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Water Electrolysis Facing the Gigawatt Challenge—Comprehensive De-Risking of Proton Exchange Membrane and Anion Exchange Membrane Electrolyser Technology

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1 | Opportunity—A Green Hydrogen Economy

Green Hydrogen (H_2) stands out as a climate-friendly fuel with the potential to de-fossilize several high carbon-emitting sectors, such as transportation and heavy industries, the chemical industry including ammonia synthesis, steel manufacturing and cement production as prominent examples [1–7]. Furthermore, H_2 can be used in de-carbonizing electric power supply by generating electricity using Hydrogen-capable combustion turbines or directly by fuel cells [8, 9]. Finally, H_2 is considered as an energy carrier to enable global energy logistics; that is, the storage, transportation and distribution of large amounts of energy [10–12]. Due to its versatile applications in the energy transition, the production of affordable and green H_2 defines a focal point of many research and industrial endeavours.

From a system perspective, green Hydrogen enables the coupling of different industrial key sectors [13] in terms of an 'integrated energy scenario,' as schematically illustrated in Figure 1. As demonstrated, H_2 can generally be produced either from fossil feedstocks, including natural gas, raw oil and coal, or from renewable feedstocks by water electrolysis and from biomass. If renewably generated electricity is used for electrolysis, 'green' Hydrogen can be obtained directly from feed water.

Today—in an existing 'grey' Hydrogen economy—the primary demand for Hydrogen is as a chemical feedstock in petroleum refining and ammonia production [15]. In the future, green Hydrogen may replace grey Hydrogen, to reduce the carbon footprint, termed as 'feedstock-shift'. Furthermore, Hydrogen can also be used to provide thermal energy in conventional heating applications, such as residential and district heating [16, 17], as well as high-temperature industrial processes in the steel or glass industry [18, 19]. Additionally, Hydrogen can be re-electrified on a large scale using H_2-ready gas turbines in gas power plants and on a smaller scale in fuel cells for applications as backup power or as easily dispatchable remote power. Hydrogen also finds increasing use as an emerging application for heavy-duty/long-distance transportation [20–23].

An anticipated demand for Hydrogen in the above sectors will come in consecutive phases: in the short term from 2025–2030, the demand will be driven by industrial hubs using Hydrogen as feedstock, such as chemicals, fertilizers, or petrochemical products. In the medium to long term from 2030–2040, the demand will be extended to new use cases of Hydrogen as an energy carrier, such as in the transport and power generation sectors. In the very long term from 2040 onwards, a continuously increased global trade of Hydrogen is expected as a result of growth in the medium- to long-term use cases.

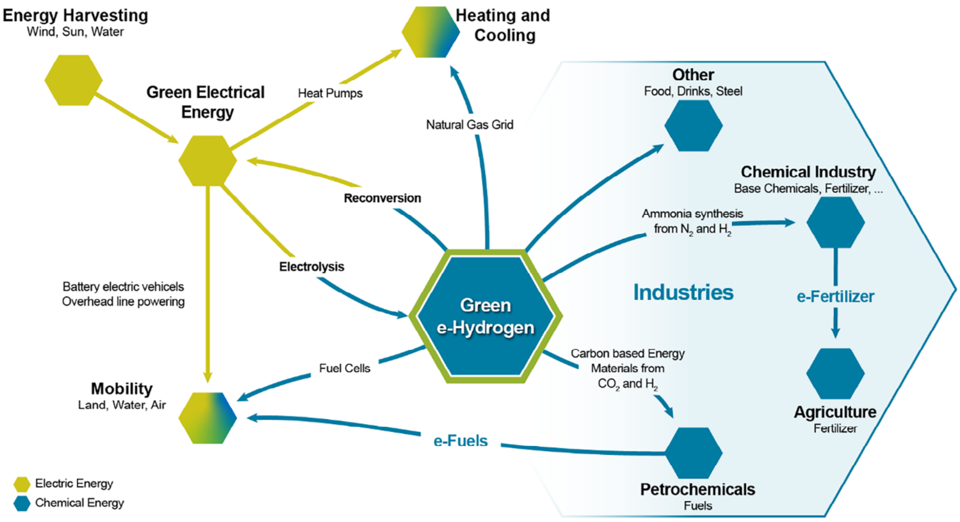

FIGURE 1 | Hydrogen as an energy carrier to enable integrated energy ('sector coupling') scenarios. Adapted from [14].

