RAMBOLL

Bright ideas.
Sustainable change.

Achieving affordable green hydrogen production plants

November 2023

Contents

Summary

Green hydrogen from electrolysis is a critical component of the energy transition for hard-to-electrify sectors. Since creating aggressive targets around green hydrogen production and offtake, many companies looking to deploy green hydrogen electrolysers are now beginning to understand that capital expenditures for green hydrogen production plants are higher than public estimates anticipated. While cyclical macro issues (i.e. inflation, interest rates, and supply chains) are in large part to blame, Ramboll is also finding important differences between expectations for designs of green hydrogen production systems that have been used in public estimates and what a "real life" system would need to operate. This has downstream consequences for estimating learning rates and cost declines for the technology. We propose a more effective framework for estimating cost declines in green hydrogen production and apply that framework to understand where industry and policy makers can best focus their efforts to reduce capital expenditure costs for new green hydrogen electrolysis facilities.

Introduction

From 2018-2022, countries, companies, and capital raced into green hydrogen. Research from industry, governments, and academia envisioned an ever-expanding market for green hydrogen built upon a near-zero-cost clean electricity and a need for decarbonisation of hard-to-abate sectors like cement, heating, steel, and transport.

By 2023 however, the market begins to question the inevitability of <$1/kg green hydrogen by 2030[1]. Rising interest rates and supply chain challenges have caused the levelised cost of energy (LCOE), especially capital-intensive green energy technologies, to rise for the first time in decades. The failure of pilot projects in certain use cases, and reports of higher-than-expected capital expenditure costs (CAPEX) and project delays begin to surface across the green hydrogen market.

Renewable power and electrolyser-based production plants must both, simultaneously, exhibit 50-90% CAPEX cost declines from current values[2] to keep the energy transition on track and for green hydrogen to play a key role in that transition. Other renewable technologies, such as solar, wind, and batteries, experienced similar cost declines in the first ten to 20 years of commercial deployment. Once the costs of renewable power and electrolyser plants sink by at least half, green hydrogen will compete with grey hydrogen and will be widely competitive as a cost-effective decarbonisation pathway at scale. Our experience in the last 40 years of renewables technology tells us that expanding manufacturing capacity should be the key to unlocking these cost declines.

However, what we are seeing in the market is the opposite. Rising interest rates and increasingly complex supply chains (both for manufactured inputs and for the power-to-x value chain) are causing the market to reconsider the inevitability of abundant, cheap, green hydrogen by 2030. The renewables sector, which is having its own moment of cost increases driven by the same factors mentioned above, is at least partly to blame. But is hydrogen production holding up its end of the promise?

This article focuses exclusively on the green hydrogen electrolyser plant. As of Fall 2023, Ramboll has worked on more than 30 power-to-X projects across the United States and European Union (EU). We leverage that experience to unpack the drivers of capital cost hydrogen production and uncover where there might be drivers to accelerate cost declines. We use a framework that has been used to explain the cost declines exhibited in other renewable energy technologies and apply that framework to green hydrogen production assets to understand whether such forecasted cost declines are viable in time to scale the industry to 2030-2050 goals.

Our analysis finds that, while there are significant opportunities for CAPEX cost reduction in green hydrogen production, industry and governments may not presently be focusing on all of the key enablers. Specifically, public estimates reviewed by Ramboll frequently overestimate the impact of decreasing electrolyser stack costs (where research, development and demonstration (RD&D) has made a lot of progress), and underestimate the impact of reducing electrolyser and hydrogen production plant costs on the total CAPEX (where lack of progress is hampering deployment). Ramboll presents recommendations to industry and policymakers on where these under-addressed opportunities may be hiding, and how they can be leveraged to accelerate the deployment of green hydrogen.

[1] IEA (2023), Global Hydrogen Review 2023, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2023, License: CC BY 4.0
[2] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

Classifying clean energy technologies by innovation potential

This paper draws inspiration from the framework put forward in "Accelerating Low-Carbon Innovation" published in Joule Volume 4, Issue 11, 2020, by Abhishek Malhotra and Tobias S. Schmidt. Maholtra and Schmidt propose that cost declines are a function of a technology's design complexity and the need for customisation. To summarise: "the design complexity refers to the number of design elements in a product and the extent to which they interact with each other… The need for customisation depends on the extent to which technologies need to be adapted to their use environments, which can be described in terms of three characteristics: user preferences, regulatory contexts, and physical environments…[3]" Each of these technologies have different cost drivers and therefore experience cost-declines at different rates and scales.

[3] Abhishek Malhotra, Tobias S. Schmidt, Accelerating Low-Carbon Innovation, Joule, Volume 4, Issue 11, 2020, Pages 2259-2267, ISSN 2542-4351, https://doi.org/10.1016/j.joule.2020.09.004

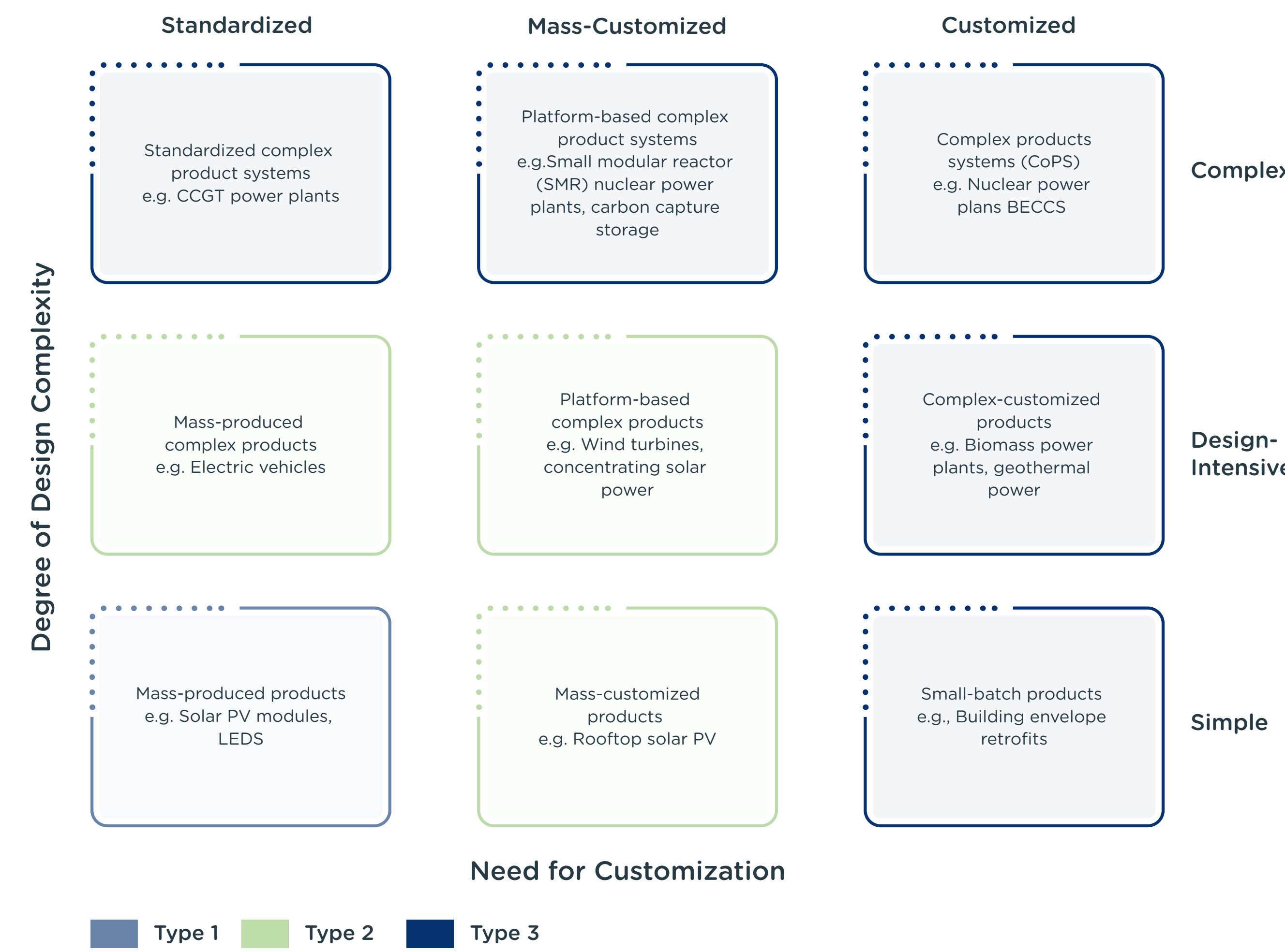


Figure 1: Malhotra and Schmidt's Schematic Characterization of Different Energy Technologies Based on Their Design Complexity and Need for Customization (adapted by Ramboll).

Type 1 products are simple and standardised technologies. Investment in mass-production facilities unlocks cost reduction. This means that as companies expand manufacturing capacity, they find cost takeout opportunities in increasing the efficiency of the material usage, the design, the manufacturing process and improve performance of the end unit with every new product iteration (think generations of televisions, photovoltaic (PV) modules or lithium ion (Li-ion) batteries). Assuming that, the first plants may be money-losers to capture market share and expand the market but each subsequent new plant design benefits from incremental improvements in operational expenditure (OPEX) and production capacity that cover the earlier investments costs. Each major cost driver: people per unit, materials per unit, electricity used per unit, building footprint per unit, output per unit can all be incrementally improved with every new iteration of an end product. All of these cost declines can happen simultaneously. The key is to simply make more.

This multifaceted cost takeout enables the sustained, double-digit price declines that semiconductors, televisions, and renewable energy technologies have all exhibited in the past decades. These cost declines have given rise to the observance of Moore's Law (which says that costs drop exponentially as a function of time (i.e., at a fixed percentage per year)) and Wright's Law (which predicts that costs drop as a power law of cumulative production, also called an experience or learning curve). Most models that forecast the deployment of green hydrogen electrolysers rely on a learning curve function to estimate year-over-year compounding cost declines by as much as 20%. Long-term, these models show a massive reduction in the CAPEX cost of hydrogen production plants as a fundamental driver for the green hydrogen transition.

Example of a Type 1 Learning Curve: PV Modules

From 2010 to 2020, global solar PV module panel production grew by 642%[4]. During the same time, the cost of a commercial-scale, fixed-tilt solar PV system declined by 84%, or an average of 15% per year according to NREL[5]. This sustained cost decline is often cited as an example of Wright's law in action and is even used as a baseline assumption for hydrogen electrolyser plant learning rates in forecasts about the hydrogen transition[6].

Maholtra and Schmidt see PV Modules as a type 1 technology. That is because they have a low design complexity, meaning that producers gain knowledge from expanding manufacturing capacity that is easy to understand, deploy, and replicate globally. They also are standardised, meaning that experience accumulates as deployments grow. So, despite increased demand, lessons learned in building new PV module manufacturing capacity actually reduced costs every year. That led to further increasing demand as the overall product (the solar PV LCOE) dropped and the virtuous cycle continued.

Within a Type 1 technology, these simultaneous cost declines are not all equal. Certain constraints may be long-term barriers before reaching a tipping point, while other cost levers exhibit slow, steady cost declines for longer periods of time. A group of MIT researchers wrote a piece on solar cost declines that elaborates on where those efficiencies were found: "We find that increased module efficiency was the leading low-level cause of cost reduction in 1980–2012, contributing to almost 25% of the decline. Government-funded and private research and development (R&D) was the most important high-level mechanism over this period. After 2001, however, scale economies became a more significant cause of cost reduction, approaching R&D in importance. Policies that stimulate market growth have played a key role in enabling PV's cost reduction, through privately-funded R&D and scale economies, and to a lesser extent learning-by-doing[7]."

