Solid Oxide Electrolysis: A Technology Status Assessment

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Executive Summary

This report provides a summary assessment of the state of solid oxide electrolysis technology. In contrast to other, more widely commercialized electrolyzer options, such as polymer membrane or alkaline cells, solid oxide electrolyzer cells (SOECs) operate at much higher temperatures. This feature confers potential efficiency advantages, which are of interest in light of strong expected future demand for clean hydrogen production using clean electricity powered electrolysis. But high-temperature operation and other features of SOEC systems also pose challenges. **Several key points emerge from this assessment:**

1. The maturity of solid oxide electrolysis technology is underestimated. But SOEC manufacturers still have a critical hurdle to clear on the path to successful commercialization: scaling their product offerings from small modules, with capacity in the single-digit megawatts, to large systems with capacities well into the hundreds of megawatts.
2. The capability to manufacture SOECs is not a bottleneck to the wider deployment of this technology – in fact, gigawatt-scale manufacturing could be built up in 18 to 36 months. As with any technology, supply chains need to be managed prudently, but there is no shortage of raw materials.
3. The types of industrial facilities that are well suited for integration with SOEC include ammonia, chemical, and steel plants, as well as refineries. The chief advantage of SOECs over other electrolyzer architectures, such as polymer electrolyte membrane (PEM), alkaline, or anion exchange membrane (AEM), is predicated on the ability to access an external source of process heat. Without an external source of heat for steam generation, the potential 20% efficiency advantage of solid oxide systems over future competing electrolyzer architectures largely disappears.
4. High-temperature operation is a double edged sword: it increases electrolyzer efficiency on the one hand but due to thermal stresses increases the probability of accelerated stack failure on the other. New materials, advances in manufacturing techniques, and growing manufacturer and operator experience, including with solid oxide fuel cells, a closely related technology, have led to vastly improved durability.
5. Wider SOEC deployment has been held back, not only by the perception that the technology is immature, but also because demand for electrolyzers in general has been limited until recently. Responding to growing interest in decarbonization options, particularly for hard to electrify sectors, some solid oxide technology vendors have begun adding an electrolyzer product to their offerings. Industrial customers that are already using hydrogen, including chemical plant and refinery operators, are actively looking at SOECs. Solid oxide electrolysis is also of strong potential interest to up-and-coming companies that are pursuing synthetic fuel production and new nuclear energy technologies, but these potential partners have yet to establish a substantial commercial presence.

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SECTION 1

Introduction

Hydrogen has been widely discussed as an option for decarbonizing sectors where direct electrification or other low-carbon options might not be practical, or even feasible at all. Examples of such sectors include the chemical and fertilizer industries, steelmaking, synthetic fuel production for long-distance shipping and aviation, and long-term energy storage. For these sectors, hydrogen offers several potential advantages: It can be produced with low emissions from a variety of feedstocks using a variety of methods, it emits no carbon dioxide (CO_2) at the point of use, and it is versatile and can be used in a range of applications.

Today, hydrogen is already produced on a large scale, primarily for use as an industrial feedstock in fertilizer production and to refine oil products, among other applications. Decarbonization efforts, however, could substantially increase global demand for hydrogen. The International Energy Agency (IEA) has estimated that future hydrogen demand could soar more than five-fold, from approximately 90 million tonnes per year at present to as much as 500 million tonnes per year by 2050.

Unfortunately, virtually all hydrogen produced today – more than 99% – is made from fossil fuels or uses fossil fuel energy inputs, without carbon abatement. As a result, it is relatively carbon intensive. For hydrogen to contribute to the achievement of net-zero goals, two challenges must be overcome: hydrogen production must be scaled up dramatically, and it must be decarbonized at the same time.

Two main pathways for decarbonizing hydrogen production are technologically available and scalable today:

1. Production from fossil fuel feedstocks with carbon capture (at CO_2 capture rates greater than 90%) and strict upstream methane controls.
2. Production using electrolysis powered with low-carbon electricity.

The term “electrolysis” describes a process in which an electrical current is used to split molecules. Theoretically, this can be done with many types of molecules, but water electrolysis – in which water molecules are split into their constituent oxygen and hydrogen elements – is the focus of this report and of most efforts to develop electrolysis technology. Water electrolysis can deliver low-emissions hydrogen if powered entirely with low-carbon electricity. In addition to its carbon-reduction benefits, some countries see this hydrogen production pathway as an opportunity to break their dependence on fossil fuel imports. Electrolysis-based, low-carbon hydrogen production could also provide system integration

Figure 1: Global Demand for Hydrogen by Sector in IEA's Net Zero Scenario, 2020–2050[1]

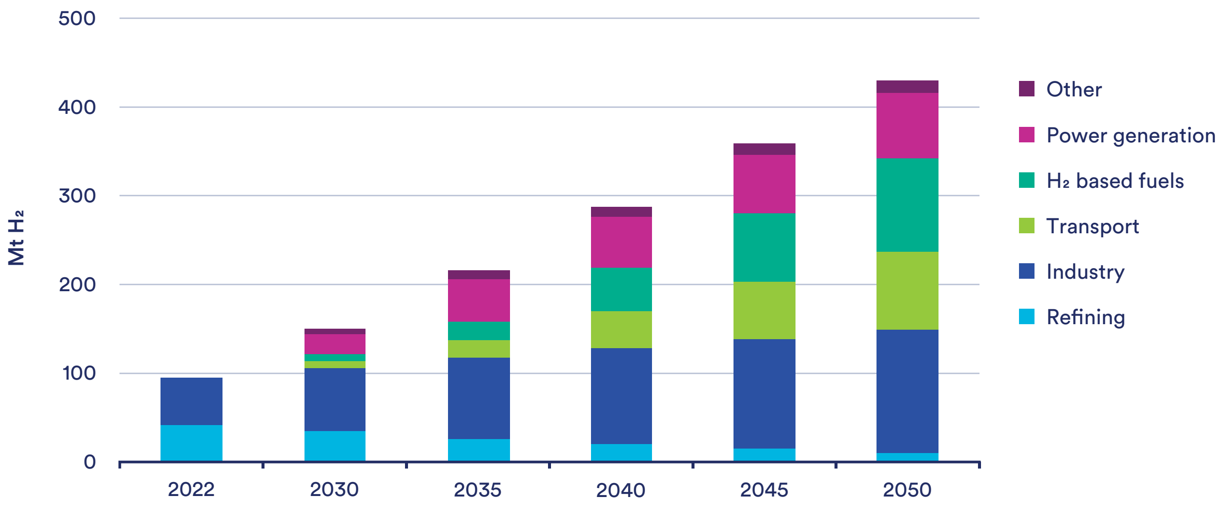
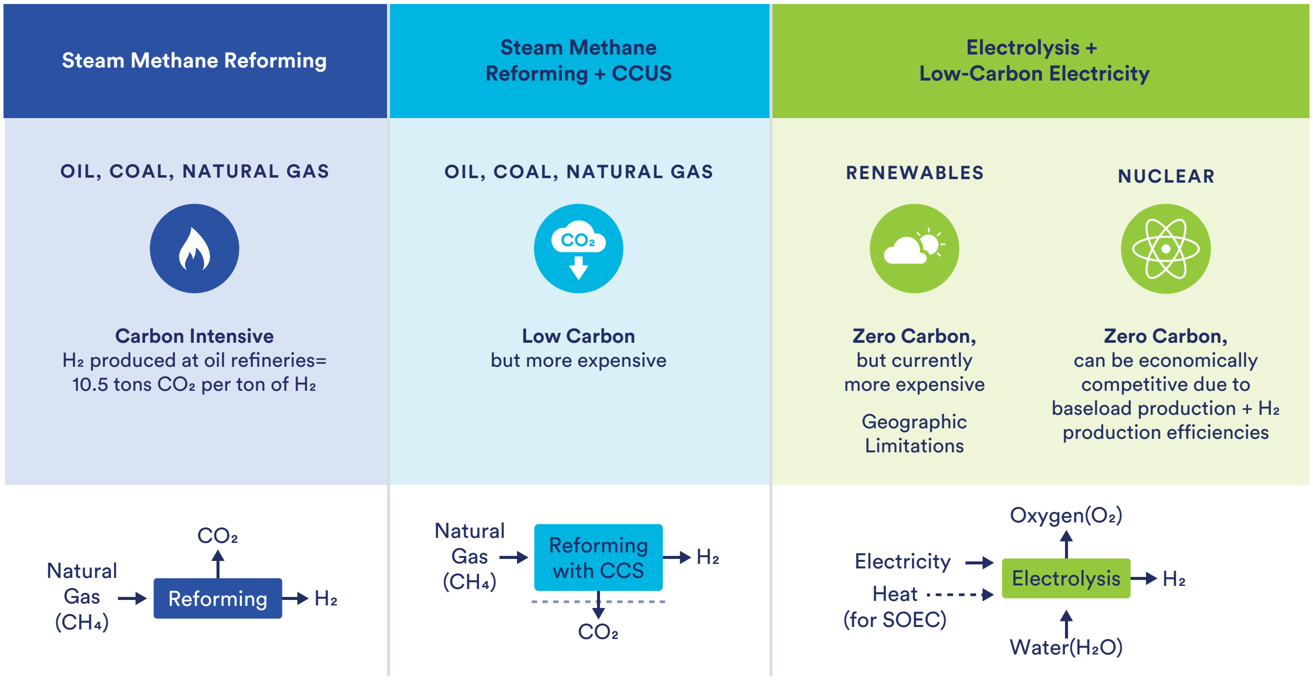