Hydrogen also offers a significant flexibility option, in terms of the ability to be used as a dispatchable load or power generation source, offering system optimization potential when operating large-scale electrolysers in grid- or system-support operation [24, 25].

2 | Vision—Global and National Hydrogen Strategies

Globally, climate change mitigation initiatives, such as the U.S. National Clean Hydrogen Strategy and Roadmap [26] aim to catalyse the adoption of a green Hydrogen economy. Globally, there were more than 1000 large-scale clean and low-hydrogen projects announced in recent years, 800 of which plan full or partial operation by 2030, as illustrated in Figure 2 [27]. Although the total investment in these projects is estimated to be around US$320 billion, only $29 billion—that is less than 10%—has passed the final investment decision (FID). More generally, consensus is achieved about the potential of Hydrogen by industries. On the other hand, final investment decisions are often delayed because green Hydrogen technologies are considered of being expensive and not yet fully 'de-risked.'

In a national context, the German government has released a Hydrogen strategy for H_2 production and usage in Germany for 2030 [28]. Green Hydrogen is considered as 'tomorrow's oil' with the potential not only to launch the next stages of the energy transition but also to secure a promising growth market in several industrial sectors as outlined before. Currently, 120 national Hydrogen projects are in planning, under construction or already in operation, providing around five gigawatts of electrolysis capacity. In operation, however, are 33 electrolysers with a capacity of 62 MW [29]. By 2030, this number will rise to 111 systems with a total capacity of 8712 MW, according to current plans.

There is hence a significant need for additional electrolysis capacity to be installed. The corresponding ramp-up, however, is a complex procedure that must generally be divided into a technology and a production ramp-up, as schematically depicted in Figure 3.

Prior to technology and production ramp up, a technological development phase comprises the development of suitable materials, compounds, cell and module architectures, as well as the system layout. The technology development phase ends with a preliminary design freeze and if the achievable key performance indicators fulfil the necessary goal specifications, the approval of pilot plant production is given.

In the following 'technology ramp-up' phase, pilot plants at a relevant scale are built, together with performing a comprehensive technology de-risking. This de-risking process is performed in parallel with an adopted operational mode design, including exploring the boundaries for a safe operation at high performance and low degradation rates. Most importantly, the de-risking process involves extensive pilot plant testing at scale, which has not been possible in earlier technology development phases. After the first pilot plant de-risking iterations have been made, possible imperfections and failures in the design of the electrolyser become apparent and systematically enable necessary modifications. Consequently, the more effort is put into de-risking, the more efficient the following manufacturing will be in terms of time and cost.

The 'production ramp-up' phase is next, which encompasses the setup of a production system. During this phase, production gradually increases from low production rates with a high share of manual work towards a fully automated series production at required production rates. The production generally builds upon the significant body of knowledge developed during the de-risking phase. Design changes in this stage can be motivated by manufacturability issues, but also driven by novel technical advances or improvements regarding sustainability as long as profitability for the overall process can still be ensured.

Being a generally more mature technology that is actively being adapted to series production, PEM electrolysers can be placed between the "technology ramp up phase" and the "production