A utility scale solar system represents a type-2 technology that relies on a mix of mass-produced products (type-1 technologies like PV modules, inverters, racking, etc.) as components. In addition, it contains a a design-intensive process to configure the optimal arrangement of arrays into a system's given unique locational constraints. However, this system is largely made up of one type-1 technology – the PV modules. In 2010, PV modules were over approximately 50% of the costs of a utility scale system, down to approximately 25% by 2020[8]. So, the type-1 nature of PV modules enabled the drastic reduction in solar production plant costs, increasing demand for solar deployment. And because deployments of solar PV have risen so drastically over the timeframe, there were more investments in production capacity and significant cost reductions in the overall CAPEX costs of constructing a solar system (excluding transmission and interconnection costs). It is a virtuous cycle.

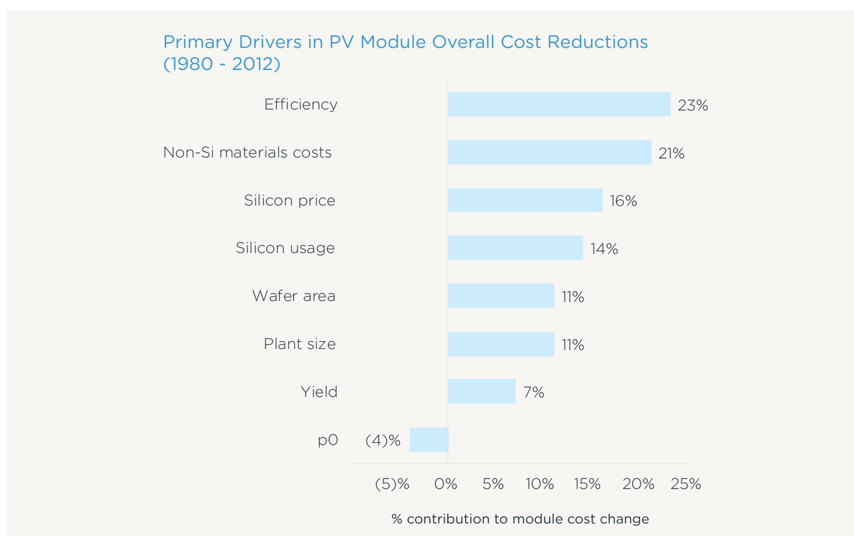


Figure 2: Kalvak, McNery, and Trancik's Findings on Contributions to PV Module Cost Reductions (adapted by Ramboll).

[4] https://www.statista.com/statistics/668764/annual-solar-module-manufacturing-globally/

[5] Ramasamy, Vignesh, Jarett Zuboy, Michael Woodhouse, Eric O'Shaughnessy, David Feldman, Jal Desai, Andy Walker, Robert Margolis, and Paul Basore. 2023. U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2023. Golden, CO: National Renewable Energy Laboratory. NREL/TP7A40-87303. https://www.nrel.gov/docsfy23osti/87303.pdf

[6] IRENA, World Energy Transitions Outlook 2022, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/DigitalReport/World-Energy-Transitions Outlook-2022#page-5

[7] Kavlak, Goksin et al. "Evaluating the causes of cost reduction in photovoltaic modules." Energy Policy 123 (December 2018): 700-710 © 2018 Elsivier Ltd. http://dx.doi.org/10.1016/j.enpol.2018.08.015

[8] Ramasamy, Vignesh, Jarett Zuboy, Michael Woodhouse, Eric O'Shaughnessy, David Feldman, Jal Desai, Andy Walker, Robert Margolis, and Paul Basore. 2023. "U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2023". Golden, CO: National Renewable Energy Laboratory. NREL/TP7A40-87303. https://www.nrel.gov/docs/fy23osti/87303.pdf

Understanding the capital costs of a hydrogen production facility

Ramboll has experienced cost engineers who have developed Association for the Advancement of Cost Engineering (AACE) Class 3 and 4 estimates for green hydrogen projects across the world. As Ramboll develops these estimates, it is common to compare against other benchmark projects and publicly available information. From recent comparisons of +100 megawatt (MW) facilities, it became clear that there was a disconnect between forecasted cost declines in green hydrogen production (on both dollars per kilowatt ($/kW) electrolyser capacity and impacts on downstream $/kg levelised costs) and our estimates.

Part of this disconnect between short-term (lack of) cost declines and long-term projections can be chalked up to macro factors: many of these studies were conducted before (or do not consider) the impacts of key recent developments such as the Russian invasion of Ukraine and rising interest rates. The result of these two factors has constrained supply chains for important electrolyser minerals (see our whitepaper) on critical minerals in green hydrogen and delayed deployment of capital into the sector. Learning rates of compounding annual decline mean that even one year of price increases will have an outsize impact on the overall capital cost over a +10-year period.

When technoeconomic forecasts focus on the potential cost declines of hydrogen, they typically focus on the major OPEX and CAPEX portions of the project. On the CAPEX side, which is where this research focuses, a green hydrogen production plant CAPEX consists of electrolysers, electrical equipment (switchgears, transformers, substations, rectifiers, delivery infrastructure), balance of system equipment (separators, scrubbers, purifiers), balance of plant equipment (compressors, water purification, cooling system), balance of plant bulks (piping, instrumentation, controls), engineering, construction, civil works (foundations, buildings), and optional infrastructure (lights, parking, offices, etc.).

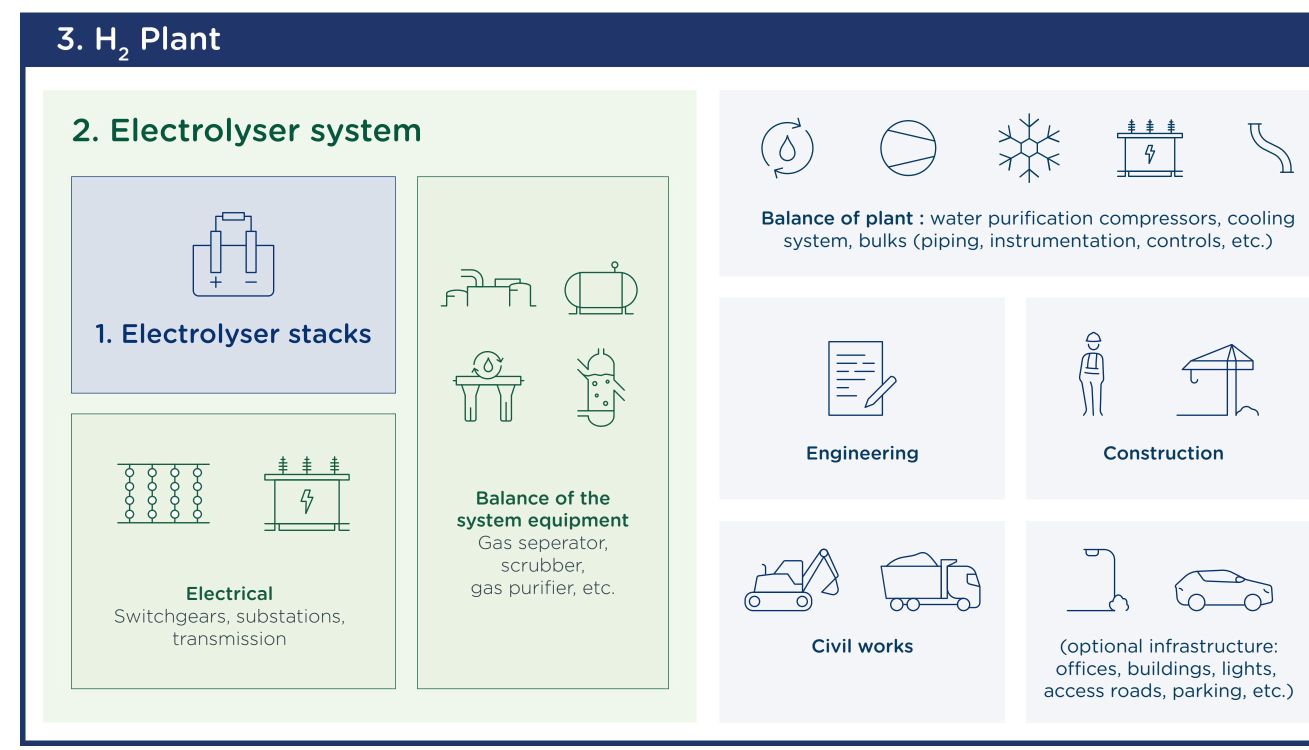


Figure 3: Simplified bill of materials for green hydrogen plant.

These green hydrogen production plants are not standalone pieces of equipment. They are interconnected with the local water and electricity systems as well. The plant uses these inputs to produce hydrogen gas that exits the system to an off-taker (which could be a storage facility, a transmission system, or a power-to-x line to synthesize electrofuels or "e-fuels") and other gasses that the project vents or captures.

In its experience designing and building green production plants around the world, Ramboll has developed an understanding of green hydrogen production as a combination of Type 1, 2, and 3 technologies. This has significant connotations for how technologies develop, what policies incentivise industrial buildout, and how far costs can come down. Ultimately, this understanding has helped Ramboll firm up the belief that steep declines in electrolyser production costs are only a part of the puzzle in reducing overnight CAPEX costs for electrolysers in line with public and industry forecasts.

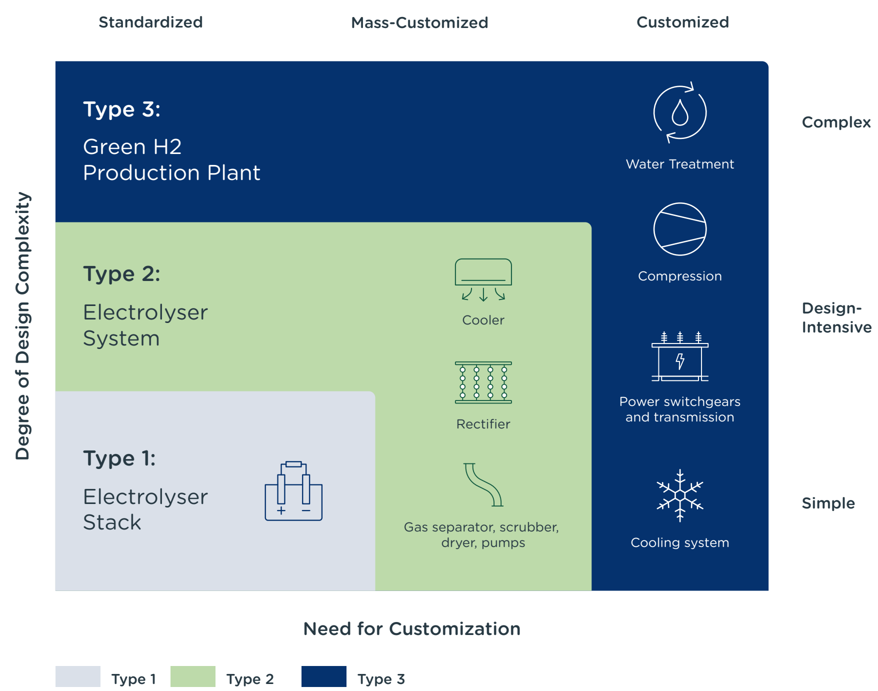


Figure 4: Hydrogen production plants are a complex, customized system of products that are built off of mass-customized and simpler, more standardized products.

