Of the existing manufacturing capacity, 43 GW (70 percent) is for ALK while 13 GW (21 percent) is for PEM. The remainder (9 percent) is for other technologies. The manufacturing landscape is highly regional: China dominates ALK manufacturing (86 percent), while Europe leads PEM production (54 percent). China, though, is also rapidly expanding into PEM, SOEC, and AEM manufacturing as well. It should be noted that country allocation of manufacturing capacity can be misleading as an electrolyzer system is a complex technology with intricate and often international supply chains.

A supply-demand imbalance has led to significant manufacturing overcapacity, and many plants are operating below utilization levels. This imbalance has contributed to sectoral consolidation, reflected in recent bankruptcies, restructuring efforts, and merger activity among electrolyzer manufacturers. Also, when referring to manufacturing capacity, it is critical to distinguish between stack assembly capacity and the ability to deliver fully integrated systems. While stack manufacturing capacity is abundant, bottlenecks persist for balance of plant (BoP) components such as power conversion and gas treatment units. Data also show that supply chain models differ across OEMs. Some manufacturers produce most or all components and materials in-house, while others rely on external suppliers for key parts.

Electrolyzer Technologies

The ALK electrolyzer category itself is diverse and encompasses a range of configurations, each with unique operational characteristics. Pressurized ALK systems, which dominate the market, feature large stacks managed by a single power unit. This design—commonly adopted by Chinese manufacturers—is trending toward even larger stacks to enhance productivity, though logistical constraints such as transport restrict further scaling. In contrast, atmospheric ALK systems offer greater operational flexibility, capable of functioning efficiently at partial loads as low as 10 percent, compared with the 30–40 percent range typical of pressurized systems. A third, more specialized variant—high-current-density ALK systems—uses advanced catalysts to boost output. These systems are produced by only a few OEMs and have yet to demonstrate cost competitiveness at scale and over time.

PEM electrolysis stacks are smaller and better suited for spatially constrained installations, such as for refueling stations. PEM is also highlighted for the way it handles variable renewables. The narrative positioning PEM electrolyzers as the future standard for large-scale hydrogen production is based largely on their perceived flexibility. But this narrative is being reassessed. Despite theoretical advantages, PEM systems have not yet demonstrated decisive performance benefits in practice, and their persistently high capital costs reduce their appeal for many developers. Evidence from large-scale deployments indicates that projects supplied by intermittent renewable power continue to favor ALK electrolyzers. To manage variability in power supply, some developers are adopting hybrid ALK/PEM system configurations, while others are integrating more battery storage to smooth fluctuations, benefiting from plummeting battery costs. At the multi-stack scale, operational flexibility becomes a less critical differentiator, and ALK technology maintains its dominance in the global project pipeline primarily due to its cost advantages. Innovations such as high-current-density cells and advanced membranes are boosting partial load capabilities, while the scaling of pressurized ALK units at both stack and module levels is driving productivity gains. As the market evolves, technology leadership will be defined not by theoretical advantages but by cost-effective, scalable, and proven solutions that meet the demands of industrial deployment.

Emerging technologies like SOEC and AEM systems offer promising long-term potential. SOECs can reduce electricity consumption by 20–30 percent when integrated into industrial processes that provide waste heat. But they must demonstrate greater durability and cost reductions to achieve commercial viability. AEM systems combine high efficiency and operational flexibility—similar to PEM but without precious metals—but they have yet to prove membrane durability at scale. Both SOEC and AEM are approaching commercial readiness, demonstrating superior performance in key strategic deployments. The primary barrier to their deployment is not technology but risk perception among financiers. OEMs are addressing this skepticism through equity participation and better warranty structures for hydrogen projects.

The electrolyzer industry is steadily increasing modularization across all technology types. Modern integrated modules, which typically range from 5 MW–100 MW, combine multiple stacks with shared systems for power supply, gas processing, and water treatment. This modular approach improves scalability, reduces capital and installation costs, and simplifies both commissioning and long-term maintenance.

System efficiency, expressed in kilowatt-hours per kilogram of hydrogen (kWh/kgH2) is a key determinant of the levelized cost of hydrogen (LCOH). Although ALK and PEM electrolyzers generally exhibit comparable initial efficiencies, PEM stacks tend to degrade more rapidly. As a result, stack replacements in PEM systems can represent up to 15 percent of total system costs, with implications for long-term operating expenditures.