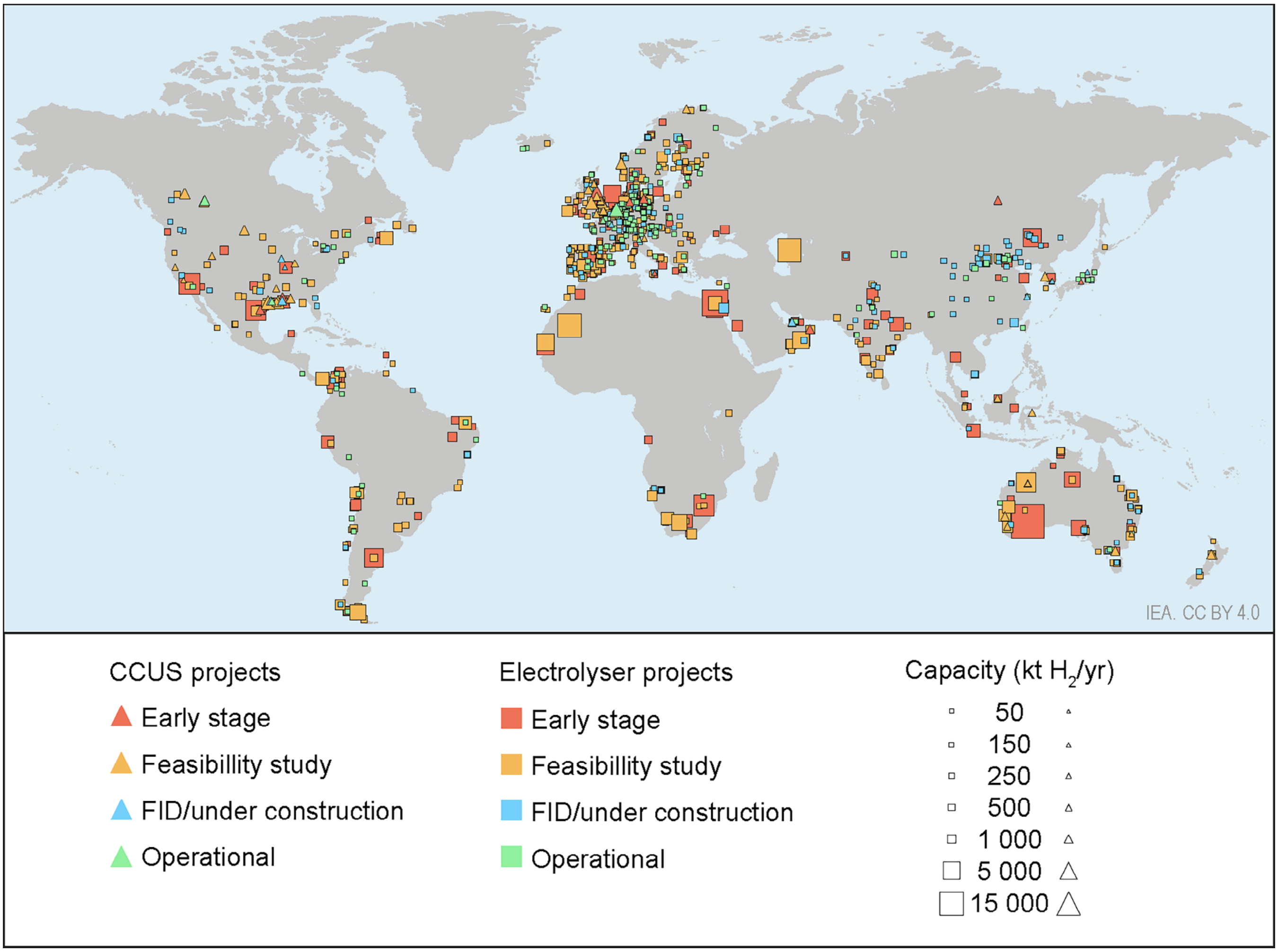

FIGURE 2 | Global map of announced Hydrogen production and "Carbon Capture, Utilization and Storage" (CCUS) projects in 2023. Taken from [15].

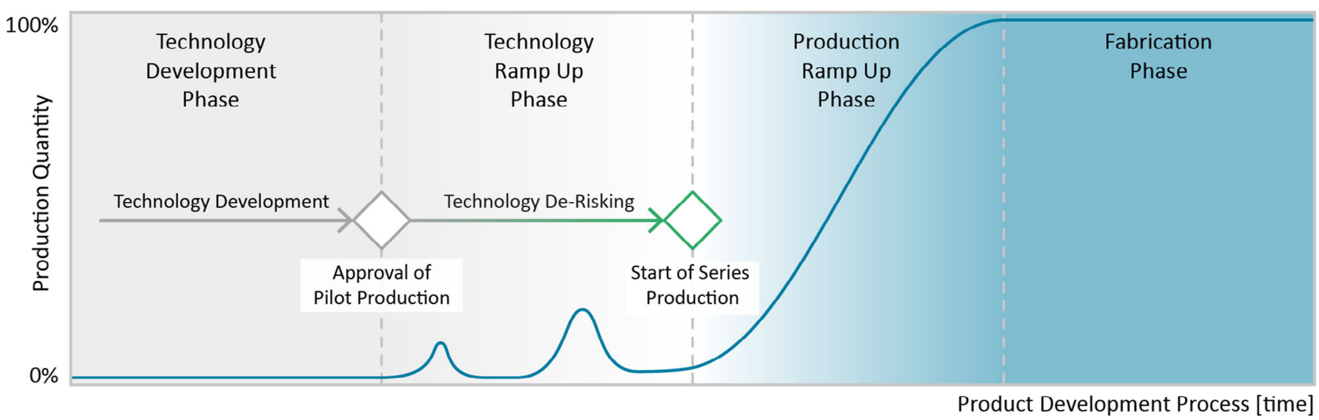

FIGURE 3 | Schematical illustration of technology and production ramp-up scenarios, with comprehensive technology de-risking as inherent gate for passing from technology to the market ramp-up phase.