Industry's case for hydrogen production as a Type 1 Technology

Increasing the manufacturing capacity of electrolysers for Type 1 technologies by ten times should reduce electrolyser costs by a similar factor. According to the International Energy Agency (IEA), there is 14 GW of manufacturing capacity available today with a goal of reaching 155 gigawatts per year (GW/year) by 2030[9]. However, green hydrogen production CAPEX (and levelised costs) is rising due to other macroeconomic trends and seemingly in spite of those announcements[10].

Many studies conducted by policymakers, trade groups, and industry participants assign learning curves from the solar industry to predict the potential cost declines in green hydrogen electrolysers and ultimately in the cost of green hydrogen[11 12]. The assumptions are simple: green hydrogen electrolysers are a Type 1 technology. If the market grows the way other renewable markets have, then manufacturing will scale and costs will decline. The chart below from the Global Hydrogen Council illustrates that point effectively, and even makes the case that sustained, double-digit cost declines of green hydrogen production might be a conservative measure compared to the developments observed in other renewables technologies[13].

Capex develpment of selected technologies over total cumulative production

Indexed to 2020 values (2010 for compartive technolgies)

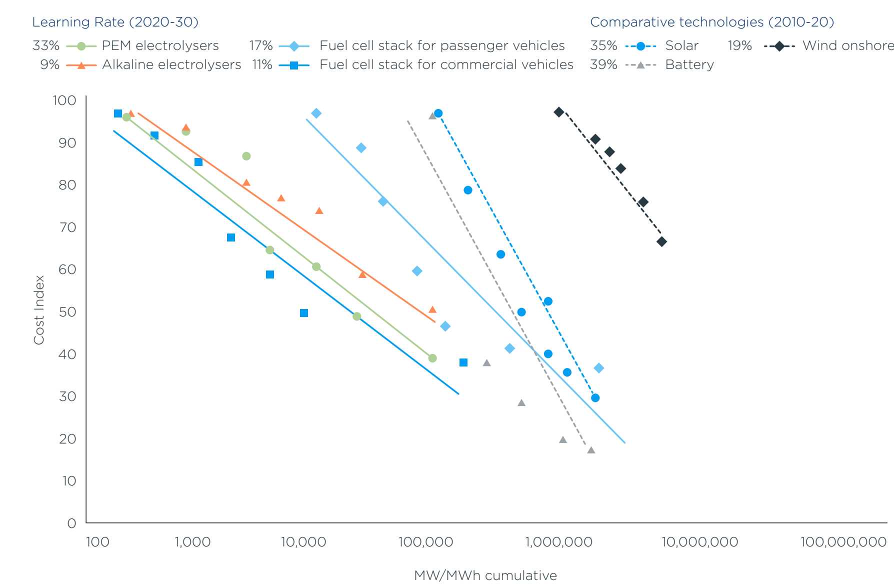


Figure 5: Hydrogen Council's Estimation of Learning Rates for Hydrogen and Clean Energy Production Technologies[14]

Recent academic studies have compared forecast and actual learning rates across solar PV, onshore wind, Li-ion batteries, and proton exchange membrane (PEM) electrolysers. A recent study by Rupert Way, Matthew Ives, Penny Mealy and J. Doyne Farmer concluded that each of the technologies have demonstrated cost declines that are in line with Wright's Law (costs drop as a power law of cumulative production) although the PEM dataset is significantly limited by the novelty of the technology[15].

[9] IEA (2023), Global Hydrogen Review 2023, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2023, License: CC BY 4.0

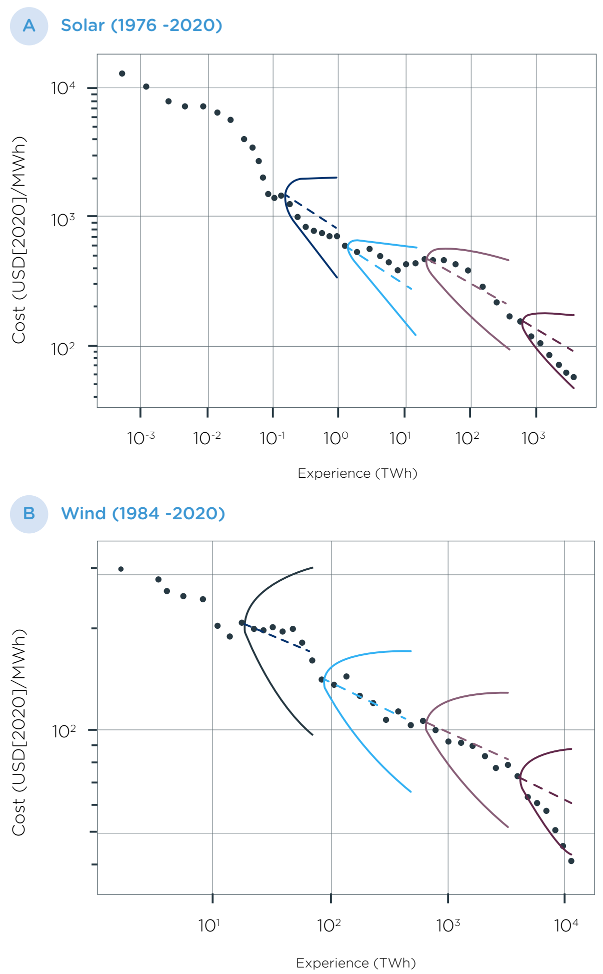
[10] Collins, Leah, "Green hydrogen price in Europe unlikely to fall below €5/kg by 2030, putting off potential offtakers: analyst", Hydrogen Insight, Oct. 19 2023 https://www.hydrogeninsight.com/production/green-hydrogen-price-in-europe-unlikely-to-fall-below-5-kg-by-2030-putting-off-potential-offtakers-analyst/2-1-1537520

[11] Revinova S, Lazanyuk I, Ratner S, Gomonov K. Forecasting Development of Green Hydrogen Production Technologies Using Component-Based Learning Curves. Energies. 2023; 16(11):4338. https://doi.org/10.3390/en16114338

[12] IEA (2022), Global Hydrogen Review 2022, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2022, License: CC BY 4.0

[13,14] Hydrogen Council, "Path to hydrogen competitiveness A cost perspective," January 2020, https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

[15] Way, Rupert, Matthew C. Ives, Penny Mealy, J. Doyne Farmer, "Empirically grounded technology forecasts and the energy transition," Joule Volume 6, Issue 9, P2057-2082, September 21, 2022, https://doi.org/10.1016/j.joule.2022.08.009



Given the huge demand for electrolysers in the green hydrogen-powered energy transition, it is easy to imagine a world where electrolysers go by the way of PV modules and exhibit a sustained 10-20% year over year (YoY) decline for the next decade as global demand soars. From extrapolating these few years of electrolyser data and anticipating cost declines similar to other renewable technologies, 9-13% learning rates per year can seem like a conservative measure for cost declines of hydrogen production system CAPEX[16].

With steep demand for electrolysers on the horizon, backed by Wright's Law's assumption that increased demand creates a virtuous cycle of cost decline, which drives further demand, green hydrogen production costs will reduce drastically, driven by a decade of annual double-digit declines in electrolyser costs (and continued long-term declines in renewable energy costs). With those two criteria met, green hydrogen competes with grey hydrogen by 2030 and, with the support of carbon emissions taxes, dominates the market by 2050[17]. Under these conditions, economic use cases for green hydrogen proliferate widely across the economy, and the green hydrogen transition seems inevitable.

However, the lack of data and the relatively small cost declines to date make it challenging to assess whether or not electrolysers are destined for years of cost reduction as the industry scales, or whether their costs will rise and fall on the basis of underlying inputs like commodity prices and interest rates, especially when estimates are made on a levelised cost basis. When focusing on the electrolyser CAPEX portion of these assumptions, Ramboll can assess the degree to which these cost declines are underway, and whether or not these projections are feasible for green hydrogen production.

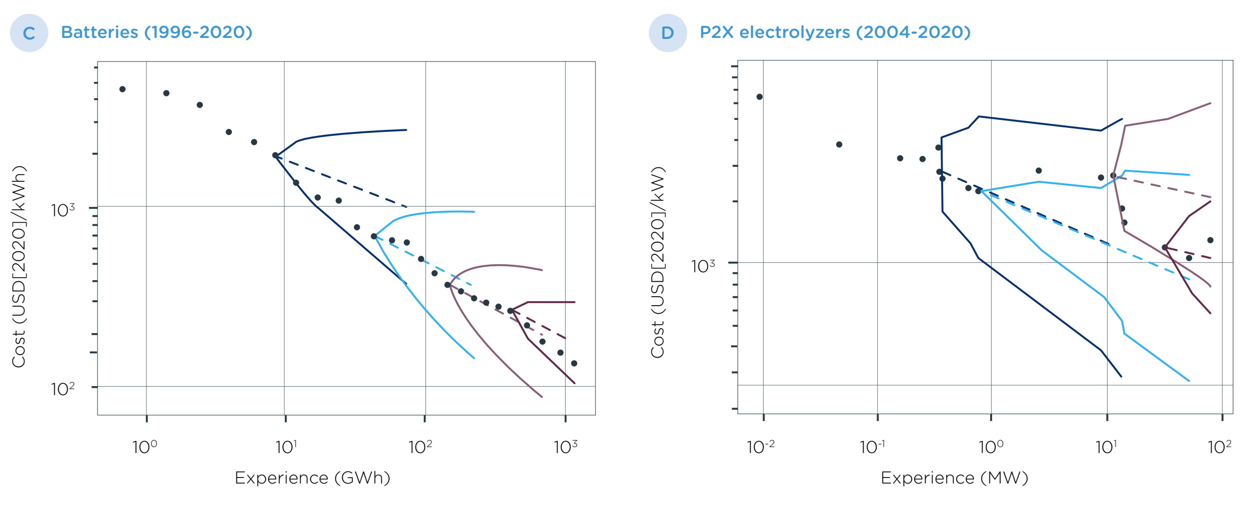


Figure 6: Way, Ives, Mealy, and Doyne Farmer's Historical performance of the stochastic experience curve forecasting method across PV, wind, battery, and electrolysers.

[16] CHydrogen Council, "Path to hydrogen competitiveness A cost perspective," January 2020, https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

[17] Hydrogen Council, "Hydrogen decarbonization pathways Potential supply scenarios," January 2021, https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-2_Supply-Scenarios.pdf

Evaluating the complexity and customisation of hydrogen plants

Leaving the availability of renewable energy aside, the first question we should ask of publicly-available estimates on green hydrogen costs is: are these cost reductions possible, and if so, how? International Renewable Energy Agency's (IRENA) analysis, which has greatly influenced the estimation work of the Hydrogen Council, industry groups, and consultancies, found that an 80% reduction in electrolyser costs and stack-level efficiency improvements would translate to a near 60% reduction in levelised costs[18]. This was largely built on the assumption that stack costs represent up to 15-35% of the total CAPEX of a system at scale, depending on the technology.

However, the stacks are simply a component within the delivered product: the electrolyser system. And those systems are typically modular and gathered together into the hydrogen production plant, which is the ultimate interface between the electrolyser stacks and the world around them.

Having created estimates for multiple power-to-x plants across many geographies, Ramboll regards the portion of CAPEX that the stacks will represent over time and at scale to be significantly lower than many publicly available estimates, especially at larger scales.