Ammonia production remains the largest end-use segment, representing approximately 42 percent of global projects now under construction. Other major applications include methanol production, hydrogen-based direct reduced iron (DRI), and the use of renewable hydrogen in refineries and refueling infrastructure. Each application imposes specific requirements for hydrogen pressure, flow stability, and purity. These factors directly influence electrolyzer selection. For example, some applications benefit from high-pressure output or additional storage capacity, while others, such as ammonia synthesis, generate waste heat that can be utilized by high-temperature SOEC systems to improve overall efficiency.

This diversity of technical requirements underscores that no single electrolyzer technology can be considered universally superior. Optimal technology selection must instead account for the full system context, including end-use application, integration needs, and characteristics of the power supply.

Table ES.1 summarizes parameters for the different technologies. Apart from cost, several other issues must be considered, including life span, variable renewable electricity integration, electric efficiency, and productivity (space). These parameters are somewhat fluid as technologies evolve.

Water, together with electricity, is a fundamental feedstock for renewable hydrogen production. Although the absolute water requirement per unit of hydrogen is modest—and lower than in fossil-based pathways such as steam methane reforming with carbon capture—its operational and environmental significance remains considerable.

While water contributes only marginally to capital and operating expenditures, its availability and quality are critical to sustainable project development. Responsible management of water resources is therefore essential. Project siting must determine local water availability, purity, and the broader ecological impacts of withdrawal and discharge. In water-stressed regions, reliance on groundwater can exacerbate scarcity, underscoring the importance of alternative sourcing strategies. Technologies such as dry-cooling systems, desalination, and the use of brackish water can slash freshwater demand with minimal effect on the LCOH.

High-purity water is also indispensable for maintaining electrolyzer performance. Contaminants can cause irreversible damage to sensitive components—particularly PEM membranes—leading to faster degradation, reduced efficiency, and unplanned outages. As a result, dedicated purification steps are often required to meet stringent feedwater specifications. Despite this dependency, OEMs typically avoid assuming responsibility for water quality management, leaving developers to ensure robust purification and monitoring systems are in place.

TABLE ES1.

Key Parameters of Electrolyzer Technologies at Scale (Cost Data Reflect Global Ranges)

KEY INVESTMENT PARAMETERS				
PARAMETER	**ALKALINE (ALK)**	**PROTON EXCHANGE MEMBRANE (PEM)**	**SOLID OXIDE ELECTROLYZER CELL (SOEC)**	**ANION EXCHANGE MEMBRANE (AEM)**
CAPEX installed system ($/kW)	500–1,500	1,000–2,000	>3,000	>3,500
Annual nonelectricity OPEX as percentage of total CAPEX	2–3%	3.5–5%	>3%	>5%
ELECTROLYZER LIFETIME				
Stack durability (estimated operating hours)	60,000–90,000	40,000–60,000	20,000–40,000	10,000–20,000
Degradation rate	0.1–0.25% per 1,000 hours	0.2–0.5% per 1,000 hours	0.5–1.0% per 1,000 hours	>1% per 1,000 hours (uncertain)
INTEGRATION WITH VRE				
Minimum load (% of nominal)	30% rated load for pressurized ALK; 10% for modern atmospheric ALK	10% rated load	50% rated load	5% rated load
Cold start time (minutes)	30–120	5–0	>360	20–30
ELECTRICITY DEMAND PER UNIT OF HYDROGEN				
Electricity consumption (kWh/kgH$_2$, AC)	51–56	53–56	35–42 (with high-T steam available on site)	51–53 (claims; limited field validation)
ELECTROLYZER'S SIZE				
Typical current density (A/cm^2, stack)	0.23–0.46 (advanced: 0.6–0.9)	1.0–2.0	0.3–1.0	0.5 (emerging)

A = ampere; AC = alternating current; CAPEX = capital expenditure; cm2 = square centimeter; kW = kilowatt; kWh/kgH2 = kilowatt hours per kilogram of hydrogen; OPEX = operational expenditure; T = temperature; VRE = variable renewable energy.