Figure 2: Technologies for Hydrogen Production Including Low- or Zero-Carbon Pathways



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[1] IEA (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector. https://www.iea.org/reports/net-zero-by-2050

services[2] for power grids that are heavily dependent on intermittent renewable generators. The main drawback of electrolysis is that current mainstream technologies require a lot of electricity to break apart water. Normally, around 30%–40% of input electricity is wasted as heat.

Among the lesser-known electrolyzer technologies, high-temperature architectures are unique in that they leverage external sources of heat to increase the electrical efficiency of electrolysis. Ideally, such high temperature electrolyzers could be paired with applications that generate a lot of high-grade process heat, including industrial processes such as steelmaking and refining, or nuclear and geothermal electricity generation.

However, high temperature electrolysis does not feature prominently in press announcements of new hydrogen projects. The technology is widely considered to be at the R&D stage, with significant technological challenges to be overcome before it is ready for commercialization. Yet, net-zero commitments and government policies, particularly those of the European Union, require massive scale-up of electrolytic capacity now.[3]

With limited time to cut carbon emissions and avoid the worst impacts of climate change, decisionmakers face pressure to promote technologies that are commercially available. This report provides an update on the status of solid oxide electrolyzer cell (SOEC) technology, which has been the focus of development efforts for high temperature electrolysis.

The remainder of this report is organized as follows: Section 2 begins with a general overview of high temperature electrolysis and SOEC. Section 3 discusses the advantages and disadvantages of SOEC relative to other electrolyzer technologies, highlighting current challenges and avenues for improvement. Section 4 summarizes available information on the technology readiness level (TRL) of SOEC systems based on early deployments in different industrial applications. Section 5 discusses market considerations and hurdles to commercial deployment. Section 6 concludes with suggestions for further policy support and investment.

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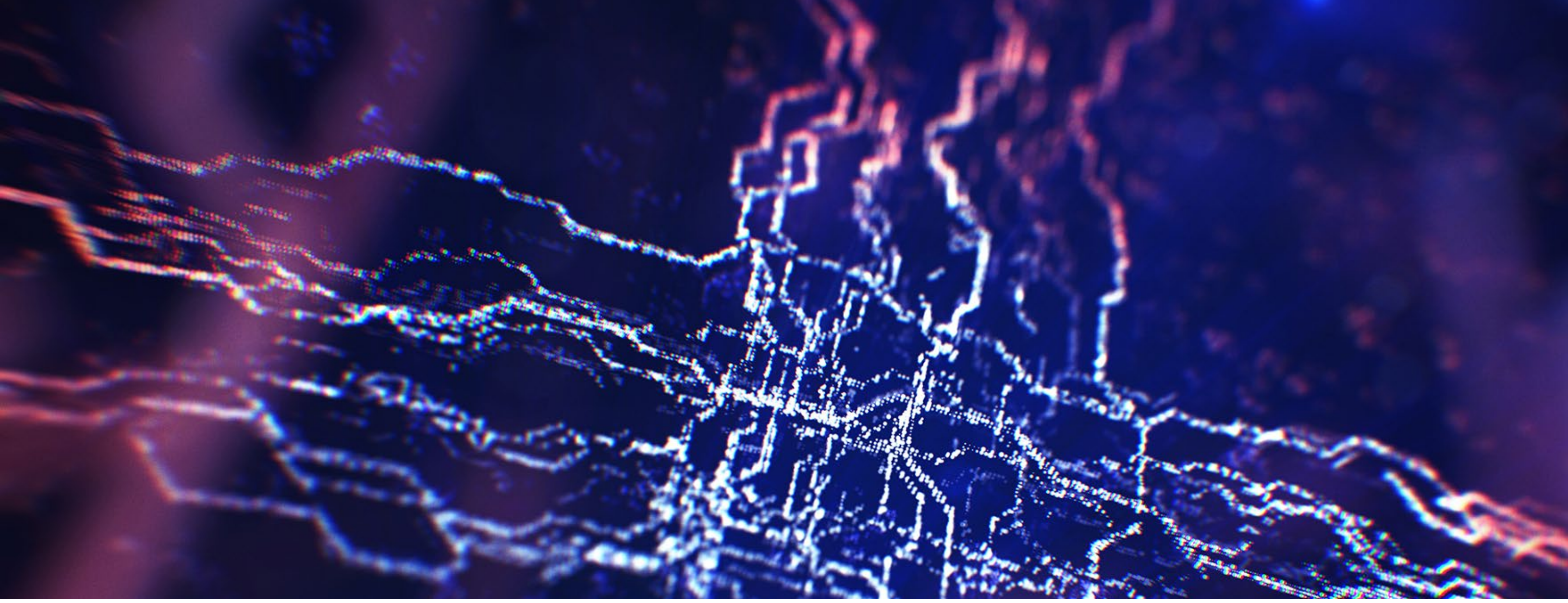
[2] For example, the use of excess wind and solar generation to power electrolysis facilities during periods of high wind and solar availability could help stabilize the grid and create storable energy (in the form of hydrogen fuel) that could potentially be used during periods of low renewables availability.

[3] Odenweller, A., Ueckerdt, F., Nemet, G.F. et al. (2022). Probabilistic feasibility space of scaling up green hydrogen supply. Nat Energy 7, 854–865. https://www.nature.com/articles/s41560-022-01097-4



SECTION 2

An Overview of High Temperature Electrolysis and SOEC Technology

2.1 Electrolysis Basics

As noted in the introduction, electrolysis involves using an electric current to split molecules in a device called an electrolyzer. Electrolysis can be performed on many types of molecules, but the focus of this report is water electrolysis. Every cell in a water electrolyzer shares the same three basic components:

- A positively charged anode where oxidation takes place.
- A negatively charged cathode where a reduction to hydrogen takes place.
- An electrolyte that conducts ions between electrodes.

Anodes, cathodes, and electrolytes can be built from a wide array of materials, but certain combinations outperform others.[4] Table 1 describes the four main electrolyzer architectures that are on the market today.[5]

2.2 Fundamentals of High Temperature Electrolysis

The terms "high temperature" and "solid oxide" electrolysis are often used interchangeably for the simple reason that solid oxide electrolyzers are uniquely capable of operation – indeed, they require operation – at temperatures between 500 and 1000 degrees Celsius (°C). Electrolyzing water (steam) at a very high temperature confers two advantages:

1. Intrinsic fast-reaction kinetics and better conductivity lead to efficiencies approaching 100%.[6]
2. The option of leveraging external sources of heat (in lieu of using internal electrical energy) creates opportunities to attain electrical efficiencies exceeding 100%.[6]

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[4] Two more electrolyzer architectures are considered emerging: membrane-less electrolysis, developed by companies like CPH_2 or Supercritical, and E-T developed by H_2Pro.