Ramboll's analysis of IRENA's achieving green hydrogen competitiveness

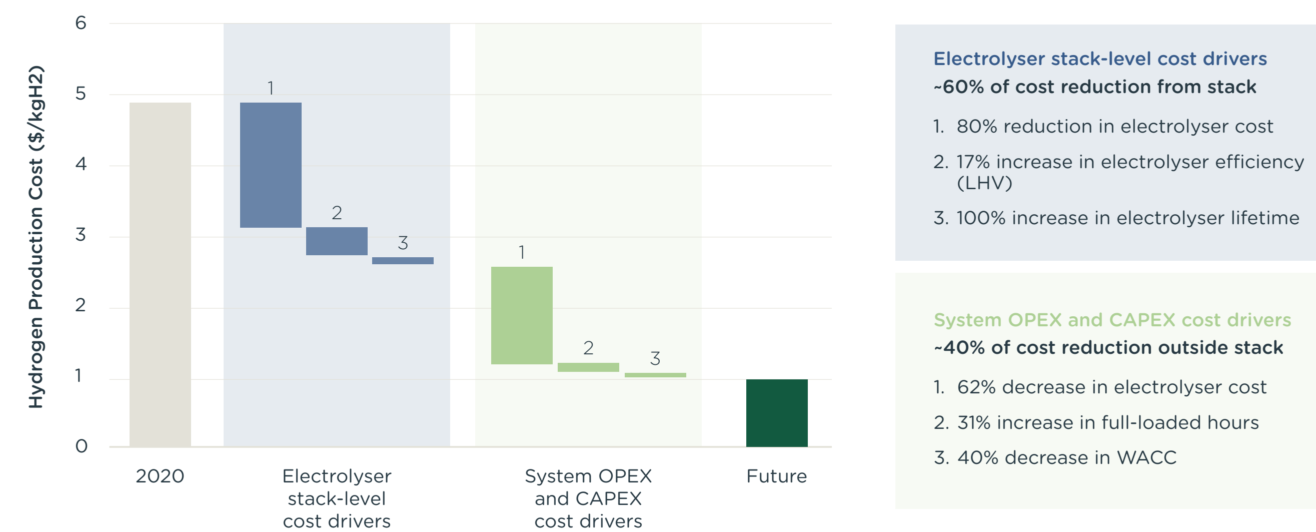


Figure 7: Ramboll's analysis of IRENA's 2020 forecast that 60% of LCOH cost declines would come from stack-level improvements.

[18] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

Understanding the CAPEX cost drivers of green hydrogen production

After completing detailed cost estimates for recent early engineering efforts, Ramboll determined that CAPEX for green hydrogen production facilities would be more expensive on a $/kW basis than what public estimates anticipate, even at large scales.

Some additional costs stem from projections on how the technology would scale over time. Early assumptions around electrolyser units scaling from 1 MW to >100 MW stacks have not yet proven viable (due to balance of system and plant related constraints discussed in sections below). Instead, Ramboll sees the electrolyser stacks will remain much smaller (typically 0.5-5 MW) where large-scale electrolyser systems are skid-framed or put inside buildings that are designed to be modular, plug-and-play, individually-operated sub-plants at the 50-200 MW scale. This drives proportionally larger system- and plant-level costs than what earlier estimates anticipate. Also, public estimates over-estimate certain cost categories, such as engineering, procurement, and construction (EPC) costs as a proportion of large project budgets (typically 15-30% of top-line CAPEX), while de-scoping other cost categories, such as buildings, electrical, indirects, and contingencies.

Ramboll understands that cost estimates are dependent on scope, and although the public sources cite their omission of "project and location specific costs", Ramboll recognises that in order to build functioning hydrogen production facilities, the industry must understand, account for and ultimately reduce the full costs associated with building these facilities. For that reason, Ramboll does not publish global estimates for green hydrogen production plant LCOH. However, synthesising across numerous estimates for clients, Ramboll sees that these differences can accumulate to 1.3-3.3x the CAPEX estimates promulgated in often-cited public reports on a $/kW basis. These increases are likely attributed to a basis of design differentiation between Ramboll and the public sources, such as inclusion of compression and/or electrical infrastructure for a high up-time facility.

As noted in Figure 8, Figure 9, and Figure 10 the Ramboll estimates are ranges that assume low-saline water input, ample electrical at the battery limit, and compression to 50 bars. The higher range includes electolyser buildings with mechanical ventilation and safety systems, and electrical infrastructure such as gas-insulated switchgears (GIS). The lower range assumes an outdoor weather rated installation of the equipment, and electrical infrastructure such as air-insulated switchgears (AIS). All Ramboll estimates exclude storage and contingency to keep consistent against the public sources.

PEM Comparison vs Public Data Sources

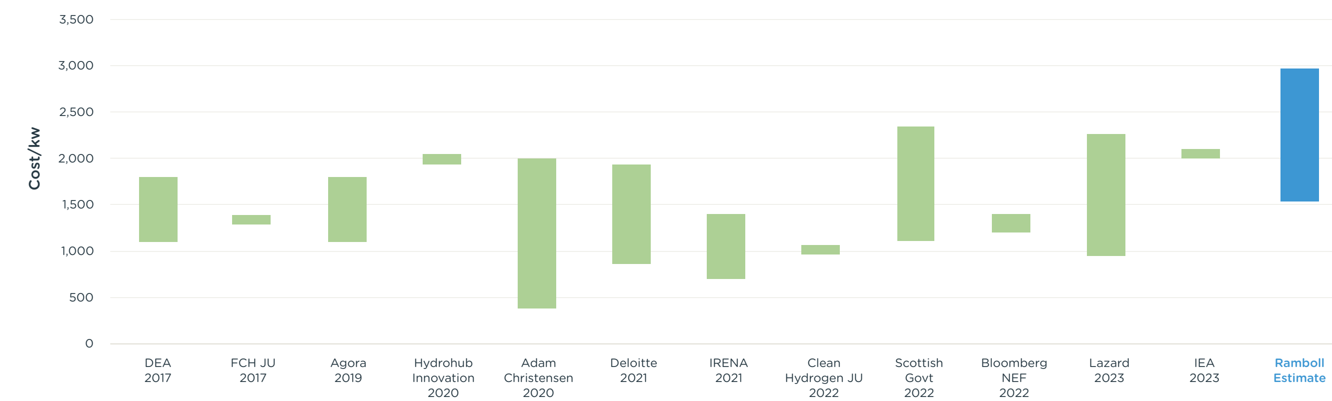


Figure 8: Ramboll estimates for PEM electrolysers hydrogen production plant CAPEX from estimates of system sizes 10MW - 1GW

AE Comparison vs Public Data Sources

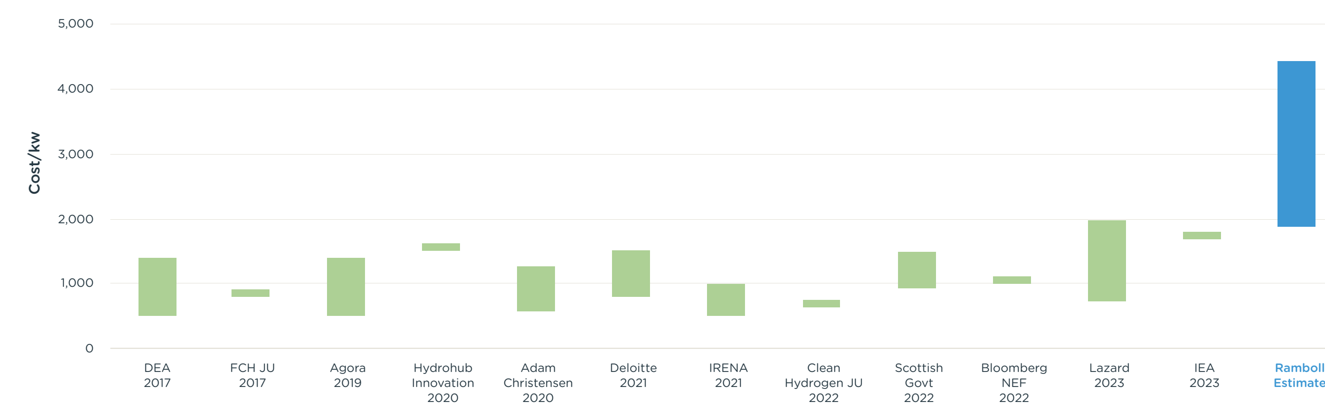


Figure 9: Ramboll estimates for AE electrolysers hydrogen production plant CAPEX from estimates of system sizes 10MW - 1GW

SOEC Comparison vs Public Data Sources

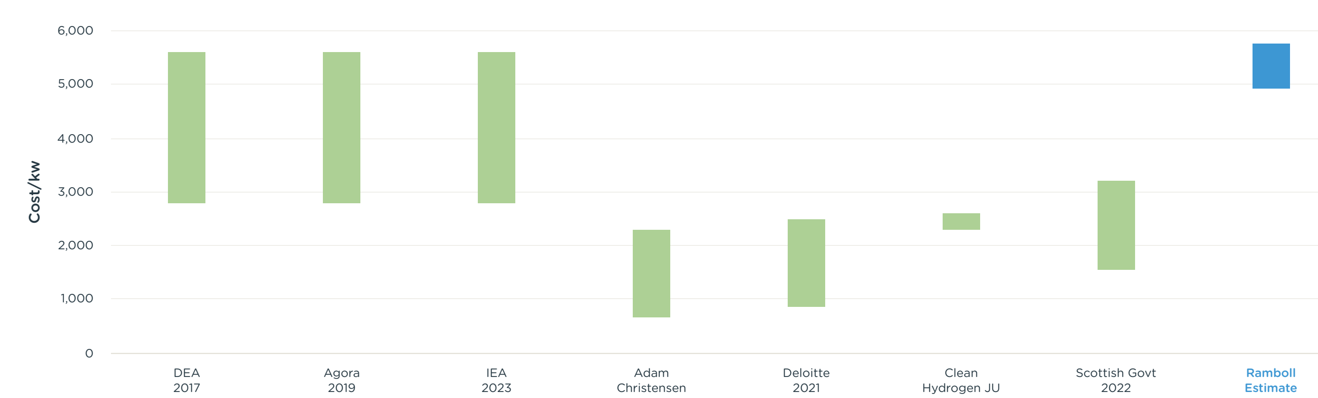


Figure 10: Ramboll estimates for SOEC electrolysers hydrogen production plant CAPEX from estimates of system sizes 10MW

Note: Ramboll Estimate assumes low-saline water input, ample electrical at battery limit, and compression to 50 bar; high includes; electrolyzer building and gas-insulated switchgear; low assumes outdoor and air-insulated switchgear; all exclude storage

PEM Component of CAPEX Estimates (% of TOTAL CAPEX)

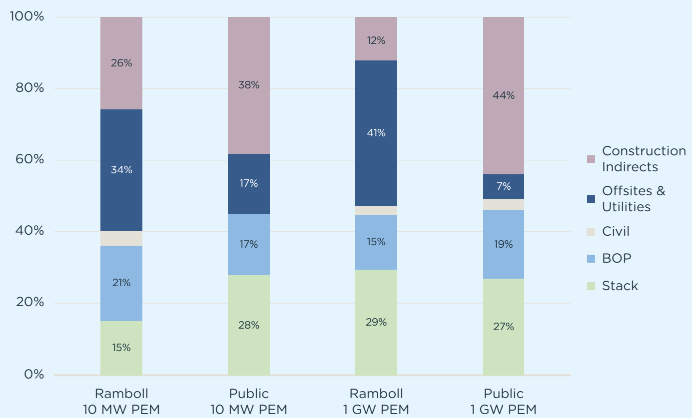


Figure 11: Ramboll vs. Public Estimates of PEM System Components at Scale (non-pressurized system).