In addition to variable inputs such as electricity and water, the material requirements of electrolyzer technologies also influence system design and technology selection. Different systems rely on distinct inputs—PEM electrolyzers, for example, use platinum group metals such as iridium and platinum, while other technologies require various rare earth elements. Where battery systems are integrated, lithium and related electrochemical materials become additional considerations. Although these materials can affect costs and present localized supply chain risks, previous analyses, including World Bank assessments, indicate that the hydrogen sector's overall material footprint is unlikely to tax the global materials markets.

Electrolyzer Costs and the Impact on Hydrogen Economics

Integrating electrolyzers with variable renewable energy remains a key challenge. Although PEM is better suited for renewable variability, large-scale projects often favor ALK due to cost and availability. Various strategies exist to deal with variability for off-grid systems. Hybrid solar-wind systems and battery storage are increasingly used to stabilize supply. Solar is by far the cheapest form of renewable power available today, in good locations at about USc1/kWh, but generation is limited to daytime. More and more plants are using battery storage in combination with solar power supply. The falling costs of battery-powered energy storage systems allows for economically viable electricity storage for more hours per day—storage that can extend the operating hours of the electrolyzers. Accordingly, fully solar-powered renewable hydrogen generation with ALK is now being considered for some projects. The technical viability of such designs remains to be proven on a commercial scale. Furthermore, innovations such as direct current (DC) coupling of solar photovoltaic (PV) with electrolyzers offer further cost savings.

Electrolyzer CAPEX Structure

The total installed cost of an electrolyzer comprises both direct and indirect capital expenditure (CAPEX). Direct CAPEX includes the stack, balance of stack (BoS), and BoP, while indirect CAPEX covers engineering, procurement, and construction (EPC); installation; and related services. Both categories contribute to overall project costs, and past cost overruns were caused by underestimated or omitted CAPEX components. Broader structural factors—such as inflation, high financing costs, and supply-chain disruptions—continue to place upward pressure on installed costs.

Although central to system performance, the stack typically represents only 20–50 percent of direct CAPEX in modern large-scale PEM and ALK electrolyzer projects. Installation and EPC activities are often the largest cost contributors, accounting for 40–50 percent of total CAPEX, particularly for large projects requiring extensive civil works, permitting, and integration. BoS and BoP elements are also substantial, jointly representing 50–80 percent of direct CAPEX, depending on technology choice and project location.

Significant regional variability persists. Chinese-manufactured ALK systems cost roughly $270–$280/kilowatt (kW) for the domestic market and around $350/kW ex-factory for export, compared with $800/kW ex-factory for ALK systems produced in Europe or the United States. After including logistics, EPC, civil works, and supporting systems such as water treatment, installed ALK costs in emerging markets range from $800–$1,200/kW for Chinese systems and $1,200–$1,800/kW for European systems in EMDCs, with higher costs for small-scale installations. It should be noted that cost and price information needs to be understood in the context of project scope. For example, in-house engineering skills may eliminate the need for an EPC contractor.

PEM systems command a notable price premium due to their reliance on platinum group metals such as iridium and platinum. While PEM offers a smaller physical footprint that can reduce building and logistics costs, this only partially offsets higher stack and component costs. As a result, complete Chinese PEM systems typically cost $700–$1,000/kW, while European systems range from $1,000–$1,600/kW ex-factory. One US supplier offers total PEM installed systems with project capital cost of $1000/kW, based on higher stack power density to reduce material intensity of platinum group metals and modular construction to lower EPC cost. Installed PEM systems to date generally fall between $1,850 and $2,500/kW in China and emerging markets. Regional price variation is lower for PEM than for ALK because PEM systems depend more heavily on globally traded components. The current price range for PEM electrolyzers indicates a substantial cost reduction potential. This will be driven by a number of factors including economies of scale, optimization of catalyst use and stack recycling at the end of life to recover precious metals.

Market conditions continue to evolve rapidly. Recent auction results in China indicate ALK stack and BoS costs as low as $100/kW, excluding BoP. This is around 60 percent below 2022 levels, demonstrating the emergence of highly competitive offers that may not always reflect underlying manufacturing costs.