[5] Renewable Hydrogen: Modular Concepts from Production over Storage to the Consumer - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Comparison-of-the-electrolysis-technologies-PEMEL-AEMEL-AEL-and-HTEL-based-on-11_fig2_349090866

[6] Elaborated further in Section 3.1 of this report.

Table 1: Summary of Main Electrolyzer Chemistries

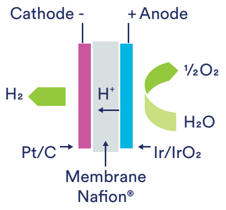
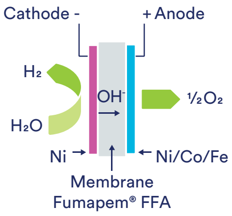
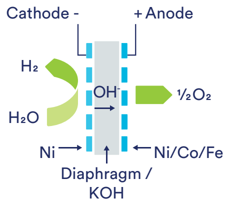
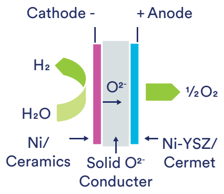
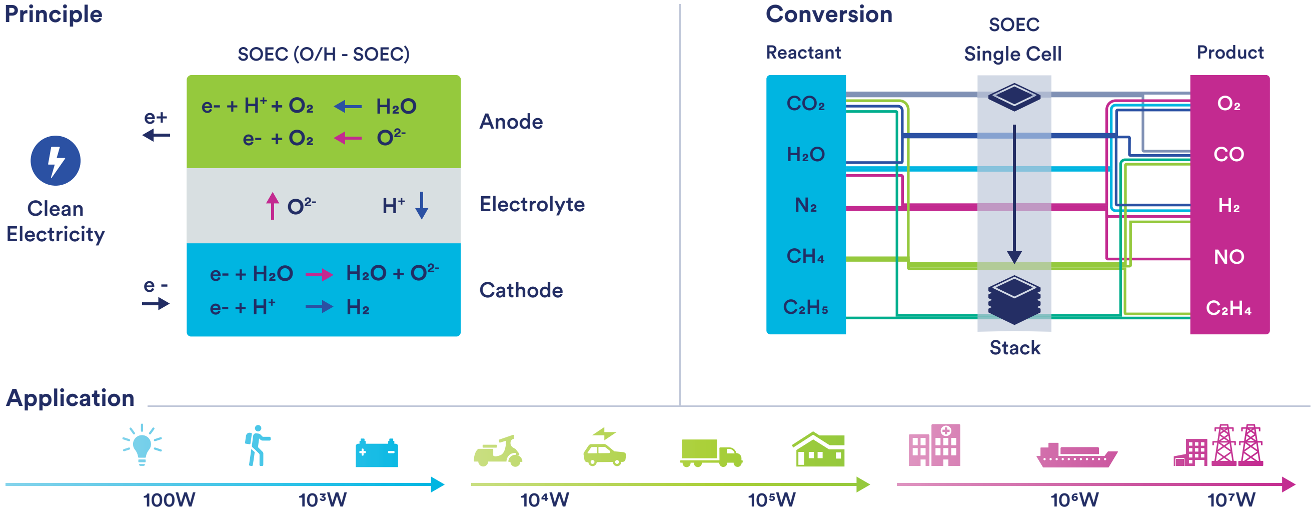
Electrolysis Technology	**PEM – Polymer Electrolyte Membrane**	**AEM –Anion Exchange Membrane**	**Alkaline**	**HT – High Temperature**
Electrolyte	Acidic Solid (polymer)	Alkaline Solid (polymer)	Alkaline Liquid	O_2 or H+ conducting Solid (ceramic)
				
Operating Temperature	50°C–80°C	40°C–80°C	60°C–95°C	500°C–900°C
Leading Manufacturers	plug ohmium ITM POWER SIEMENS energy PH2 Peric Hydrogen SUNGROW	Enapter	LONGi John Cockerill thyssenkrupp PH2 Peric Hydrogen SUNGROW Hydrogen pro AUYAN nel sunfire H2 中电丰业 SinoHy Energy	sunfire TOPSOE Bloomenergy FuelCell Energy

Figure 3: Possible Combinations of Reactants and Products in Solid Oxide Electrolyzers[7]



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[7] Zheng, Y., Chen, Z. & Zhang, J. (2021). Solid Oxide Electrolysis of H_2O and CO_2 to Produce Hydrogen and Low-Carbon Fuels. Electrochem. Energ. Rev. 4, 508–517. https://doi.org/10.1007/s41918-021-00097-4

While the focus of this report is on water electrolysis, it is worth mentioning that SOECs can be used to electrolyze other combinations of molecules so long as at least one of these molecules, owing to the ion-conducting properties of the solid oxide electrolyte, can donate an oxygen or a hydrogen ion. A notable combination would be steam and carbon dioxide, which, when electrolyzed, produces a mixture of carbon monoxide, hydrogen, and steam. This mixture, commonly referred to as syngas, can be further processed into synthetic fuels. Figure 3 shows combinations of potential reactants and their products.

Despite its advantages, SOEC is often portrayed as a much less mature technology compared to polymer (PEM) and alkaline electrolyzers. Low stack power and high operating temperature, which in turn requires more ancillary equipment to operate the electrolyzer, are widely viewed as the main drawbacks of SOEC technology. SOEC systems are also considered to have a shorter operating life due to thermal stress.

The largest SOEC systems installed to date range between 100 kilowatts (kW) and 1 megawatt (MW) in size. Most have been installed as pilot or demonstration projects, and thus do not represent commercial deployments.[8] However, judging the commercial readiness of SOEC based on these projects would not do the technology justice: SOECs are practically identical in design and manufacturing to solid oxide fuel cells (SOFC), which have already been deployed at well above gigawatt (GW) scale in backup power generation and microgrid applications. Thus, learnings from SOFC deployments and manufacturing experience could be expected to translate to SOEC. Perhaps unsurprisingly, many companies that are active in SOFC development have recently expressed interest in manufacturing SOECs as demand for electrolyzers has ballooned.

2.3 Basic Elements of Solid Oxide Electrolyzer Cells and Systems

Figure 4 illustrates the basic elements of a unit solid oxide cell, which include:

- A metal separator, also known as an interconnector, on both sides of the cell. The separator conducts current.
- A cathode where water is reduced to hydrogen. The cathode is fashioned out of perovskite or perovskite-like[9] oxides to make it ionically conductive and coated with a nickel catalyst to make it electrically conductive.
- The eponymous ceramic, solid oxide electrolyte. The electrolyte provides ionic conductivity for the oxygen ions to cross while blocking gas diffusion from the cathode. It must be electrically insulating, mechanically strong, and capable of withstanding high temperatures. Doping, which is a term for adding small impurities to a semiconductor, is used to mitigate cracking caused by thermal expansion.
- An anode where the oxide will donate electrons to produce oxygen. Anodes must be ionically conductive to receive oxide ions. They are usually made from perovskite or perovskite-like oxides.

The typical solid oxide electrolyzer cell will have power measured in tens or hundreds of watts, due to its small surface area. Small surface area makes it easier maintain cell quality when SOECs are manufactured *en masse*, and to distribute heat evenly across the stack during operation. To raise power per unit area, multiple cells are placed on top of each other and linked using interconnects to form an electrolyzer stack. Glass, glass-ceramics, metallic solders, or compressive gaskets are used to ensure a gas-tight seal between the cells.[10]

Stacks can come in different shapes. Figure 5 shows an example of a square solid oxide fuel cell stack. While SOFCs are distinct from SOECs, the visualization largely applies to a solid oxide electrolyzer as well, with the key difference that cathode and anode are inverted, and the chemical reactions proceed in the opposite direction.

Other common stack designs include rectangular, hexagonal, or even disc shapes, and reflect different approaches to manufacturing. However, even in a stack configuration, solid oxide technology will typically have a power rating at least one order or, in some cases, two orders of magnitude less than competing technologies. Thus, while a generic solid oxide stack today might be rated at 10 kW, a typical PEM stack would be rated in hundreds of kW and an alkaline stack in thousands of kW. Solid oxide stacks will be connected into modules to achieve cumulative power ratings in the range of hundreds of kW.