For PEM public estimates at the 10 MW and 1 GW level, Ramboll sees significant differences between balance of plant (BOP) and stack costs as a percentage of total CAPEX. This is particularly pronounced at the 10 MW level, where Ramboll estimates have shown that stack and BOP costs are around 36% of total overnight CAPEX compared to 45% average of major industry estimates. The offsites and utilities (including power delivery infrastructure onsite as well as grid interconnection) make up the majority of the difference, and becomes especially important at the GW scale, making up nearly 41% of the total CAPEX.

Alkaline electrolyser (AE) cost breakdowns at the 10 MW and 1 GW levels show similar incongruities between stack and BOP compared to expectations. On either the small or large level, Ramboll estimates that stacks make up 6-14% of the total CAPEX costs, rather than the 13-24% range forecasted in some public estimates at either scale.

Simply put, electrolyser stack costs may be drastically reduced by the simple act of manufacturing more stacks every year, but stack costs represent a smaller portion of total of CAPEX required to produce hydrogen at scale. So, these drastic costs declines, by themselves, may not be enough to move the needle on green hydrogen production CAPEX in line with where we need to be in the next 20 years.

Furthermore, a critical attribute of Type 1 technology is that learnings are transferrable between projects, geographies, and companies. As these technologies are so simple and standardised, efficiencies learned in one corner of the industry can be quickly applied across the board. While this is true for manufacturing of electrolysers (which is a relatively simple electrochemical process), it ignores the challenges of using electrolysers. An operational electrolyser requires connections to water, gas, and power infrastructure. The ability to connect and leverage these utilities is not standard throughout the world, so the supporting

AE Component of CAPEX Estimates (% of Total CAPEX)

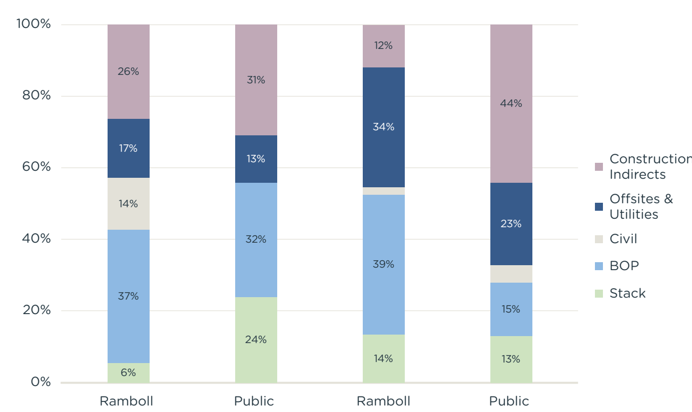


Figure 12: Ramboll vs. Public Estimates of AE System Components at scale (non-pressurized system).

infrastructure surrounding the electrolyser requires more customisation and complexity than the stack itself. This limits the applicability of learnings from one market to another.

So, while scaling manufacturing may substantially reduce the costs of electrolysers in line with estimates, the conclusion from this data is that green hydrogen production is not a Type-1 technology. Which begs the question, what is it, and how can we use that knowledge to unlock more cost reductions and deployments?

The electrolyser stacks are mass-produced, simple products

Industry may be hyper focused on stack costs as the key to reducing green hydrogen CAPEX costs. The thinking follows the Type 1 technology playbook: stacks are the most expensive piece of equipment in the electrolyser system, and they are mass producible. Expanding production capacity will lead to cheaper electrolysers and thus abundant, affordable green hydrogen. The race to announce new electrolyser manufacturing facilities should then be an important signal that inexpensive electrolysis is on the horizon.

According to Hans Böhm, Sebastian Goers, and Andreas Zauner's "Estimating future costs of power-to-gas – a component-based approach for technological learning" in the International Journal of Hydrogen Energy in 2019 (and replicated by IRENA's 2019 analysis), learning rates can be assumed about the cost drivers for the electrolyser stacks on the basis of their constituent components. The same publication assumes learning rates between 5-18% for each component of each electrolyser stack technology.[19]

Ramboll reviewed the improvements that have and can be made from generation to generation of stack manufacturing. Ramboll also reviews whether or not there are RD&D investments supporting each of these activities at a level that could make a significant impact on 2030 production. As of 2023, we are seeing significant investment in RD&D at the stack level for each of these technologies. Efforts to enhance the cost-efficiency of electrolysis systems, including AE cell (AEC), PEM electrolysis cell (PEMEC), and solid oxide electrolysis cell (SOEC) technologies, are centred on multiple key objectives. These include:

Reducing Stack Footprint:
less space or materials for the same unit of output

- high catalyst surface area and utilisation
- increasing catalyst utilisation
- scaling up stack components for larger stack MW units (SOEC)

Material Replacement:
reducing loading factors of the most expensive critical minerals

- addressing these challenges involves employing iridium-free catalysts (PEMEC)
- creating noble metal-free protective layers and titanium-free porous transport layers (PTLs) (PEMEC)

Improving Reaction Efficiency:
less energy or waste per unit of production

- improved reaction kinetics for hydrogen and oxygen evolution
- reducing interface resistances
- identifying stable polymer chemistry for ionomer use
- enhancing stability (PEMEC)
- stabilising electrode chemical structures (SOEC)
- improving catalytic activity at lower temperatures (SOEC)
- addressing contamination and thermal instability concerns (SOEC)

Lengthening Lifetime:
reducing degradation, build-up of reaction-limiting agents

- counteracting catalyst poisoning or deactivation by foreign elements
- prevention of nickel-hydrogen (NiH) formation (AEC)
- the development and integration of recombination catalysts to reduce gas permeation, mitigation of critical catalyst degradation (PEMEC)
- eliminating mechanical degradation of catalyst layers (AEC, PEMEC)
- mitigating membrane poisoning, minimising ohmic losses and gas permeation (PEMEC)
- controlling the oxidation state of electrocatalysts (SOEC)
- resolving delamination issues from the electrolyte (SOEC)

[19] Böhm, Hans & Goers, Sebastian & Zauner, Andreas. (2019). Estimating future costs of power-to-gas – a component-based approach for technological learning. International Journal of Hydrogen Energy. 44. 30789-30805. https://doi.org/10.1016/j.ijhydene.2019.09.230

AEC cost reduction initiatives

AEC costs can be cut significantly when reducing footprint and improving lifetime. Recent research has shown improvements in catalysts, which due to their efficient use of space may reduce footprint. Some examples are creating configurations of 3D nickel sulfide (Ni3S2), hollow microspheres in the case of molybdenum oxide (MoOx)/Ni3S2 (increasing effectiveness by 37 times!) and trying alternative substrates such as graphene and graphene oxide[20]. Increasing the lifetime can be addressed by decreasing the degradation, which has also been researched. 3D nickel-iron-cobalt (NiFeCo) foam substrate is promising, enhancing catalytic performance. Researchers have also explored variations in the active surface area among films, discovering that nickel outperforms iron in catalysing the hydrogen evolution reaction (HER), emphasizing the importance of composition in green hydrogen production. The optimal composition found is however a 50% iron and 50% nickel composition[21]. Reducing the overpotential can decrease the stress on the cell and improve the cost efficiency due to the lowered energy use per output. In this regard, a promising finding has been NixFe1-x allow-oxyhydroxide nanowire arrays.

PEMEC cost reduction initiatives

Expensive materials in PEMEC are also a large issue. Therefore, researchers are actively looking for alternatives or reducing the amount of gold (Au), platinum (Pt), iridium (Ir) among others. Research varying the loading of Ir as a protective layer on a titanium (Ti)-based PTL has shown that with small amounts of Ir, the benefits level off at about 0.025 mg/cm^2, a smaller amount than was thought necessary. In fact, this also allowed for a 40-fold reduction compared to Au or Pt use. Nickel (Ni) and iron (Fe) have also been shown to work well together for the oxygen evolution reaction (OER)[22]. Other promising PGM free catalysts materials include co-containing complex metal-oxygen bound structures, nickel-manganese (Ni-Mn) antimonate (i.e., containing antimony/Sb) catalysts, and FeN_4 sites within carbon structures[23]. While much progress has been made in the previous years, suggested solutions still pose cost and longevity trade-offs. However, most of the improvements that enhance efficiency also increase cost.

Reducing lifetime improvements can also reduce costs down the line, with the aforementioned Ir solutions helping reduce ohmic resistance, improving efficiency and decreasing degradation. Strategies to enhance ruthenium (Ru) catalyst stability are being considered, including embedding single Ru atoms within a platinum-rich environment, and designing heterostructured Ru@IrOx catalysts, both of which show promise in boosting activity and durability.

Ramboll explored the exposure of renewable energy and electrolyser technologies in a companion piece:

Mineral Risk in the Green Hydrogen Transition

[20] https://doi.org/10.1016/j.gee.2023.02.01

[21] Sergio I. Perez Bakovic, Prashant Acharya, Morgan Watkins, Hannah Thornton, Shixuan Hou, Lauren F. Greenlee, Electrochemically active surface area controls HER activity for FexNi100−x films in alkaline electrolyte, Journal of Catalysis, Volume 394, 2021, Pages 104-112, ISSN 0021-9517, https://doi.org/10.1016/j.jcat.2020.12.037

[22,23] Li, Y., Wang, H., Priest, C., Li, S., Xu, P. and Wu, G. (2021), Electrocatalysis: Advanced Electrocatalysis for Energy and Environmental Sustainability via Water and Nitrogen Reactions (Adv. Mater. 6/2021). Adv. Mater., 33: 2170042. https://doi.org/10.1002/adma.202170042

SOEC cost reduction initiatives

Advancements in SOECs aim to stabilise electrode structures and materials. The combined use of materials such as lanthanum (La), strontium (Sr), oxygen (O), gallium (Ga), calcium (Ca), manganese, cobalt, and iron have shown promising results. $La_{0.8}Sr_{0.2}MnO_3$ (LSM) has been known for its stability, but new materials like $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$ (LSCF) and $La_{0.8}Sr_{0.2}Mn_{0.9}Fe_{0.1}O_3$ (LSMF) have been shown to perform even better. These materials have a special structure that reduces resistance and makes the cells last longer. LSCF is particularly excellent at conducting electricity and ions due to how oxygen moves through it. ($La_{0.9}Sr_{0.1}Ga_{0.8}Fe_{0.2}O_3$) LSGF similarly has excellent conductive properties as well as stability, but has processing challenges and interactions with some hydrogen electrode materials. Materials like nickelate-based compounds hold potential but require further refinement to meet long-term stability standards[24].

Lower operating temperature will increase efficiency and durability. The material gadolinium-doped ceria has shown to operate at lower temperatures. Lastly, $La_{0.6}Ca_{0.4}Fe_{08}Ni_{0.2}O_{3-\delta}$ (LCaFN) is a promising O_2 electrode material, avoiding problematic elements.

Other than composition, scaling up SOEC stack components for larger MW units is a key focus, aligning with projections for high-temperature balance of system (HT BoS) units ideally in the range of 500-1,500 kW based on estimates by Bloom Energy, Sunfire and Topsoe, organised into modular clusters to enable multi-MW plant development, ultimately reducing costs[25].

In conclusion, electrolyser stacks, which are the basic building block of electrolysers, are indeed manufactured in a way consistent with other Type 1 technologies. They are simple and easy to mass produce once a design is ready for production. While they are expensive today, each of the three leading technologies has a clear pathway toward key cost reductions on materials and efficiency. In the meantime, companies will automate their processes, compete for market share, and ultimately drive down the cost of electrolysers over time. However, as a percentage of the overall CAPEX of a hydrogen production plant, electrolysers are a smaller proportion of total cost than anticipated, once accounting for the complexities of a hydrogen production facility at scale. While there are significant opportunities for hydrogen electrolyser stack costs to decrease substantially over the coming decades, that alone will not result in massive declines in green hydrogen production plant CAPEX the same way that PV module cost declines ultimately impacted solar PV system production costs.