Among newer technologies, SOEC and AEM systems remain the most capital intensive. Current pilot-scale SOEC installations cost $5,000–$5,800/kW, far more than ALK and PEM systems. Manufacturers report, however, that industrial-scale SOEC and AEM equipment can now be delivered at under $2,000/kW. Further cost reductions can be expected as production capacity expands and component standardization improves.

Across global markets, installed costs in Asia remain lower than in Europe, North America, and Australia. These differences are driven less by electrolyzer hardware and more by soft costs, including EPC, financing, risk premiums, and labor. As the sector matures, project developers are realizing that advanced, high-specification technologies are not always necessary; in many cases, proven and cost-effective solutions are sufficient to accelerate near-term deployment.

Key Drivers of the LCOH

A rigorous assessment of the LCOH is central to evaluating electrolyzer technologies and project feasibility. The LCOH must reflect both total CAPEX and operational expenditure (OPEX), including the costs of managing renewable power variability. The biggest opportunities for cost reduction lie not in the electrolyzer stack, where most research and development (R&D) is now focused, but in the BoP, construction, and system integration elements. Installed-cost data also indicate noteworthy economies of scale as project sizes grow from the megawatt to the hundred-megawatt range.

In most projects, OPEX dominates LCOH, with CAPEX playing a secondary role. The most competitive projects today can achieve hydrogen production costs of around $3/kilogram (kg), but the majority still face higher costs. While technology choice can influence LCOH through efficiency gains or lower power supply costs, the major cost levers sit outside the stack itself. For full system deployments, site-specific and integration-related factors often have a greater impact on economics.

Electricity is the largest OPEX component and the primary driver of project economics. Electricity prices are highly location dependent. Although solar PV can be procured at low cost in favorable regions, electrolyzer operation requires higher capacity factors and minimum load thresholds. This often necessitates a mix of renewable sources, battery systems, or pumped storage, raising the effective electricity cost. Transmission charges can add costs. Global average supply costs typically fall in the 3–5 USDcents/kWh range in good locations but can be much higher. It is therefore essential to align electrolyzer technology, system design, and operating strategy with local energy conditions. Developers are adopting hybrid system designs and battery storage to optimize their access to low-cost electricity. Grid-connected projects operating under power purchase agreements face different cost dynamics than fully self-supplied renewable projects.

Financing conditions also play a critical role. An assessment of the weighted average nominal cost of capital across leading emerging and developing countries (EMDCs) shows a range of 9.4–18.4 percent, making financing strategies pivotal for lowering the LCOH. Less mature electrolyzer technologies carry higher perceived technology risk and may therefore face elevated financing costs unless risks are mitigated through warranties, guarantees, or other risk reduction instruments.

Overall, achieving competitive hydrogen production costs requires a holistic approach: optimizing electricity sourcing and flexibility, minimizing indirect CAPEX, capturing economies of scale, and deploying effective financing and risk mitigation strategies.

Cost Reduction Opportunities

Major reductions in LCOH are expected in the coming years. Because electricity accounts for roughly two-thirds of LCOH, the most immediate cost reduction opportunities lie in lowering the cost of power supply. Strategic site selection, better renewable power mixes, and more competitive battery technologies (which enable greater use of low-cost solar PV) are central to near-term improvements.

Although the electrolyzer stack represents a minority of total system CAPEX, it remains a primary focus of manufacturing innovation. Ongoing R&D aims to decrease the use of precious metals in PEM systems and improve electrical efficiency in next-generation designs, with potential efficiency gains of up to 20 percent.

The largest cost reduction potential, however, lies in the BoS and BoP components. Economies of scale, design standardization, containerization, modular skids, and supply chain consolidation can meaningfully reduce costs. Smaller installations continue to face much higher unit costs, underscoring the strong economic advantages of large-scale deployment.

In EMDCs, cost reduction focuses on easing expenditures on EPC and civil works. While first-of-a-kind projects often require full EPC involvement, experienced developers are reducing total project costs by 20–40 percent by limiting EPC scope or bypassing EPC contractors entirely. Although this approach can lower installed costs, it requires strong in-house engineering capability and close collaboration with equipment suppliers. Lender requirements may still necessitate EPC lump-sum turnkey arrangements where developer capabilities or risk mitigation instruments are insufficient.