ramp up phase" section. AEM electrolysers on the other hand still face more challenges, especially regarding upscaling of the technology, which places them currently between the "technology development phase" and "technology ramp up phase". In conclusion, the more comprehensive the understanding of the electrolyser technology, the more predictable and quicker a production ramp-up can be achieved.

The attainable acceleration in electrolyser scale-up is important not only from a climate perspective but also provides marked

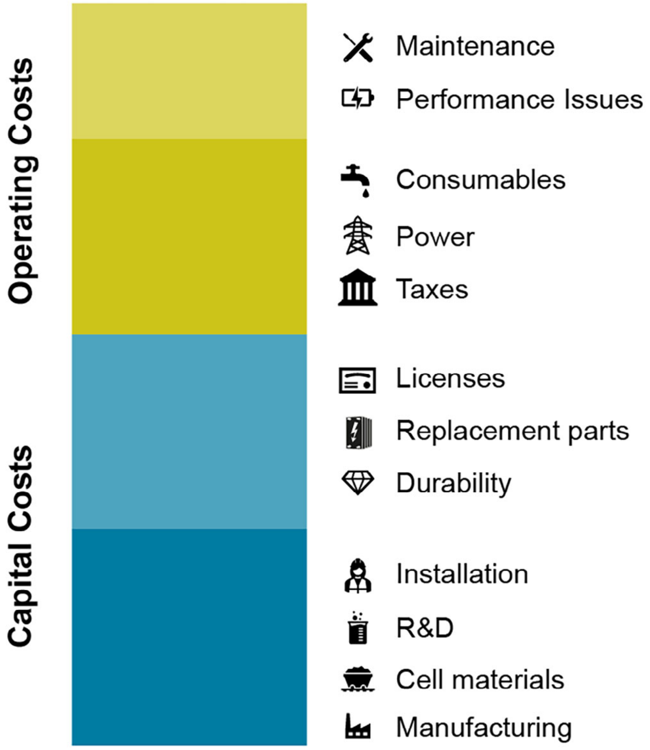

FIGURE 4 | Key contributors to capital and operating costs of electrolysis. Adapted from [30].

importance for technology companies, as time-to-volume directly affects the financial success of a product. A successful technology de-risking cycle leads to a frictionless production ramp-up and thus a faster widespread implementation electrolyser technologies.

3 | Mission—Technology De-Risking

There are several factors hindering the development of electrolyser projects and slowing down investment decisions. In particular, Hydrogen production costs are central to market adoption. In that context, the primary factor is the high total cost of ownership associated with water electrolysers [30]. A corresponding cost breakdown is illustrated in Figure 4.

To approximately equal parts, the total cost of ownership consists of contributions from electrolyser durability, materials and components, operational cost, as well as maintenance and infrastructure. In principle, one approach consists in further developing next-generation materials for electrocatalysts, membranes, or (metallic) cell components to reduce both capital and operating costs. However, given the urgent time frame imposed to ramp up climate change mitigation technologies, this approach is tentatively not synchronized with the technology ramp-up needs. Alternatively, enhancing durability on basis of the currently available electrolyser layout is key to reduce CAPEX and thereby reducing the total cost of ownership.