[24] Aziz Nechache, Stéphane Hody, Alternative and innovative solid oxide electrolysis cell materials: A short review, Renewable and Sustainable Energy Reviews, Volume 149, 2021, 111322, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.111322

[25] Hans van 't Noordende, Frans van Berkel, Maciej Stodolny, "Next Level Solid Oxide Electrolysis: Upscaling potential and techno-economical evaluation for 3 industrial use cases," Institute for Sustainable Process Technology, Public Report, 2023 https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf

Electrolyser OEMs offer a pre-packaged, mass-customised system

Electrolyser systems are more than their stacks. When an EPC orders a green hydrogen electrolyser product to build a project, they aren't usually ordering a bare stack. Rather, they work with an original equipment manufacturer (OEM) to develop and deliver an electrolyser system to the specifications required by the project. These systems are often containerised solutions, with the OEM providing support to customers in designing the rest of the plant around what comes the standard issue "in the box".

At the electrolyser system level, we begin to see a complex and customised series of components forming an end product (an electrolyser system) which is modular and, ideally, contains all of the equipment needed to fulfil its purpose once it is connected to water, electricity, and gas streams.

These systems include the stack, components that connect the stacks to power, water, and gas processes, as well as products that enable these points of interconnection. For example, stacks require direct current (DC) power to run continuously. But the power electronics controlling the stack may require alternating current (AC) power, and the whole unit will need to run entirely on AC power if it is ever going to connect to the grid as a primary or backup power source. For that reason, electrolyser systems tend to have rectifiers at the system level that allow them to run some (or all) of the equipment utilising AC power some (or all) of the time.

At this level, what these electrolyser systems need depends more on the locations where they are built. Whether or not an electrolyser system needs a high-quality water purification system depends more on the quality of the water in the region than it depends on performance factors inherent in the electrolyser system itself. Ramboll sees these requirements as varying by region, location, and project design. Rather than the design simplicity of a solar array, which only needs to be positioned at the proper angle depending on the sunlight of a site, there are many more complicated and customised upfront design considerations when considering the optimal procurement and operation of an electrolyser system.

Furthermore, Ramboll has found a great degree of heterogeneity in terms of electrolyser system configurations, especially in scaling existing electrolyser technologies (typically consisting of 1-5 MW stacks) into the 100 and 1,000 MW scale. This suggests that although the electrolyser stack itself may be a Type 1 technology, the delivered product to a developer is a complex system of electrolyser and other components that ultimately form a Type 2 solution. This adds to the overall system complexity (each OEM has a different kit with different performance attributes, creating customer lock-in and limiting the transferability of learning rates between OEMs as technologies improve).

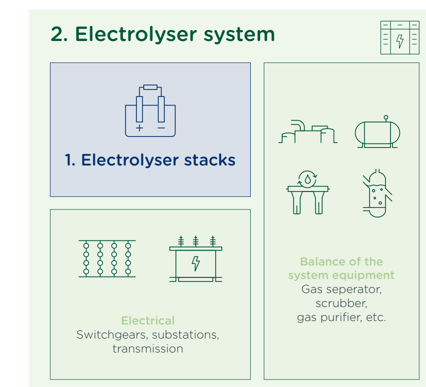


Figure 13: Illustrative bill of materials for an electrolyser system.

In an OEM survey conducted by Ramboll, we found that commercially available supplies for AE, PEM, and SOEC electrolyser systems varied widely in what was included within the system. The largest, most consistent variations were found in electrical equipment: transformers and rectifiers. Given the relative cost of these components to the rest of the system, this represents a significant variability in how much of the actual CAPEX required for an electrolyser system comes "already in the box" between different suppliers.

Electrolyser System Technology Type	ALK	PEM	SOE
Models Surveyed (Commercially-available)	10	12	2
Min Capacity (MW)	0.5	1.0	1.8
Max Capacity (MW)	20.0	17.0	2.7
Monitored Enclosure Included	40%	50%	0%
Transformer Included	40%	58%	50%
Rectifier Included	70%	92%	50%
Water Filtration Included	60%	92%	50%
Gas Separation Included	80%	92%	0%
Compressor Included	30%	25%	0%

Figure 14: Ramboll comparison of components included in today's commercially available electrolyser systems.

Electrolyser systems are therefore more complex and more customised than the stack inside of them. This issue is further complicated by the current variability between what suppliers are offering; there is no standard electrolyser system to benchmark against in 2023. Ramboll expects product offerings to evolve and standardise over time, but in current market, where companies are building first-of their kind projects, it is very important to rationalise public estimates against actual quotes and a bill-of-materials that meet project-specific needs for critical electrolyser system attributes such as power access, power quality, and water treatment requirements.

On the electrolyser size issue, there are limits to the size of the power electronics that feed the stack itself. These power electronics have been shown to be the key limiting factor for the size of the stack. In conversations with vendors, Ramboll found limited availability or RD&D activity for components that would solve these bottlenecks. The cost of a near-future (to 2030) 1 GW production facility is therefore limited by the capacity of today's power electronics. As a result, electrolysis systems stay at the 2-5 MW range (a 1 GW system is therefore a string of 200 x 5 MW electrolysers side-by-side). While this configuration provides some operational benefits in its modularity, it contests the assumptions made by academia and industry that increasing the power density of electrolysers alone will have significant cost reduction effects on the entire system.

Unlocking cost reductions in Type 2 technologies

Overall, Ramboll sees these Type 2 challenges as a critical issue that is currently not being adequately addressed by the market. More electrolyser manufacturing quantity will lessen the price of the electrolyser system substantially. However, as a Type 2 technology, electrolyser systems require more than increased production volume to unlock significant cost reductions.

Standardisation of electrolyser offerings will make it easier for EPCs and developers to "shop around" for the best-performing product for their project. At the same time, OEMs and component manufacturers will begin to develop more integrated and cohesive solutions. Many of the components of an electrolyser system today are standard components that are used across applications to handle many forms of gas or electrochemical reactions. There are significant opportunities in cost reduction at the Type 2 level by integrating and improving the designs of specific balance of system components. Critical improvements in the cost and scale of electrical equipment, particularly rectifiers and power equipment, represent opportunities for electrolyser system costs to scale down at the same time (and potentially at the same rate) as electrolyser stacks come down their cost curve.

Locating plants in areas with existing or excess electrical support infrastructure is a short-term fix to solve the issue of expensive investments in transmission interconnection.

Investments in RD&D to unify and scale electric components of electrolyser system offerings will be critical to unlocking potential. In a survey of OEMs, Ramboll found that certain system components will become critical bottlenecks above the 10 MW scale. Rectifiers are perhaps the most important component where cost and scale are prohibiting system size, yet there are few signs of the industry supporting development of rectifiers purpose-built to overcome these challenges in a green hydrogen electrolyser system. DC power could also be used, eliminating the need for a rectifier, but requiring new designs for other components to accommodate accepting DC power.

Hydrogen production plants are complex and customised to their surroundings

The highest-level unit of analysis, the green hydrogen production facility, contains the electrolyser system, as well as the balance of plant and multiple process loops that connect with the outside environment: such as the water, electrical, and gas streams flowing in and out of the plant. These interfaces with the outside world make the plants highly customised to their specific location (not just their region, but their physical location) and thus reduce the impact of learning and scale. Think of how many fewer factors there are to consider in the design of a utility-scale PV system compared to a green hydrogen facility converting green electricity and water into an industrial stream of hydrogen or e-fuels.

In a recent study, Ramboll focused on just one of these attributes, interconnection with the power grid, and found that costs were significantly higher than estimated by the literature. In our estimates, we found that there were significantly less economies of scale and scope when upsizing the facility to 100+ or 1000+ MWs than anticipated. This countered the expectations that have been set by public estimates, which envision delivered costs falling while average system sizes increase substantially.

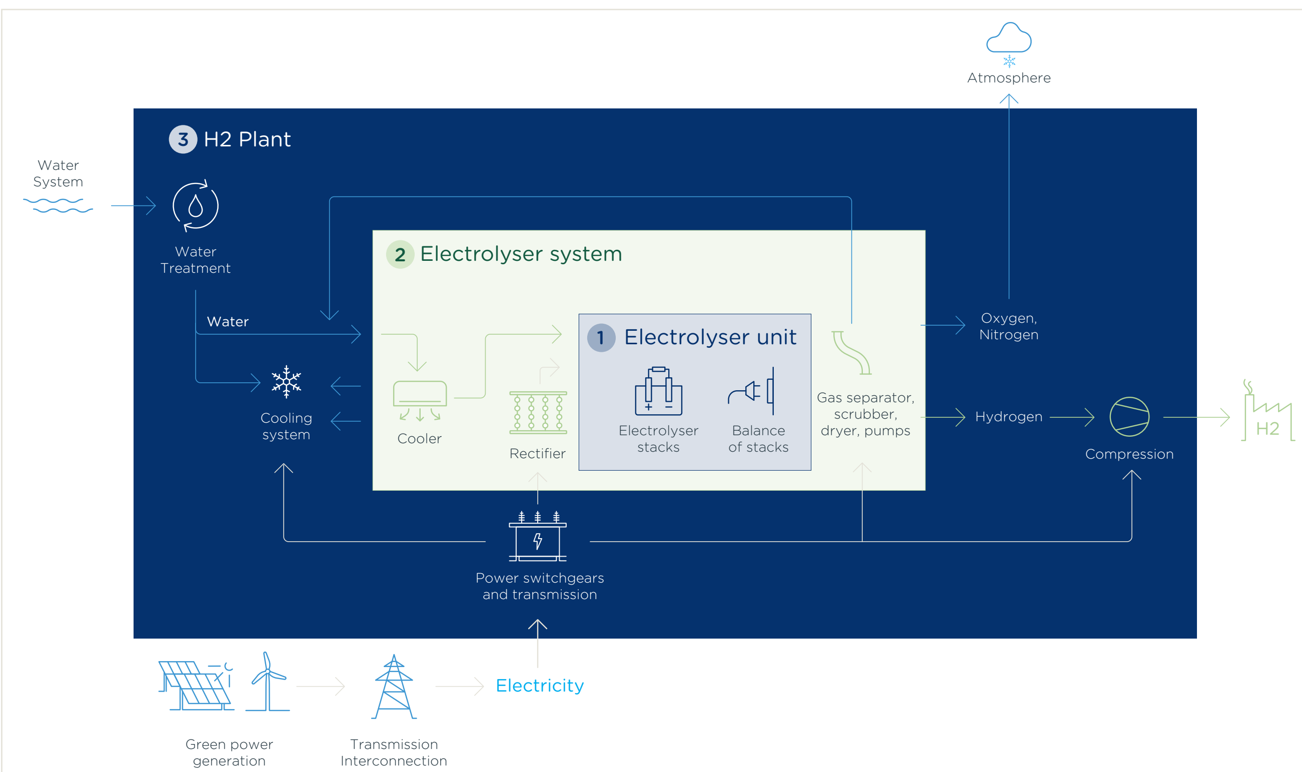


Figure 15: Visualising the interconnectivity of a H2 plant.