Manufacturers worldwide are adopting advanced production methods, including automation and design optimization to reduce stack costs. Meanwhile, digital technologies such as artificial intelligence (AI)-enabled automation, digital twins, and predictive maintenance offer opportunities to lower both CAPEX and OPEX by accelerating commissioning, extending stack life, and improving capacity factors.

Better operational track records, stronger performance guarantees, and more standardized modular electrolyzers will reduce risk premiums and improve project bankability.

Finally, policy frameworks continue to shape electrolyzer markets and cost structures. Local content requirements, manufacturing incentives, and industrial strategies can support domestic production but may hike equipment costs when markets contract. International experience with renewables and other clean energy sectors informs us that innovation, competition, and diversified supply chains remain the most effective drivers of long-term cost reduction.

Commercial Aspects

OEM strategies in the hydrogen-electrolysis market vary in product scope, delivery models, and after-sales commitments. Suppliers range from those offering stack-only solutions to OEMs providing stack + BoS packages to a smaller group delivering full BoP systems that include gas purification, drying, thermal management, water treatment, and site-level integration services. Delivery models also differ. Containerized, turnkey module solutions from the International Organization for Standardization (ISO) dominate small-scale projects, whereas large-scale installations rely on skid-mounted systems and on-site assembly of factory-tested modules.

After-sales offerings likewise vary. Most OEMs provide a standard two-year equipment warranty, with optional long-term service agreements and performance guarantees offered at additional cost. Indicative data suggest that full service contracts may add approximately 3 percent of equipment CAPEX per year. Long-term dependence on OEM support remains a concern, given uncertain supplier viability over 10–20-year project horizons, regional limits on service coverage, and limited multiyear operating track records. In several utility-scale projects, electrolyzer performance has diverged from OEM specifications, although some systems now incorporate supervisory control and data acquisition (SCADA)-based remote monitoring and diagnostics to support maintenance and improve reliability.

Feedback from project developers reveals additional execution-related risks not highlighted in OEM marketing material. These risks include delays in equipment delivery, incomplete technical documentation, and difficulty meeting water purity requirements, particularly for PEM systems, when water treatment infrastructure falls outside the supplier's scope.

These observations underscore the need for a holistic evaluation framework when selecting electrolyzer systems. Key considerations include:

- System boundary definition (stack only vs. BoS vs. BoP)
- Installation logistics and integration risks (containerized vs. skid mounted; factory tested vs. field assembled)
- Warranty depth, service contract cost, and supplier durability over the project life cycle
- Auxiliary infrastructure maturity, including deionized water supply, cooling loops, and gas drying
- Real-world performance track record, including long-term stack degradation and operational reliability

The supply landscape is increasingly globalized. Many North American and European OEMs rely on Asian-manufactured components, while Asian suppliers are expanding production and service footprints in major overseas markets to address local-content requirements and logistical constraints. Although some regional specialization persists, distinctions across supply regions are becoming less pronounced as global supply chains mature.

Recommendations for Equipment Selection and Due Diligence

There is no universal best electrolyzer technology. ALK systems nevertheless show the lowest capital costs with comprehensive offerings. Some suppliers include installation support, which can reduce or even eliminate the need for EPC contractors resulting in potential cost savings.

Regarding the design of hydrogen projects, several factors must be evaluated: total installed cost, operational expenses, technology maturity and risk, the OEM offering in its totality, service and warranty provisions, electrical efficiency, degradation rates, and minimum load capabilities. These parameters are critical in selecting the most suitable technology for a given context.

At present, OEM offerings are not standardized, so due diligence is essential. Policy makers and investors must define system boundaries—such as stack, BoS, BoP, and installation scope. This is crucial for benchmarking CAPEX and for fairly comparing technology providers. Many general reports present cost estimates based on a host of assumptions that can skew conclusions. A harmonized approach to CAPEX benchmarking is needed to support informed decision-making.

Policy interventions also play a role in shaping market dynamics. Measures such as local content requirements for electrolyzers can influence technology selection and pricing. While these policies may support domestic industries, they can also lead to higher equipment costs if not carefully designed.