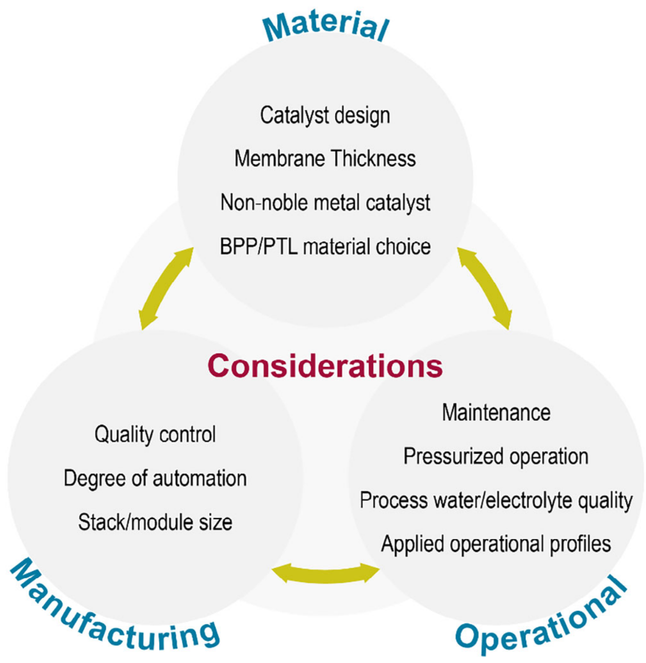

FIGURE 5 | Several examples of material, manufacturing and operational considerations affecting CAPEX and OPEX for water electrolysers.

3.1 | Electrolyser Durability and Cost

Considering the above-mentioned research approaches to improve electrolyser performance—and thereby reducing both operational expenditure (OPEX) and capital expenditure (CAPEX)—in terms of catalysts, membranes, and (metallic) cell components, there exist several frameworks and aspects that can be optimized. Underlying is however a complex interplay of often counteracting factors affecting both cost and long-term stability when trying to reduce the expenditure or improve the efficiency. A listing of several examples of these necessary considerations is shown in Figure 5.

For example, in PEM electrolyzers, when reducing the amount of Iridium in terms of nano-structured catalyst particles, the electrocatalytically active interface might be enhanced, which can increase the catalytic activity and thus the overall performance [31–33]. However, at the same time, the durability of the catalyst layer is typically reduced, owing to particle coarsening or catalyst dissolution [34, 35]. Analogously, iridium might be replaced by various non-noble electrocatalyst compositions, which have reported superior short-term performance, but to date have failed in maintaining performance for long-term operation [36].

Optimization potential also lies in decreasing the membrane thickness, by which the current density can be increased [37]. In case of PEM electrolysis, thinner membranes have another advantage by reducing the amount of deployed PFSA material, reducing the resource cost and minimizing the use of a critically discussed material. Additionally, transient and discontinuous load profiles become more feasible. However, thinner membranes generally result in accelerated membrane degradation, which reduces electrolyser durability [38, 39].

So, in the case of these two examples, increased performance by variation in catalyst layer and membrane thickness can result in a reduced OPEX but simultaneously tends to reduce durability which results in an increased CAPEX. Further strategies to reduce OPEX consider pressurized operation or adjusting feed water quality. While pressurized operation will reduce the OPEX, it can have an adverse effect on electrolyser durability, thus increasing the CAPEX indirectly. Higher quality feed water/electrolyte however increases the OPEX, due to higher costs for for example, water purification, but can have beneficial effects on long-term operational stability. Often trade-offs between two counteracting factors need to be considered in order to find a 'pareto optimal' state for the most efficient manufacturing and operation of electrolysis plants.

Another much more general consideration is the choice of electrolyser technology in the first place. In alkaline or AEM electrolysers for example, the use of noble metal catalysts can be in principle avoided, leading to a much lower material cost and thus lower CAPEX compared to PEM electrolysis, at least initially. However, PEM electrolysers can typically run at higher current densities compared to alkaline/AEM electrolysers which in turn leads to a lower OPEX for PEM electrolysers. Also, the more compact balance of plants and faster response time in varying load conditions can necessitate the use of a PEM electrolyser in some cases.

In conclusion, enhancing durability is key to reduce electrolyser CAPEX, while improving the overall efficiency and the operational profiles are key to reduce electrolyser OPEX. Both are essential for reducing the total cost of ownership of electrolysers regardless of technology. But also, the general choice of electrolyser technology needs to be considered in each case, since different applications can weigh CAPEX, OPEX and general durability of the electrolyser differently.

3.2 | Degradation Accelerators

For industrial applications, electrolysers must guarantee a sufficient lifetime with stable and safe operation, which can be in some cases much longer than typical testing protocols cover. Accordingly, there is an urgent need to develop accelerated stress test protocols, which in turn have to be based on a fundamental and holistic understanding of degradation mechanisms over several scales from the material to the module. The current understanding typically considers catalyst dissolution, membrane chemical decomposition, and corrosion of metal components as the main degradation mechanisms, as schematically depicted in Figure 6.