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[8] More information on pilot and demonstration projects is provided in Section 4 of this report.

[9] That is, with the same crystal lattice structure as perovskite, or calcium titanate (CaTiO3).

[10] Ivanova, M. E., et al. (2023). Technological Pathways to produce compressed and highly pure hydrogen from solar power. *Angewandte Chemie International Edition*, 62(32). https://doi.org/10.1002/anie.202218850

Figure 4: Cross Section of a Planar SOEC Stack[11]

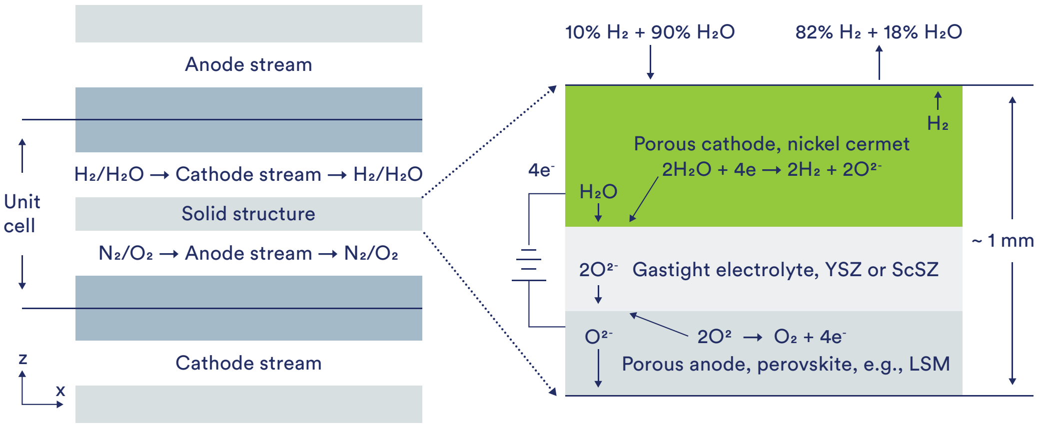
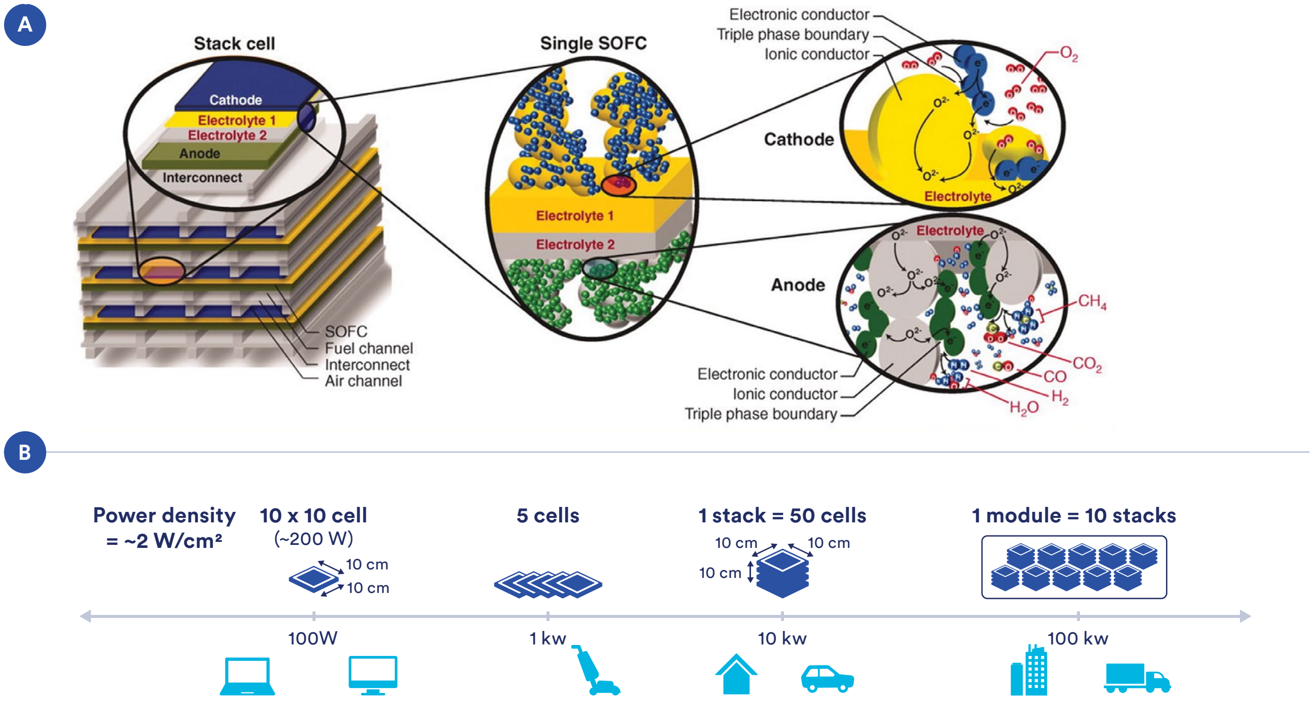


Figure 5: (A) Square Solid Oxide Stack; (B) Upsizing the Power of a Solid Oxide System by Stacking Cells and Combining Stacks into Modules[12]



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[11] Idaho National Lab. 2019. *Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest.* https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_18785.pdf

[12] Wachsman, E. D., & Lee, K. T. (2011). Lowering the Temperature of Solid Oxide Fuel Cells. *Science.* https://www.science.org/doi/10.1126/science.1204090

Other supporting components and auxiliary systems needed to operate a working SOEC system are known as 'balance of plant' (BoP). For example, SOEC systems require a top up heater to bring incoming steam to the stack's operating temperature and ensure that no temperature gradients form that might damage the stack. As the electrolysis reaction proceeds at high temperature, high-grade heat can be recovered and recycled with the use of heat exchangers. All of this will typically take place inside a 'hot box' which also houses the array of SOEC stacks.

Other generic BoP elements include:

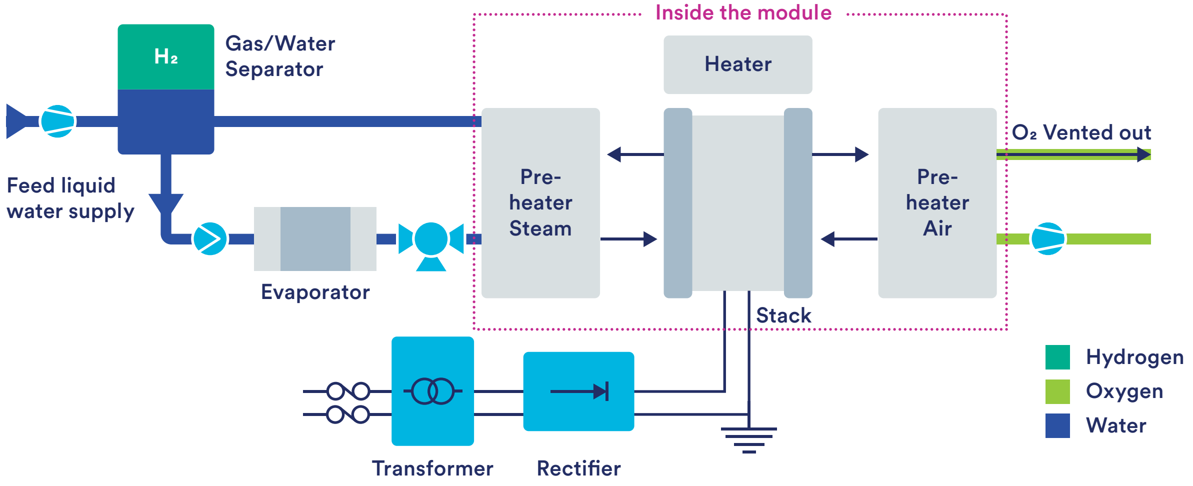
- A water purifier to ensure deionised water.
- A water feed and recycle pumps.
- A water vaporiser to turn water into steam.
- A hydrogen/steam separator (as hydrogen gas is produced at the same electrode where steam is fed, a mixture of steam and hydrogen is produced which requires separation).
- Power electronics such as DC/DC converters, rectifiers, and transformers.
- Heat exchangers/recuperators to recycle heat, including from external sources.
- A dryer to ensure the hydrogen output is completely pure.
- Compressors for hydrogen and oxygen.
- Instrumentation to monitor and control the performance of the electrolyzer.