The analysis suggests that lessons learned from upscaling and cost reduction with other forms of mass manufactured clean energy technologies also apply in the case of electrolyzers. Policy efforts need to focus on technology innovations to reduce electrolyzer cost, strategies that enable integration of low cost renewable electricity, and market support for clean hydrogen and derivatives, using financial incentives and a premium price. At the same time this should be combined with appropriate carbon pricing for conventional hydrogen.

Proprietary databases can provide valuable insights to support informed technology selection. For example, the one operated by Det Norske Veritas (DNV) tracks 165 electrolyzer parameters. These platforms offer detailed, standardized data that can help policy makers and developers assess equipment performance, reliability, and cost-effectiveness.

This report presents a five-step methodology for selecting an electrolyzer supplier, integrating both technology choices and supplier-specific considerations. Figure ES.1 summarizes the approach.

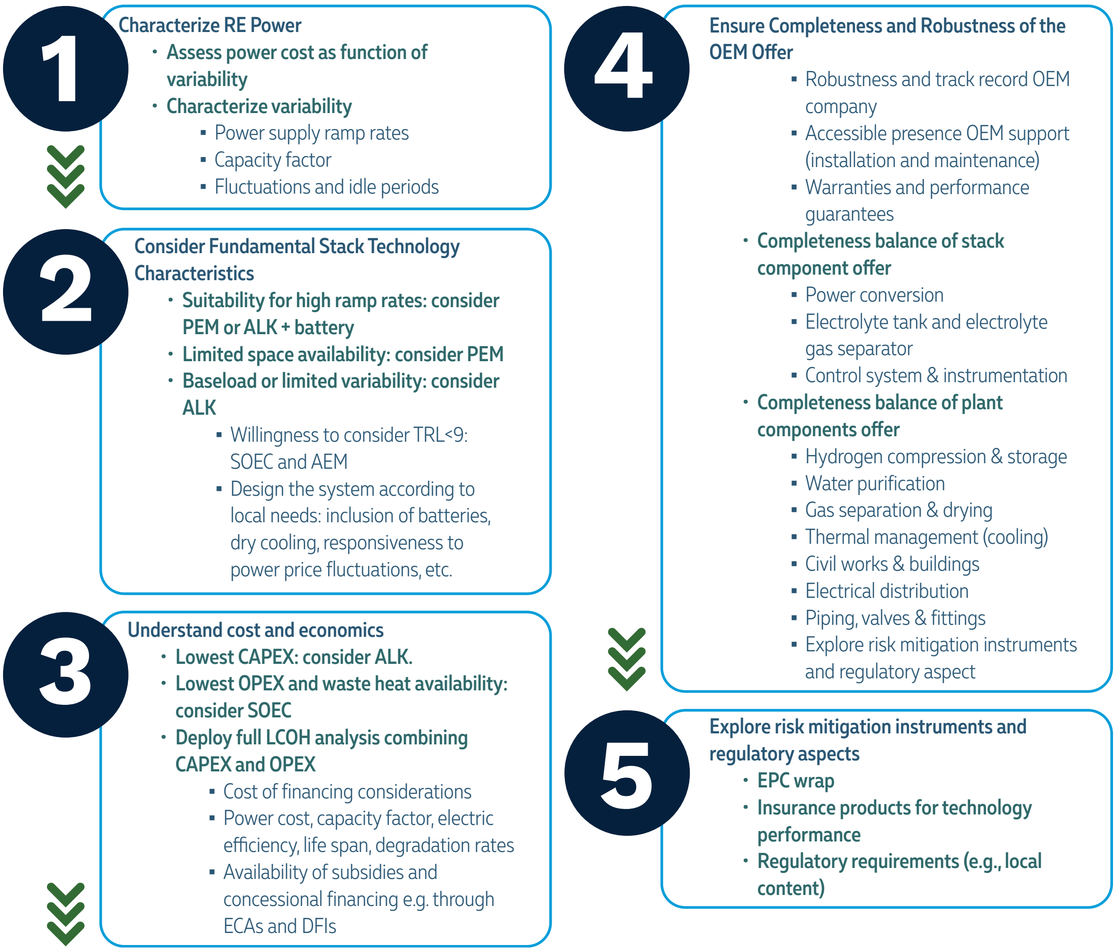
The electrolyzer technology affects CAPEX, OPEX, and revenue streams. When choosing among the various technology options, decision-makers would do well to consider the following factors:

- **Electrical efficiency.** The amount of power required per unit of hydrogen will affect total electricity demand and LCOH.
- **Operational flexibility.** Electrolyzer capability for flexible and intermittent operation can be critical, notably when low-cost variable PV and wind power sources are deployed.
- **Degradation and stack replacement**. Efficiency losses and the cost and frequency of stack replacements are major OPEX components.
- **Technology maturity and bankability.** Limited experience with long-term, large-scale electrolyzer operation heightens project and financing risks. Long-term service agreements, warranties, and insurance instruments are critical as contractual mitigants.
- **Equipment reliability.** The performance and reliability of OEMs vary widely across a range of factors that include scope of supply, after-sales service, warranties, and performance guarantees.
- **Financing constraints.** Commercial banks and development finance institutions often impose eligibility requirements like the use of EPC contractors or proven OEM technologies. These restrict how project design addresses the concerns of demand flexibility and energy efficiency. They also affect the cost structure of projects, increasing costs.

- **Policy framework.** The choice of equipment manufacturing location may also be affected by local content requirements, subsidies, and other support policies. Finance institutions require continuous capacity building and regular knowledge updates so they can stay abreast of technology innovations.

FIGURE ES.1

A methodology for selecting electrolyzers



1

Characterize RE Power

- **Assess power cost as function of variability**
- **Characterize variability**
  - Power supply ramp rates
  - Capacity factor
  - Fluctuations and idle periods

2

Consider Fundamental Stack Technology Characteristics

- **Suitability for high ramp rates: consider PEM or ALK + battery**
- **Limited space availability: consider PEM**
- **Baseload or limited variability: consider ALK**
  - Willingness to consider TRL<9: SOEC and AEM
  - Design the system according to local needs: inclusion of batteries, dry cooling, responsiveness to power price fluctuations, etc.

3

Understand cost and economics

- **Lowest CAPEX: consider ALK.**
- **Lowest OPEX and waste heat availability: consider SOEC**
- **Deploy full LCOH analysis combining CAPEX and OPEX**
  - Cost of financing considerations
  - Power cost, capacity factor, electric efficiency, life span, degradation rates
  - Availability of subsidies and concessional financing e.g. through ECAs and DFIs

4

Ensure Completeness and Robustness of the OEM Offer

- Robustness and track record OEM company
- Accessible presence OEM support (installation and maintenance)
- Warranties and performance guarantees
- **Completeness balance of stack component offer**
  - Power conversion
  - Electrolyte tank and electrolyte gas separator
  - Control system & instrumentation
- **Completeness balance of plant components offer**
  - Hydrogen compression & storage
  - Water purification
  - Gas separation & drying
  - Thermal management (cooling)
  - Civil works & buildings
  - Electrical distribution
  - Piping, valves & fittings
  - Explore risk mitigation instruments and regulatory aspect