Catalyst dissolution, especially of the anode catalyst, is one of the most prominently discussed degradation mechanisms for PEM electrolysers. Due to the harsh reaction conditions at the anode and the water splitting reaction being the rate-determining step for the overall reaction due to the comparatively sluggish kinetics of the oxygen evolution reaction, it is often discussed as the main driver for PEM electrolyser degradation [40, 41]. Besides this mechanism, another often discussed, and also previously mentioned, the mechanism is the degradation of the PFSA membranes, typically Nafion and similar derivatives. Impurities from the feed water, for example, iron, can lead, together with in situ generated Hydrogen peroxide, to chemical reactions with the polymer, typically assigned to a reaction mechanism analogous to the 'Fenton reaction,' that can lead to membrane thinning [42, 43]. Lastly, the corrosion or passivation of the bipolar plates or porous transport layers is also often mentioned as a source of device degradation [44].

These degradation mechanisms can generally be accelerated or are caused in the first place by 'stressors' such as contaminated feed water, inappropriate operation at high current density, transient load operation, and uncontrolled hard shutdown cycles [45, 46]. More generally, there are different operational requirements for large-scale electrolysis depending on the system layout and integration, which in turn will favour one stressor over another. Accordingly, degradation pathways will be a function of operational mode and cannot be generalized [47]. In that regard, it must be distinguished between an electrolyser integrated into an electrical grid or into an energy-intense industrial environment.

From an energy system perspective, a large-scale electrolyser provides a significant electrical load, which can be actively used for either 'grid- or system-support' operational strategies by the electrical grid operator. A grid-support operation aims to avoid grid bottlenecks in terms of voltage and frequency control, whereas a system-support operation provides primary, secondary and tertiary reserves to stabilize the electrical grid. Correspondingly, electrolyser operation modes include transient (i.e., voltage and current steps) and dis-continuous (i.e., start–stop cycles), as indicated in Figure 7a.

Contrary to an energy system perspective, an industry perspective requires operational strategies to minimize the levelized cost of H_2 production, which is provided in a 'market-support operation' scenario. Accordingly, electrolysers are transiently operated under part and full load according to the electricity spot price; if un-used (stranded) renewably generated power is available in the grid, the electricity prices are lower and the electrolyser operation is ramped up. Vice versa, the electrolyser is ramped down at low availability of renewable electricity and accordingly high prices. A corresponding load profile is depicted in Figure 7b.

3.3 | Accelerated Stress Testing

Given the above-listed impact of stressors on the electrolyser lifetime, accelerated stress tests can be developed by selectively imposing electrolyser systems to increase stressors. The first approach to develop suitable accelerated stress tests for PEM electrolysis attempted to transfer protocols from PEM fuel cells [50, 51]. A direct transfer is not possible, as the accelerated stress tests are more commonly related to bus and passenger car drive cycles than to electrolyser operation scenarios. Furthermore, degradation phenomena for fuel cell operation can differ from those relevant to electrolyser operation. An accelerated stress protocol involving high-power and transient operation for the electrolyzer mode has therefore most recently been proposed, including the stressors high current density and dis-continuous operation [52]. A suggestion for a corresponding accelerated stress protocol is illustrated in Figure 8.

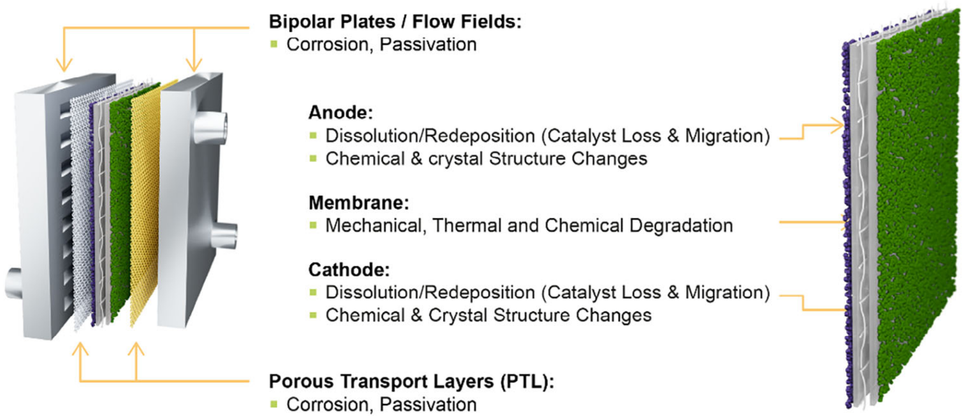

FIGURE 6 | Most relevant degradation phenomena in proton/anion exchange membrane electrolysis, broken down by individual components.