A simplified diagram of a solid oxide system is shown in Figure 6.

Figure 7 shows an experimental setup of a SOEC module housing a single 16 kW stack by FuelCell Energy. The picture includes BoP components like the power and controls cabinet and the vaporizer outside the stack 'hot box.'

To put the size of a solid oxide electrolyzer in context, a comparison to similar, containerized turnkey alkaline, PEM, and AEM products is helpful. Generally, the rough power of the electrolyzer can be predicted from its physical dimensions and operating current density. Accordingly, PEM electrolyzers would be expected to be the most compact, delivering about twice the power of AEM, alkaline, or solid oxide electrolyzers for the same footprint. For instance, the images in Figure 8 show that while a 2.5 MW PEM electrolyzer would fit in a 40-ft container, the same container could house only 1 MW AEM or alkaline electrolyzers, or a 720-kW SOEC system.

Figure 6: Diagram of an Electrolyzer, Complete with Balance-of-Plant Components[13]



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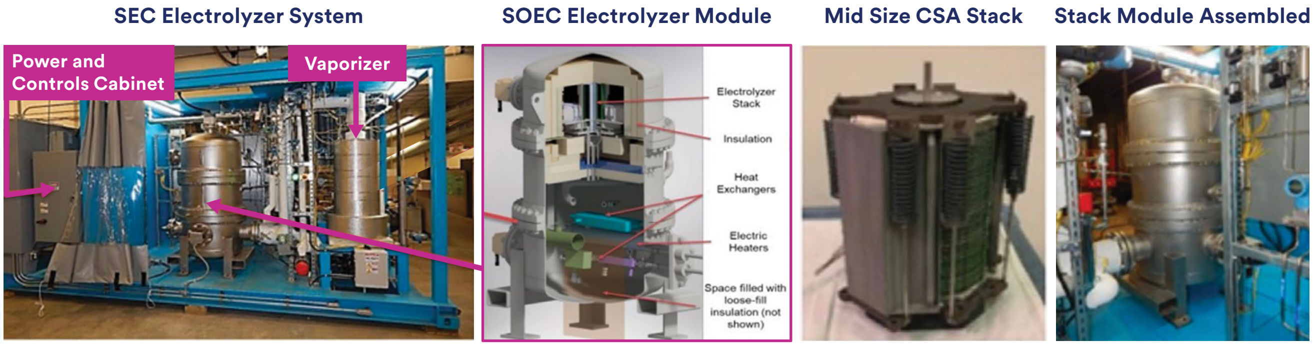
[13] International Renewable Energy Agency. (2020). *Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5C Climate Goal.* https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

Figure 7: FuelCell Energy Single-Stack, 16-kW SOEC Module[14]



SOEC Stack Module:

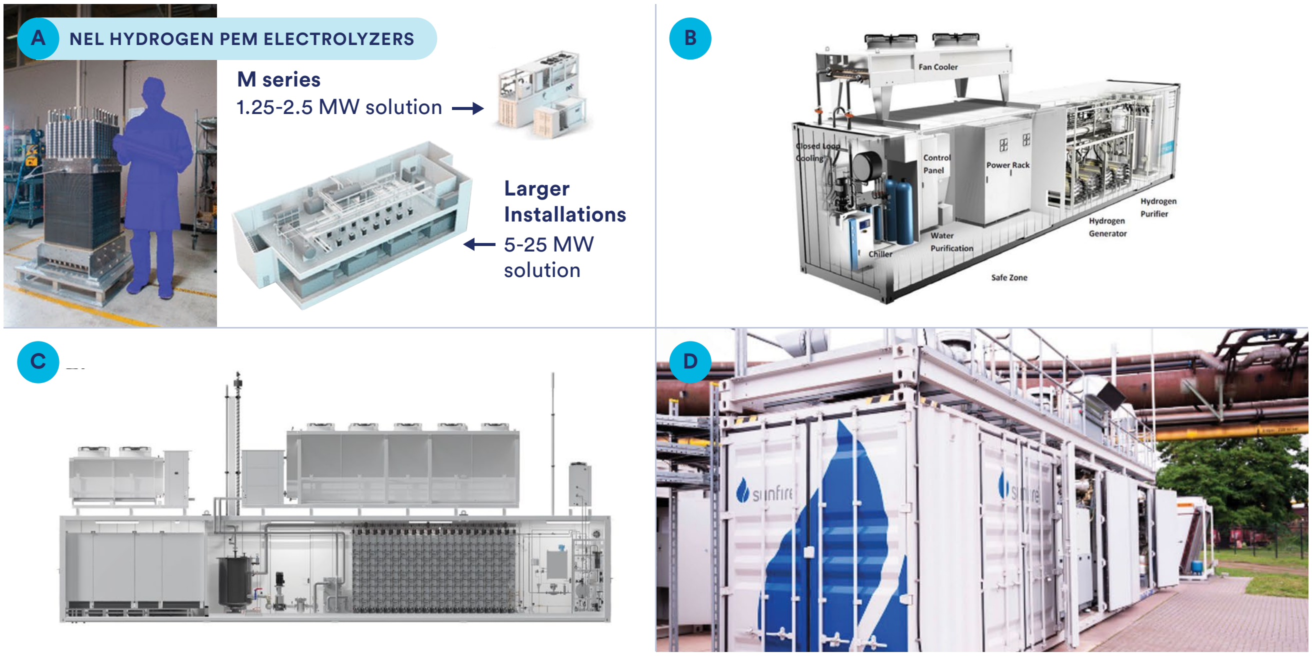
125 psig (8.6 barg) design pressure

Accommodates 1x150-cell stack or 4x45-cell stacks with adapter

Enclosure vessel is designed in accordance with ASME B&PV Code Section VIII Div. II, with internal insulation to allow a touch-safe vessel wall temperature

Figure 8: Turnkey Containerized Products from Electrolyzer Manufacturers

(A) Nel's 1.25–2.5 MW PEM,[15] (B) Cummins 1-MW Alkaline,[16] C) A Rendering of Enapter's AEM 1-MW Multicore,[17] and (D) Sunfire's 720 kW SOEC[18]



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[14] Ghezel-Ayaagh, H. (2021). Performance Improvements for Reversible Solid Oxide Fuel Cell Systems [PowerPoint slides]. Fuelcellenergy. https://netl.doe.gov/sites/default/files/netl-file/21SOFC_Ghezel-Ayagh17.pdf

[15] Ouimet, R. J., Glenn, J. R., De Porcellinis, D., Motz, A. R., Carmo, M., & Ayers, K. E. (2022). The role of electrocatalysts in the development of gigawatt-scale PEM electrolyzers. *ACS Catalysis,* 12(10), 6159–6171. https://doi.org/10.1021/acscatal.2c00570

[16] Cummins Inc. (2021). *Hydrogen: The Next Generation*. Columbus, IN; Cummins Inc. Retrieved from https://www.cummins.com/sites/default/files/2021-08/cummins-hydrogen-generation-brochure-20210603.pdf

[17] *# AEM Multicore.* Enapter Handbook. (n.d.). https://handbook.enapter.com/electrolyser/aem_multicore/aem_multicore.html

[18] *Grinhy2.0.* SALCOS®. (n.d.). https://salcos.salzgitter-ag.com/en/grinhy-20.html

Of course, not all customers will buy turnkey containerized systems. Developers of larger projects (100s to 1000s of MWs) will probably opt for larger stack-module sizes. For instance, John Cockerill's 5-MW stack occupies most of the container, leaving insufficient space for balance of plant, which might have to be shipped separately. When the whole system is integrated at its destination, it could occupy a similar space as two standalone containerized PEM products while delivering the same amount of hydrogen.