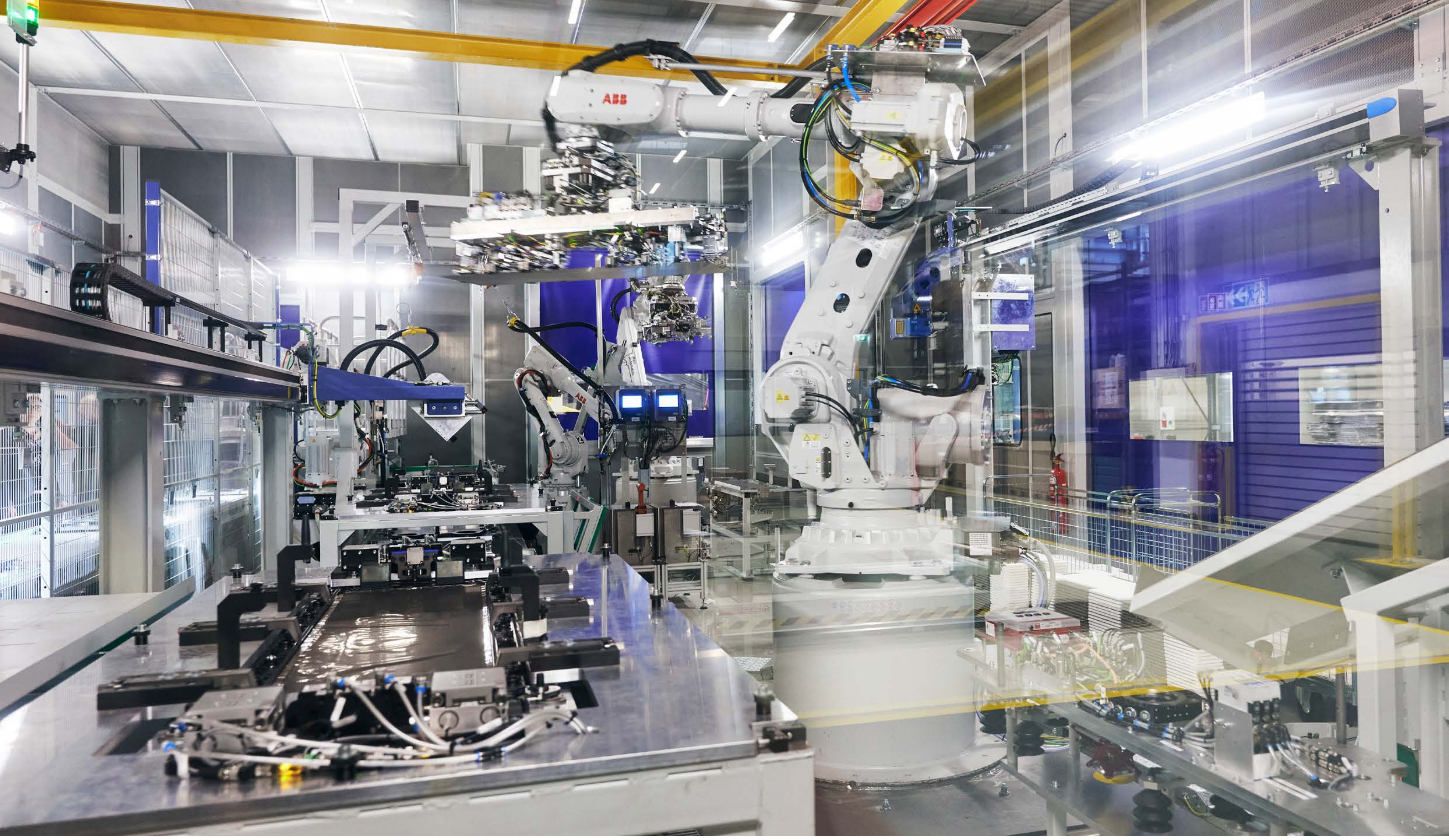
5

Explore risk mitigation instruments and regulatory aspects

- **EPC wrap**
- **Insurance products for technology performance**
- **Regulatory requirements (e.g., local content)**

Source: World Bank staff analysis.

Note: AEM = anion exchange membrane; ALK = alkaline; CAPEX = capital expenditure; DFI = development finance institution; ECA = export credit agency; EPC = engineering, procurement, and construction; LCOH = levelized cost of hydrogen; OEM = original equipment manufacturer; OPEX = operational expenditure; PEM = proton exchange membrane; RE = renewable energy; SOEC = solid oxide electrolyzer cell; TRL = technology readiness level.



Caveats and Future Research

This analysis provides only a snapshot of a fluid technology. There is growing recognition that as the sector develops, standardized and quality information will be critical. The validity of information available today is not always clear and often contradictory. The paucity of real-world, large-scale, and multiyear applications make it difficult to issue definitive statements about technology choices. While commercial databases can support due diligence, there is limited performance information in the public domain. But as more projects come on stream, the situation will improve. The analysis highlights the capability to integrate variable renewables as a key factor. A lot of electrolyzer system innovation targets better integration, allowing systems to tap into low-cost renewables. Monitoring new system design performance is warranted. Costs are also changing rapidly, so continuous monitoring and benchmarking will be needed to assess the latest progress so decision-makers can interpret the available information correctly.

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