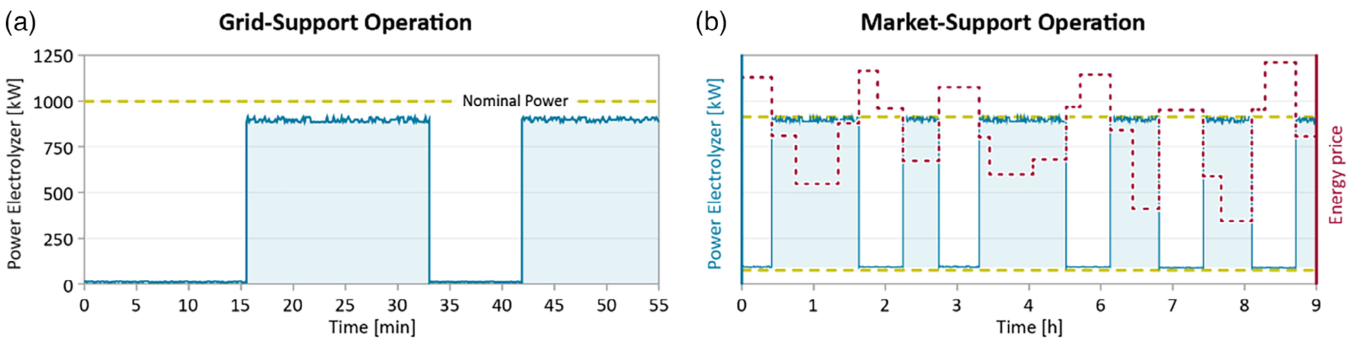

FIGURE 7 | Generic representation of elementary discontinuous and transient load profiles for a grid-support (a) and a market-support (b) operation. Adapted from [48] and [49].

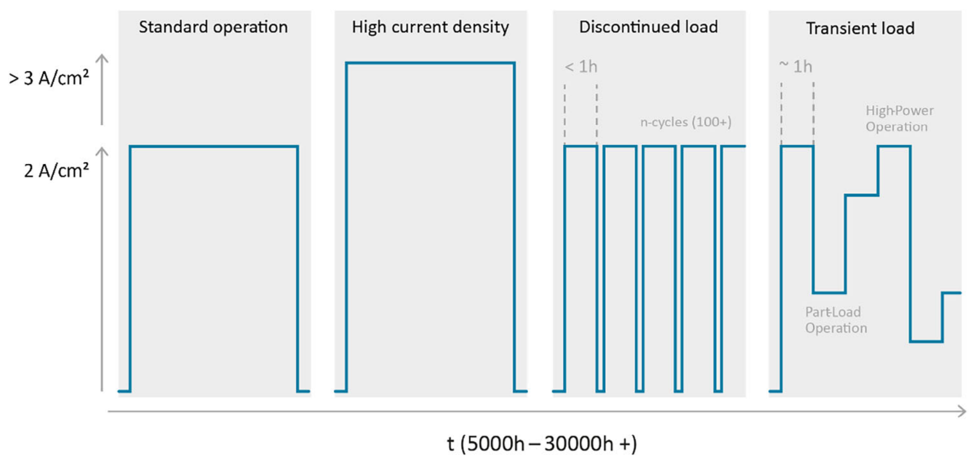

FIGURE 8 | Status-quo of load profiles for accelerated stress testing for PEM-electrolysis.

Feedwater impurities as an important stressor, which typically impose membrane poisoning-related degradation mechanisms [53], have not yet been considered for accelerated stress test protocols so far. More importantly, also scaling effects associated to cells in fully industrial-relevant height and electrolysers containing all relevant system components, which require the consideration of field data from industrial-scale electrolysers, have not been published so far. It is therefore crucial to correlate and validate accelerated stress test results to those obtained from long-term operation experiments at the megawatt scale from field data.

3.4 | Comprehensive Electrolyser De-Risking

Taking into account the above-derived importance of improving electrolyser durability, a comprehensive technology de-risking stands out in research needs for scaling up water electrolysis.