While the rules are being written about how to certify green production, the industry is exploring multiple configurations of grid interconnection for the electrolyser systems. Grid connection for green hydrogen offers a diversity of green energy production facilities that provides the producer with greater flexibility and resilience in the procurement of green energy, ultimately improving uptime and lowering the LCOE (which is the most significant contributor to a system's levelised cost of hydrogen (LCOH)). In jurisdictions like the Unites States, where the green premium / subsidy to green hydrogen is determined by the end product's carbon intensity, grid interconnection provides more significant flexibility and potential for economic optimisation. Many green hydrogen cost forecasts depend on rapidly declining LCOE and increasing hours of 100% green energy production as critical paths to LCOH cost reductions, which are most easily achieved by leveraging the diversity of resources and balancing capabilities that a larger grid can provide. On the other side, studies that assume no interconnection of electrolysers to the grid often fail to account for the spatial and geographic constraints that current zero-carbon electricity sources pose, adopting best-in-class production figures for solar and wind resources across wide geographic areas.

Furthermore, green hydrogen must be supplied into offtake infrastructure (either hydrogen storage, hydrogen offtake, or a power-to-x process) at a standardised flow rate. Relying on wind and solar alone means periods of significant interruption are likely, requiring overbuild of electricity generation, onsite energy storage, and grid support to green hydrogen processing equipment. While these problems can be solved in ways that are optimised around off-grid production, there is a lack of clarity in the regulatory arena around whether such facilities can be cited in developed energy / utilities markets around the world at the GW scale.

Ramboll therefore anticipates that in the near term, grid connection will be the rule of thumb for most large-scale industrial green production facilities. However, Ramboll has found that many of the assumptions on system configuration taken in pursuit of drastic YoY cost declines would not meet permitting and operating requirements for a 100 or 1,000 MW load. The public data shows that many studies omit project and location costs. These would likely include water purification, office buildings, and any electrical past the original transformation and rectifier. These assumptions include the system-level rectifiers and the first transformers whereas Ramboll sees requirements for multiple switchgears and multiple transformers in addition to the rectifiers to accept, step down, and moderate the electrical needs for a full-time, reliable generation facility above the electrolyser system level.

Similar challenges exist with interconnection to water systems (which may require purification or desalinisation infrastructure at the plant-level) or with the gas systems (which will have specific requirements based on the local codes for gas transport infrastructure that may vary based on the means of transport). Direct integration of a plant into a power-to-X facility, further complicates the green hydrogen production, offtake, and storage requirements. Many of these factors interact not only with real infrastructure systems (e.g. the grid, the gas network) but also with a cascading system of national and local laws. These complexities require further customisation of plant design, reducing the transferability of lessons learned from one facility to another and ultimately slowing the learning rate of green hydrogen production.

Reducing Costs of Type 3 Technologies

The challenge of the green hydrogen industry, as a Type 3 technology is that upstream commitments of new electrolyser manufacturing capacity buildout alone are not enough of a signal that there will be a future market for these technologies. For this reason, we see many announcements of large green hydrogen projects both in upstream electrolyser manufacturing and downstream hydrogen production, not reaching final investment decision (FID). Of the 140 GW of electrolyser manufacturing capacity expected by the Energy Information Administration (EIA) prior to 2030, only 8% of that capacity has reached FID. Increasing global manufacturing capacity ten times could unlock Wright's Law for electrolysers as predicted in our analysis of Type 1 technologies. However the delay of FID for this capacity demonstrates that decisions about production are ultimately tied into the cost-competitiveness of the Type-3 green hydrogen plant technology rather than its own self-fulfilling prophecy.

On the flipside, achieving milestones simultaneously at the stack, system, and plant levels will unlock a virtuous cycle effect, similar to that observed in offshore wind between 2000 and 2020, where upstream push and downstream pull complement one another and unlock competitive forces that drive significant, sustained cost reductions YoY. If this positive feedback loop between downstream plant economics and upstream stack manufacturing can be established and leveraged, similar to the virtuous cycle that sustained solar PV manufacturing capacity expansions and PV system cost declines, green hydrogen CAPEX costs could indeed meet public projections by 2030.

At the plant level, scaling and standardising electrolyser system production will make impacts, but will not be enough to ensure that lessons learned in one jurisdiction speed deployment in another jurisdiction. Technologies that are so complex and customised in their design require collaboration across OEMs, developers, financiers, regulators, and governments to unify the enabling environment for these technologies at regional and global scales. For hydrogen production, this will require the harmonisation of certification and regulatory frameworks, the definition of interconnection standards and tariffs, and enhanced industry coordination on RD&D.

Harmonising certification and regulation across borders will be critical to enabling a global exchange of learnings. As of the writing of this paper, the United States still lacks a formal definition of green hydrogen, a necessary prerequisite for the development of the industry. Whether the US follows the guidelines laid out by the EU's Renewable Energy Directive (RED) and Renewable Fuels from Non-Biological Origins (RFNBO) packages will have significant downstream impact on the industry. Lax rules in the United States compared to the EU will draw significant investment in electrolyser deployment, potentially at the expense of meeting EU targets, but ultimately will produce a more carbon-intensive

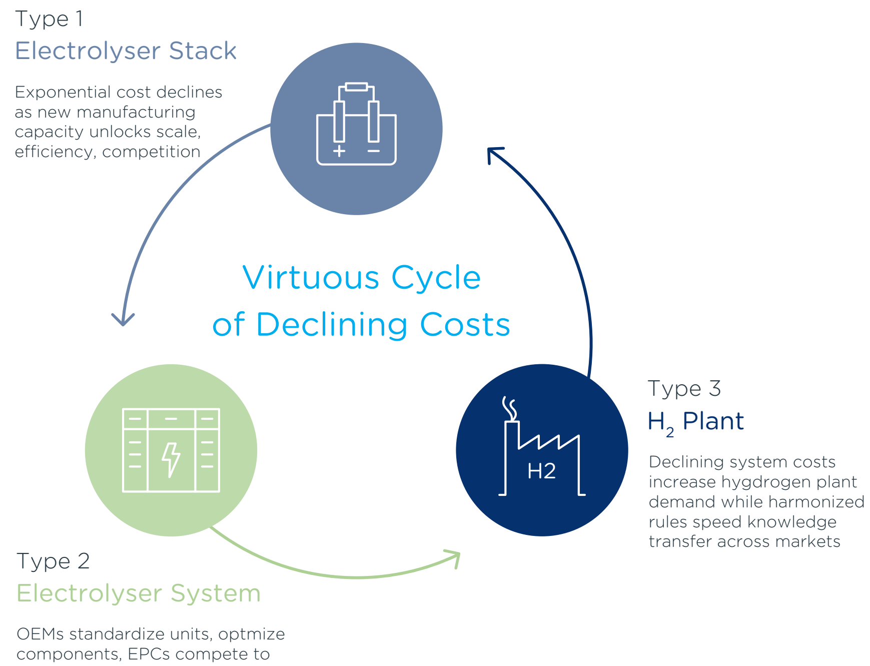


Figure 16: Creating a virtuous cycle of declining costs in hydrogen production requires attention to stack-, system-, and plant-level innovations.

hydrogen production industry. On the other hand, if green hydrogen rules are not synchronized across geographies, learnings about plant design, system optimisation, and asset operation will be contained by geography, slowing the exchange of knowledge between countries and companies in different jurisdictions. The EU and the United States are currently out of step with one another on their certification and regulation schemes, with the EU ahead in terms of definition and all eyes on the Unites States waiting for Internal Revenue Service (IRS) guidance. If the two end up pursuing similar rules, especially around issues of additionality, time-matching, and deliverability of green electricity, then lessons learned in one jurisdiction will be readily applicable to another and the two markets may ultimately be linked by trade. If the United States chooses a less stringent direction, then two distinct markets will form and global plant-level learning rates may suffer over the long term (even if the end result is more electrolysers deployed).

Defining and aligning interconnection rules between green hydrogen plants and other systems will enhance the portability of project designs. Assuming that the green hydrogen certification in the Unites States provides some options for grid-powered electrolysis, an important next step will be working between regulators, electricity system operators like independent system operator, regional transmission organization, and distribution system operator (ISO/RTO/DSOs) and electric utility companies to define interconnection requirements and tariffs for green hydrogen plants. As discussed above, current interconnection processes are long, expensive, and antiquated proceedings. Furthermore, they do not anticipate assets whose controls follow grid carbon intensity as the primary operating condition. These features of green hydrogen production could be a boon to the productivity and resilience of energy systems, but they require regulators, policy makers, system operators and industry to create new definitions, asset rules, proceedings, and tariffs to enable the full value of these assets. To date, minimal progress has been made in terms of developing green hydrogen-plant specific tariffs

or interconnection processes, although the industry may be able to leverage the success of datacentres, many of which have negotiated for specialised tariffs and interconnection processes across the United States and EU to provide them with clean energy and priority access to the system at higher voltages[26].

Enhancing international coordination on RD&D can make sure that each player is contributing towards the highest-value solutions. The green hydrogen industry has grown substantially over the past five years on the back of landmark climate laws in the United States and EU and a massive amount of support across industries, legacy oil and gas producers, and utilities. As of the end of 2023, 41 countries had green hydrogen strategies in place, most focused on scaling green hydrogen production domestically[27]. Alongside this expansion has been a proliferation of coordinating bodies at international, regional, state, industry, and functional levels. At the same time, new public funding for hydrogen RD&D has expanded significantly, with the United States, EU, United Kingdom, Japan, and China all announcing large public investments across research, development, and deployment of green hydrogen production[28].

How can green hydrogen live up to such low expectations?

Despite Ramboll's findings that accelerating green hydrogen project deployment is about much more than electrolyser manufacturing capacity, we have also found that by focusing on the right technology levers, significant CAPEX cost reductions are possible.

The direct costs make up 75 - 90% of the total installed costs estimated by Ramboll. Of this direct cost, between 60%-90% of the costs are from the stacks, compressors, and the electrical equipment, depending on technology. To see a reduction in generation facilities as anticipated by the green hydrogen community, there are a few focus areas that Ramboll suggests draw the focus.

CAPEX relative cost by category, illustrative based on system in 10 MW - 1 GW scales designed by Ramboll in 2023

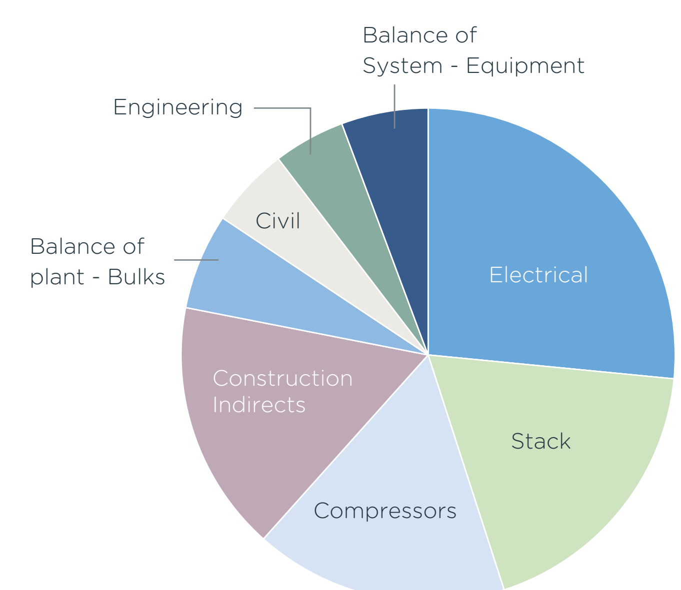


Figure 17: Ramboll's estimates show that local requirements for interconnections to power and offtake systems, such as electrical (grid connection, resiliency, power quality), compressors, and other balance of plant components drive a higher share of CAPEX than public estimates, even at larger (100+ MW) scales.