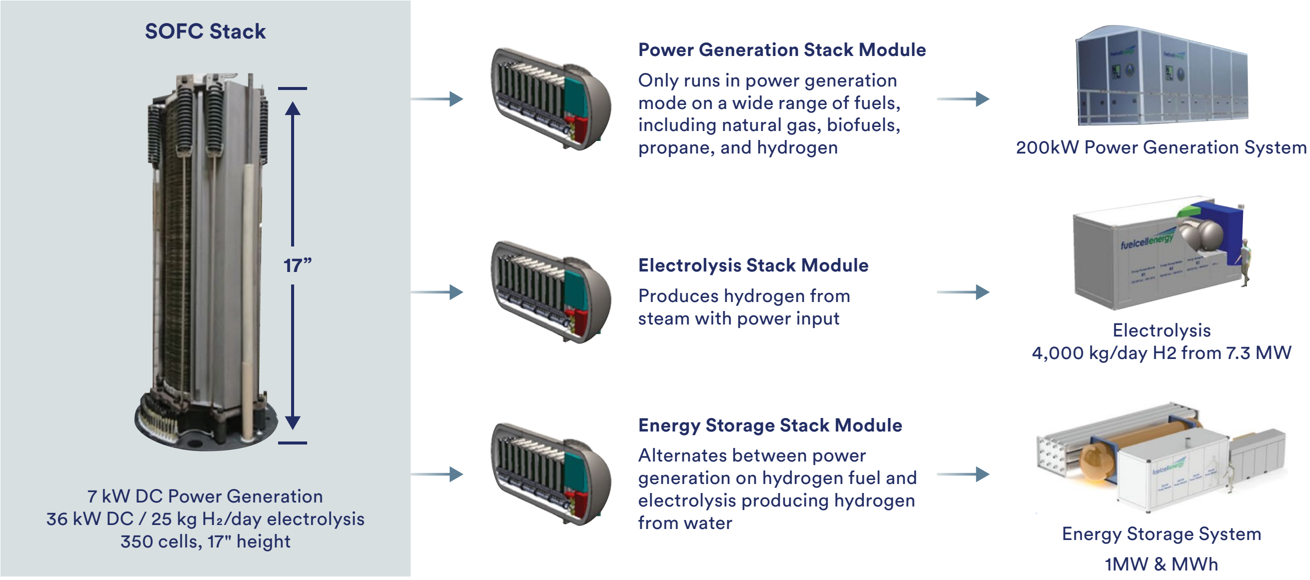
Upsizing the power of a single solid oxide stack is difficult because a larger cell area creates thermal distribution problems. However, solid oxide stacks can be connected into larger arrays – all this requires is a larger hotbox (Figure 10).

At the end of the day, the physical footprint of an electrolyzer system will depend on the interplay of the cell's power density, the stack-module size, and the overall plant design. Nevertheless, since PEM technology has intrinsically high cell density, PEM plants are generally likely to be the most compact. In comparison, electrolyzer systems that rely on AEM, alkaline, and solid oxide technologies will generally be twice as big.

Should there be a need to upsize a solid oxide system to gigawatt (GW) scale, modules can be connected in parallel to form a larger, more powerful block that shares some *system-level* BoP components, such as middle- and low-temperature heat recuperators, compressors, water and hydrogen purification and storage systems, and power electronics.

Figure 9: John Cockerill's 5 MW-Alkaline Stack (right) Connected to its Balance of Plant

Figure 10: FuelCell Energy's Solid Oxide Stacks can be Bundled Together Inside a Single Hotbox Module[19]



7 kW DC Power Generation
36 kW DC / 25 kg H_2/day electrolysis
350 cells, 17" height

Power Generation Stack Module
Only runs in power generation mode on a wide range of fuels, including natural gas, biofuels, propane, and hydrogen

200kW Power Generation System

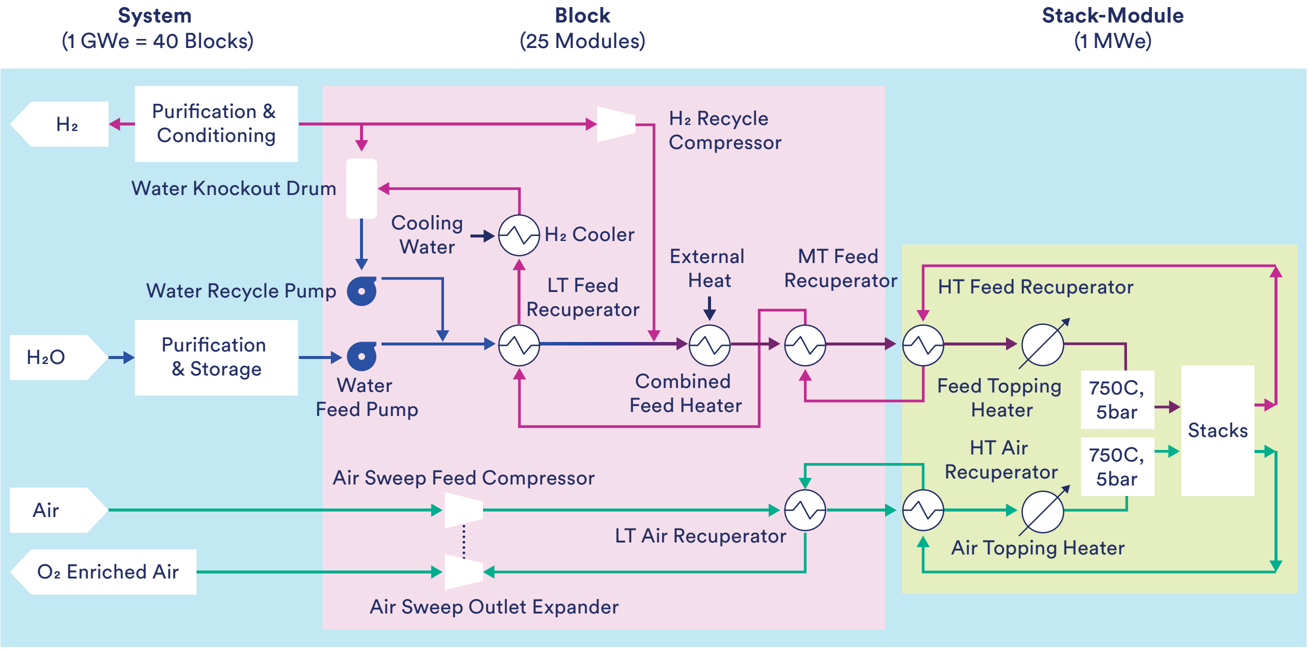
Electrolysis Stack Module
Produces hydrogen from steam with power input

Electrolysis
4,000 kg/day H2 from 7.3 MW

Energy Storage Stack Module
Alternates between power generation on hydrogen fuel and electrolysis producing hydrogen from water

Energy Storage System
1MW & MWh

Figure 11: System Design of a GW-Scale Solid Oxide Electrolyzer Plant[20]



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[19] Ghezel-Ayaagh, H. (2021). Performance Improvements for Reversible Solid Oxide Fuel Cell Systems [PowerPoint slides]. Fuelcellenergy. https://netl.doe.gov/sites/default/files/netl-file/21SOFC_Ghezel-Ayagh17.pdf

[20] James, B.D., Prosser, J.H., & Das S. (2022) HTE Stack Manufacturing Cost Analysis [PowerPoint slides]. Strategic Analysis. https://www.energy.gov/sites/default/files/2022-03/HTE%20Workshop-Strategic%20Analysis.pdf

Block sizes may vary initially as manufacturers and developers figure out the optimal size, but they will likely end up in the tens of MW up to 100 MW. For instance, FuelCell Energy has proposed a GW-scale system composed of twenty 50-MW blocks, with each block composed of two 25-MW stack-modules, housing hundreds of stacks (Figure 12).

While there are no technical barriers to making ever larger blocks, there are trade-offs between BoP costs and redundancy. Figure 13 illustrates three possible configurations of hot-boxes and BoP for the same nameplate capacity.