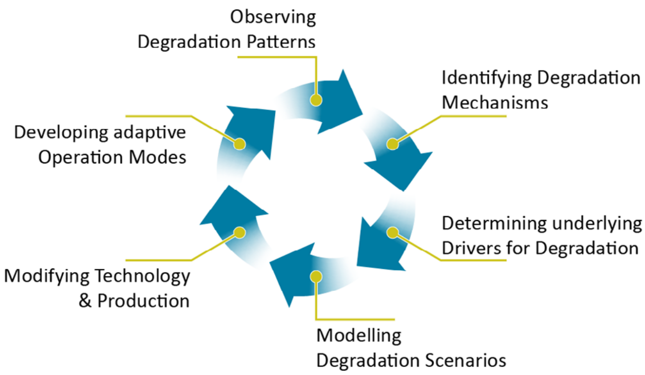

FIGURE 9 | Concept of a comprehensive technology de-risking workflow.

To accurately predict the effective operation hours (EOH) of an electrolyser, and in perspective also to adopt load profiles during operation of an electrolyser to extend EOH, as well as to provide data for accurate business cases determination to reliably prepare investment decisions, a comprehensive de-risking approach has no alternative and is a necessary prerequisite. A comprehensive de-risking workflow consists of a holistic approach, as schematically represented in Figure 9.

A comprehensive de-risking workflow needs to start with testing electrolysis operations on a large enough scale in order to represent actual devices used in the industry of for grid stabilization purposes. Degradation patterns which are observed in such tests need to be studied in depth in order to identify degradation mechanisms and determine underlying drivers for degradation. This could be done in principle by a purely data-driven machine learning approach through applying a wide matrix of operational and material parameters to a dedicated test rig or studying a wide enough array of in-field operated electrolysis plants, but for a true understanding of the mechanistic intricacies, it would be most sensible to support this by employing advanced analytical characterization techniques on post-test samples with methods such as X-ray computed tomography, scanning electron microscopy or nuclear magnetic resonance, just to name a few. The information gained this way can be used to set up a knowledge-based degradation model to assess the performance of the device over time. The data can also be used to adjust and validate physics-based models of the electrolysis cell or system which paves the way for building up a robust digital twin to extract potential failure mechanisms before electrolyser operation. With all this knowledge both the technology itself and the production, as well as the operational strategy can be adjusted in order to provide a more stable and efficient long-term operation. This process can be used iteratively to further optimize and de-risk the technology which allows building a robust business case and makes the decision for making investments easier for potential stakeholders.

In this topical issue, we address the most relevant contributions to a comprehensive de-risking of PEM and AEM electrolysis. This begins with fundamental research into novel catalyst materials for the next generation of PGM-free AEM electrolysers and developing novel insights into state-of-the-art materials with advanced electrochemical characterization using carbon nanoelectrodes as local voltammetric pH sensors. On a device level, the important impact of different conditioning protocols on PEM electrolyser performance is studied and novel atmospherically plasma-sprayed microporous layers are used in order to improve the electrolysis performance by using optimized porous transport layer designs. Of special interest for AEM electrolyser operation are so-called “dry cathode” approaches for which a short overview of the current state of research is given. Besides experimental work, the modelling of electrochemical cells is also of utmost importance to promote a fundamental understanding of the processes. Here, a study elucidating the impact of parasitic currents in PEM electrolyzers with physics-based and data-driven modelling is shown and a novel “Modelica” library for the modular dynamic modelling of electrochemical reactors called “eCherry” is introduced. Lastly, the large-scale implementation of electrolyser technology is also of most crucial importance for establishing a green Hydrogen economy. For this, the degradation state of industrial water electrolyser fleets is investigated and a planning approach for scalable factory concepts for the rapid upscaling of electrolyser production is introduced.

4 | Conclusion and Outlook

Green Hydrogen clearly possesses the potential to play a major role, as a clean, energy-carrying intermediate. However, improving the economics of Hydrogen—its production, storage, transport, distribution, and utilization—is critical. A green Hydrogen economy will result in decreasing costs with increased implementation of H_2 in many major industrial key sectors, addressing issues that include grid resiliency, energy security, employment, manufacturing, environmental benefits, and innovation. However, the goal of ramping up a green Hydrogen economy to an industrially relevant scale can only be achieved by comprehensive technology de-risking as a mandatory prerequisite, given the investment in infrastructure required.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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