[26] https://www.datacenterknowledge.com/energy/dominion-creates-clean-energy-tariff-facebook-data-center-virginia
[27] IEA (2023), Global Hydrogen Review 2023, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2023, License: CC BY 4.0
[28] Benedicte Delaval, Trevor Rapson Raghav Sharma, Will Hugh-Jones, Erin McClure, Max Temminghoff, Vivek Srinivasan (2022) Hydrogen RD&D Collaboration Opportunities: Global Report. CSIRO, Australia, http://mission-innovation.net/wp-content/uploads/2022/09/H2RDD-Global-FINAL.pdf

Electrolyser stack level (Type 1): reducing stack costs

Efficiency of raw materials

Using less raw materials in manufacturing the stack will reduce capital cost and extend the lifetime of electrolysers. As evidenced in earlier sections, electrolyser manufacturers are working to reduce the raw materials required for their product, to help with cost savings from their OPEX budget and for raw resource scarcity management. However, manufacturers are focused to get to market share and are hesitant to use resources optimising their design while there is a race to the market.

Automating manufacturing

There is a target to reduce operating costs for the stack through automation. This could reduce the amount of labour and human error in the product yield, however there could be larger electrical costs and troubleshooting shutdowns.

Competition for market share

Many manufacturers are racing for market share with little differentiation between each competitor's products. To gain that market share, manufacturers could be tempted to drop their price to win contracts, however they will need to balance their expenses.

Electrolyser system level (Type 2): reducing system electrical equipment costs

Use of existing electrical facilities

In the short term, projects that have access to existing electric infrastructure will have significant cost advantages. This could include projects running behind the metre on surplus energy alone with a variable green hydrogen offtake or facilities collocated near existing high-power switchgears. This would allow for the facility to leverage the existing infrastructure versus installing their own. However, these capital cost savings would come with associated operating cost increases. In the case of a behind-the-meter facility, the intermittency of green hydrogen (or the requirement for green hydrogen storage) may reduce the ultimate cost savings. In the case of using existing electric infrastructure, there may be operating expenses to the infrastructure owner to allow that utility to earn back their investment. Either of these changes would be highly project-specific and therefore are not considered in Ramboll's projections as a systematic means to reduce green hydrogen future costs.

Technology advancement of electrolyser systems to accept DC power

Advancing the system technology to accept DC power, and therefore reduce the electrical infrastructure requirement, could reduce the need for rectifiers. Electrolyser system OEMs may not have many resources dedicated to developing and testing this solution because there is a current applicable solution, however if a rectifier and stepdown transformers are not required, then there could be significant cost savings.

Less reliability, redundancy reduces need for some equipment

If local jurisdictions would accept redundancy only for the safety systems, or if the owner could allow for intermittent downtime, this could reduce the required electrical infrastructure. This would be a business decision on behalf of the owner, however most Ramboll clients are considering production with firm offtake agreements (aiming for uptime greater than the 20-60% capacity factors provided by wind and solar resources).

Green hydrogen production plant level (Type 3): reducing balance of plant costs

Technology advancement for reciprocating and screw compressors

Compressors are a significant cost to in the bill of materials, especially as the plants scale past 100 MW. There is not much definition in how the compressor technology could advance, however Ramboll is aware of compressor vendors who are actively looking for solutions for the green hydrogen compression market. Due to the well-developed compressor market, this is unlikely, but not impossible to achieve a reduction.

Generate green hydrogen at lower pressure to reduce number of compressors

PEM already output at 30-40 bar while commercially available AEs can operate at 10-30 and SOECs between 0-2 bar. If the owner could use and sell the green hydrogen at the pressure that is output by the electrolyser, there would be a large cost savings to the project (20%-30% of the direct costs). This again changes the basis of the project and therefore is not considered in Ramboll's ideas on green hydrogen future costs.

Footprint reduction for BOP bulks and equipment from reducing electrolyser system size

Although AE is significantly less expensive than PEM stacks, AE is only developed to have about 2.5 MW per container (as opposed to +5 MW), and therefore many containers would be required for a 100 MW+ design. With more containers comes additional excavation and concrete, more pipe branches, more electrical cable, and instrumentation. The challenge is that the bulk materials are on average about 15-40% of the direct costs depending on technology type, and could not reduce likely more than 50% due to the requirement to have all the ancillary systems and equipment.

Hydrogen production CAPEX costs reductions achievable from addressing stack, system and plant level technology challenges

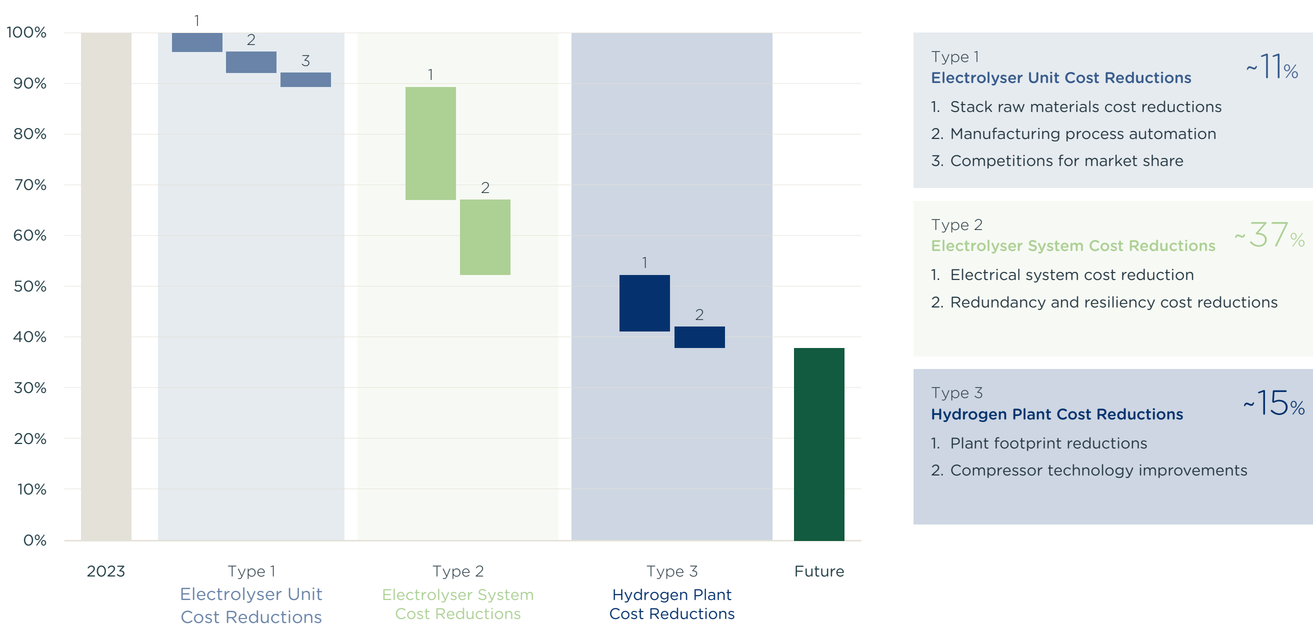


Figure 18: Ramboll analysis of potential hydrogen production plant CAPEX cost reductions from overcoming technology challenges.

Ramboll assigned reasonable target savings percentages and applied them to the appropriate cost code of account to develop a waterfall graph as shown in . This graphic only includes the opportunities that would not change the project objective or scope of work. By applying the target savings percentages, it results in a more than 60% reduction target if all opportunities come to fruition. The biggest savings comes from the technology advancement that allow for stacks to accept DC power, less requirements for redundancy or resiliency of electrical infrastructure, and reduction in footprint for all ancillary equipment and bulks. Therefore Ramboll encourages investments to be targeted toward these applications.

Conclusion

Green hydrogen production is a unique opportunity because it marries the simplicity and scalability of a mass-produced technology (electrolysers) with the complexity and customisation of an industrial-scale system. From a demand side, cheap, green hydrogen could be a solution to the hard-to-abate sectors that currently have limited viable technological alternatives. However, the promises of the steep cost declines of Wright's Law exhibited by solar and storage technologies are mitigated by the challenges of green hydrogen production which is an interlocking system of technologies. Many forward cost estimates discount the degree to which green hydrogen production requires integration between existing complex products and systems.

Our analysis highlights that these cost declines are possible, but that investment costs at the H2 production system level will not decline on the basis of deployment alone. Standardisation of components, definition of interconnection processes, and harmonisation of regulatory environments across borders are the keys to unlocking sustained CAPEX cost declines over time for green hydrogen production plants.

Need for Customization, Degree of Design Complexity

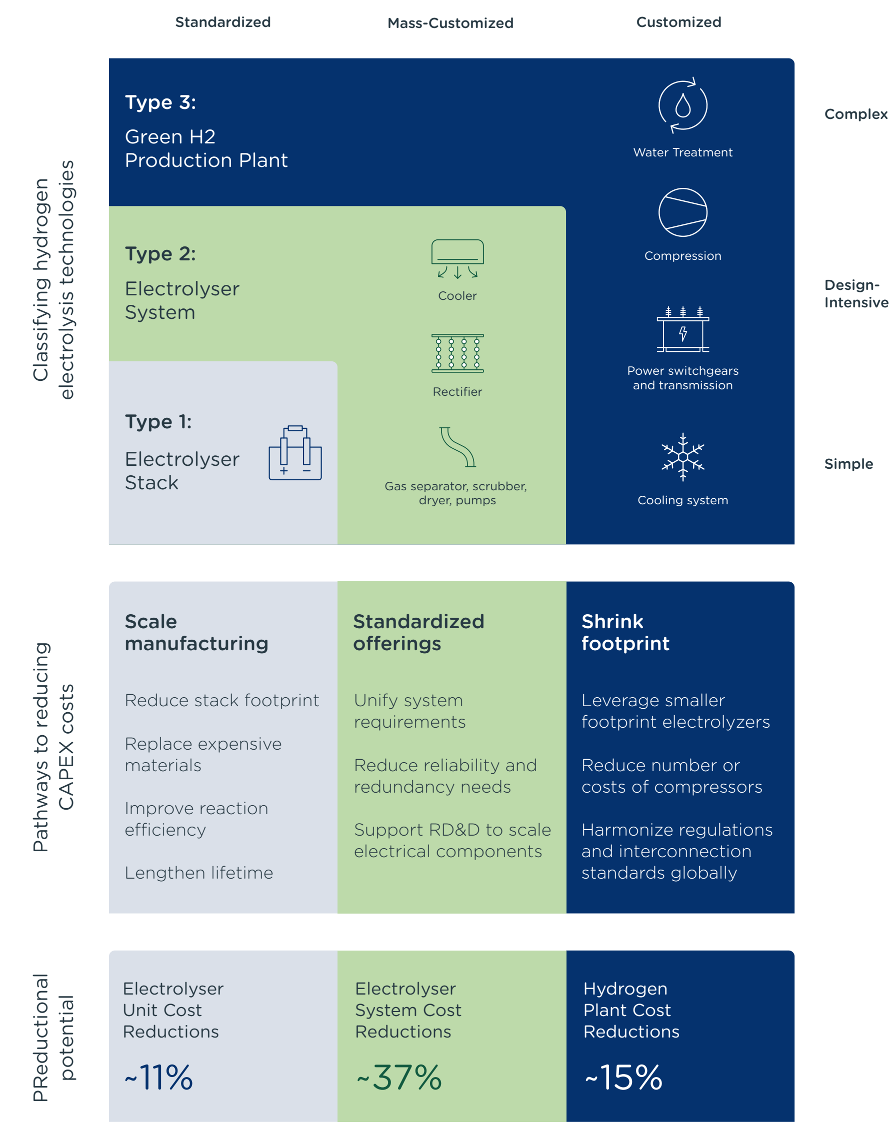


Figure 19: Achieving lower capital expenditure costs for each type of technology used in hydrogen production plants.

Achieving affordable green hydrogen production plants

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