Figure 12: FuelCell Energy's Design for a GW-Scale System for Converting Off-Peak Nuclear Power to Hydrogen[21]

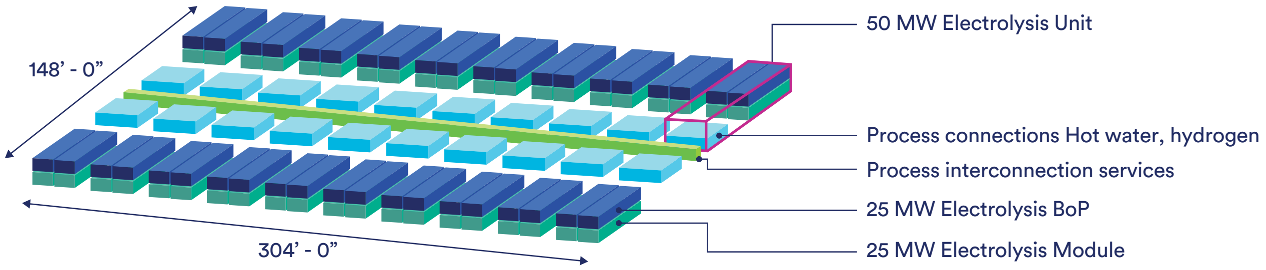
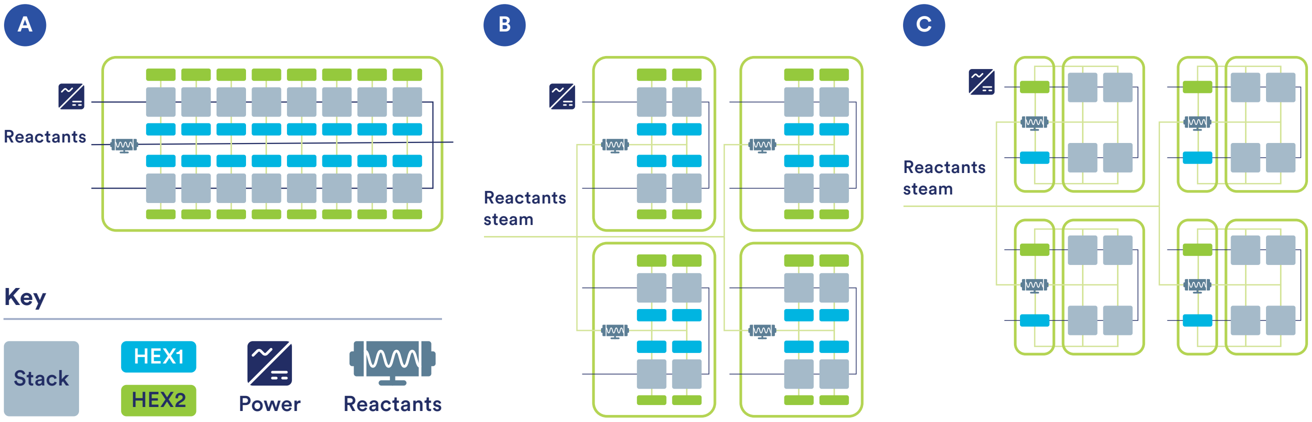


Figure 13: Scaled-Up Designs of SOEC Hot-Boxes with Balance of Plant Elements for the Heating System:

(A) 1 Hot-Box of 1.5 MW with 16 of 94 kW Stacks and Integrated Heat BoP,
(B) 4 Hot-Boxes of 0.4 MW (i.e. 4 of 94 kW Stacks Per Hotbox) with Integrated Heat BoP, and
(C) 4 Hot-Boxes of 0.4 MW (i.e. 4 of 94 kW Stacks) with Separate Stack-Box and Heat BoP-Box[22]



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[21] (2022) FuelCell Energy Platforms for Hydrogen Production [PowerPoint Slides]. FuelCell Energy. https://www.energy.gov/sites/default/files/2022-03/Bulk%20Storage%20Workshop_Day1_06.pdf

[22] Institute for Sustainable Process Technology. (2023). Next Level Solid Oxide Electrolysis. https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf

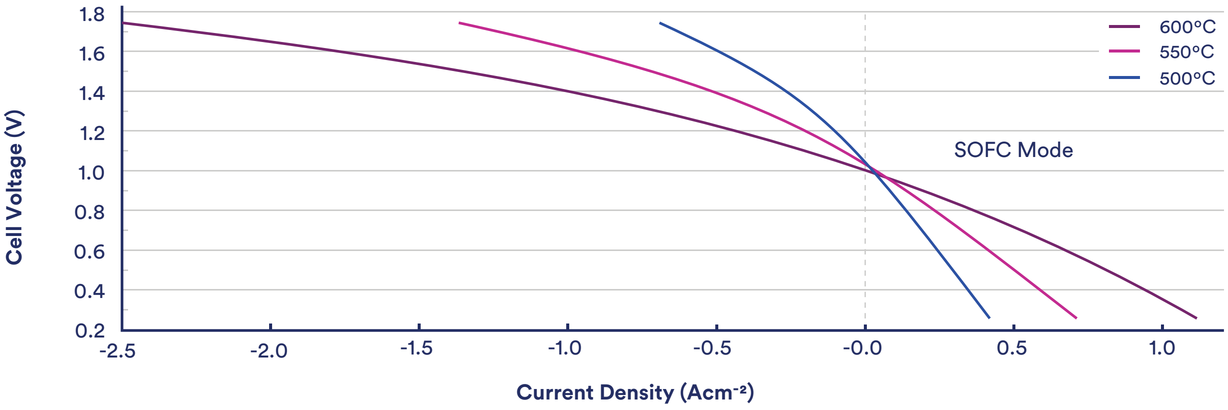
The Science of High-Temperature Electrolysis

Solid oxide electrolyzers are also often referred to as high-temperature electrolyzers because they are unique in operating at temperatures between 500°C and 1000°C. High-temperature operation is a requirement of the ionic conductivity of a solid oxide electrolyte. Every electrolyte has its own activation energy that needs to be reached for optimal ionic conduction. Since the temperature of an object is an average of the energy of its constituent particles, an object might exhibit some conductivity even at temperatures below the activation energy, but this conductivity will be weak. The gain in reaction kinetics is fastest at the point where temperature matches activation energy. Adding more heat will improve conductivity, but with diminishing returns.

Higher temperature thus leads to higher conductivity, which translates into higher current density at a given voltage, as seen in Figure 14. Higher current density decreases equipment costs and the physical footprint of the system as fewer stacks and balance-of-plant components are needed to produce the same quantity of hydrogen. However, improvements in conductivity must be weighed against practical considerations such as the durability of the electrolyzer. From a durability standpoint, high-temperature operation results in more thermal stress, leading to faster degradation and increasing the probability of component failure.

Solid oxide electrolyzers will usually be designed with a temperature sweet spot that optimizes for stack lifetime and performance. Different manufacturers will target different sweet spots depending on their choice of materials and stack design. Some systems will work optimally at 600°C, while others will be designed to operate at 700°C or even above 800°C. Aside from choice of material, the thickness of the solid electrolyte will influence the optimal operating temperature: thicker electrolytes are less conductive and will require higher temperatures to match the conductivity of thinner electrolytes.

Figure 14: Cell Voltage vs. Current Density of a Solid Oxide Cell[23]



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[23] Wu, W., Ding, H., Zhang, Y., Ding, Y., Katiyar, P., Majumdar, P. K., He, T., & Ding, D. (2018). 3D self-architectured steam electrode enabled efficient and durable hydrogen production in a proton-conducting solid oxide electrolysis cell at temperatures lower than 600 °C. *Advanced Science,* 5(11). https://doi.org/10.1002/advs.201800360

SECTION 3

Technology Advantages and Challenges

3.1 The Advantages of Operating an Electrolyzer at High Temperature

High-temperature operation enables a step change in efficiency because the electrolyzer will be fed with water in the form of steam. Thus, an external source of heat above 100°C can be used to evaporate the water, effectively relieving the electrolyzer stack from having to provide the latent heat of evaporation. In terms of the electricity required to produce hydrogen, this results in an efficiency gain of 0.5 kilowatt-hours per normal cubic meter (kWh/Nm^3) of hydrogen, or 6 kWh per kilogram (kg) of hydrogen.[24] The ability to make use of imported steam is particularly relevant to industrial processes, which typically discard large amounts of low-grade heat, especially steam at 100°C–150°C, in the condensate system.

A solid oxide electrolyzer that is importing steam from an industrial source is thus at the very least 14% more efficient than any alkaline, PEM, or AEM competitor. In practice, the efficiency gap today is even larger – around 25% – because of imperfect operation of PEM, alkaline, or AEM systems. However, continuous improvements in alkaline and PEM technologies will likely reduce losses from imperfect operation by 2030s, leaving solid oxide with only the efficiency advantage of importing steam.

SOEC operation coupled with steam imports has already been demonstrated at a sub-megawatt scale by FuelCell Energy,[25] as well as by Bloom Energy,[26] with the

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[24] Note how this is equal to the difference between the higher heating value of hydrogen (39.4 kWh/kg) and the lower heating value of hydrogen (33.3 kWh/kg).

[25] Venkataraman, V. (2021). High Temperature Solid Oxide Electrolyzer [PowerPoint Slides]. Bloom Energy. https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-panel1-hte-industrial-panel_0.pdf

[26] Idaho National Lab and Bloom Energy Produce Hydrogen at Record-Setting Efficiencies. (2022, August 9). *Bloom Energy.* Retrieved from https://www.bloomenergy.com/news/idaho-national-lab-and-bloom-energy-produce-hydrogen-at-record-setting-efficiencies/.

Table 2: Typical Stack Energy Consumption for Different Electrolyzer Architectures

	Alkaline[28]	PEM[27]	AEM[29]	SOEC[30]
Stack (DC) energy consumption (kWh/kg H2)	47 – 66	47 – 66	51.5 – 66	34

former achieving 38.7 kWh of electricity consumption at the stack level (DC) to produce a kilogram of hydrogen (H_2) and the latter reaching a record low of 37.7 kWh/kg of H_2, also at stack level. The heat source was a simulated[27] nuclear plant.

Another advantage of high-temperature operation is the possibility for further integration with heat imports to enable operation in *endothermic* mode (meaning that the process absorbs rather than releases heat). By default, a solid oxide electrolyzer will operate in 'thermoneutral voltage' – i.e., the voltage at which the internal resistance of the stack components creates just enough heat to reach and maintain optimal kinetics through the solid electrolyte. This voltage is around 1.29 Volts (V) compared with 1.48 V for alkaline, PEM, or AEM electrolytes. Since the theoretical minimum potential difference for water electrolysis is 1.23 V, solid oxide electrolyzers will generally be more efficient than competing architectures at the stack level.

If there is a source of high-grade heat, the steam that is destined for electrolysis can be heated to or near the operating temperature of the electrolyzer. This allows the electrolyzer to draw in heat from its surroundings, which results in endothermic operation. Depending on the temperature of the steam and the temperature of the electrolyzer, endothermic operation could theoretically reduce electricity demand by another 0.5 kWh/Nm^3 of H_2 (Figure 15).

In endothermic operation the electrical efficiency of the reaction at the cell level can be understood as exceeding 100% (HHV basis). This is because the electrolyzer would be producing more in hydrogen energy than it would be consuming in electrical energy.

Altogether, leveraging a high-grade waste heat source at 600°C to its maximum, that is to evaporate water and heat the stack, could theoretically lower the electricity required to produce hydrogen to around 2.7kWh/Nm^3 or 30 kWh/kg, which would be equivalent to 131% efficiency at the cell level for the higher heating value (HHV) of hydrogen or 111% cell efficiency for the lower heating value (LHV) of hydrogen. Stack efficiencies, excluding balance of plant, will be only marginally less than cell efficiencies due to non-ideal fields and flow (e.g., eddy currents).

However, endothermic operation is challenging, since distributing external high-grade heat within the stack causes temperature gradients that in turn cause thermal stress. Moreover, industrial processes that simply discard high-grade heat are extremely rare, since this heat can be used to do mechanical work.

While the stack is typically the most power-hungry element of an electrolyzer by a large margin, the overall efficiency of the system (also known as *system* efficiency or energy demand) also depends on energy consumption by other BoP components. Figure 16, from the company FuelCell Energy, shows a flow diagram for an SOEC electrolyzer coupled with a nuclear power plant. In this flow diagram, BoP energy consumption is estimated at 4 kWh per kg of hydrogen, which means that with steam imports, the company hopes to use as little as 38 kWh of electrical energy to produce a kilogram of H_2. Given hydrogen's higher heating value of 39.4 kWh/kg, FuelCell Energy's system, under these conditions, would achieve greater than '100% *electrical* efficiency (HHV)' even on a system level.

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[27] Simulated in this case means that the input steam was heated to a temperature comparable to the output of a nuclear reactor using an external heat source.

[28] Ivanova, M. E., et al. (2023). Technological Pathways to produce compressed and highly pure hydrogen from solar power. *Angewandte Chemie International Edition,* 62(32). https://doi.org/10.1002/anie.202218850

[29] *What is the overall efficiency of Enapter's electrolyser?* Enapter. (2023, January 9). https://www.enapter.com/newsroom/kb_post/what-is-the-overall-efficiency-of-enapters-electrolyser

[30] Institute for Sustainable Process Technology. (2023). Next Level Solid Oxide Electrolysis. https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf

This example underlines how solid oxide technology is unique in being able to leverage external sources of heat to minimize electricity consumption.

This makes solid oxide electrolyzers an ideal candidate for *system integration* with industrial sources of process or waste heat.

Figure 15: Energy Demand in Water Electrolysis as a Function of Temperature, Excluding Balance of Plant[31]

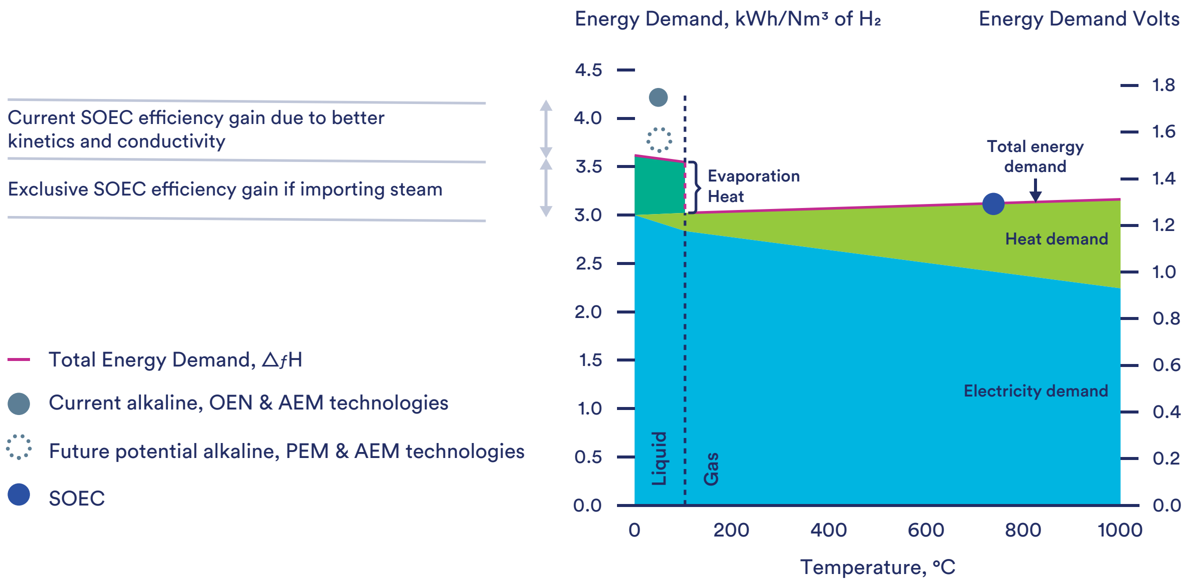
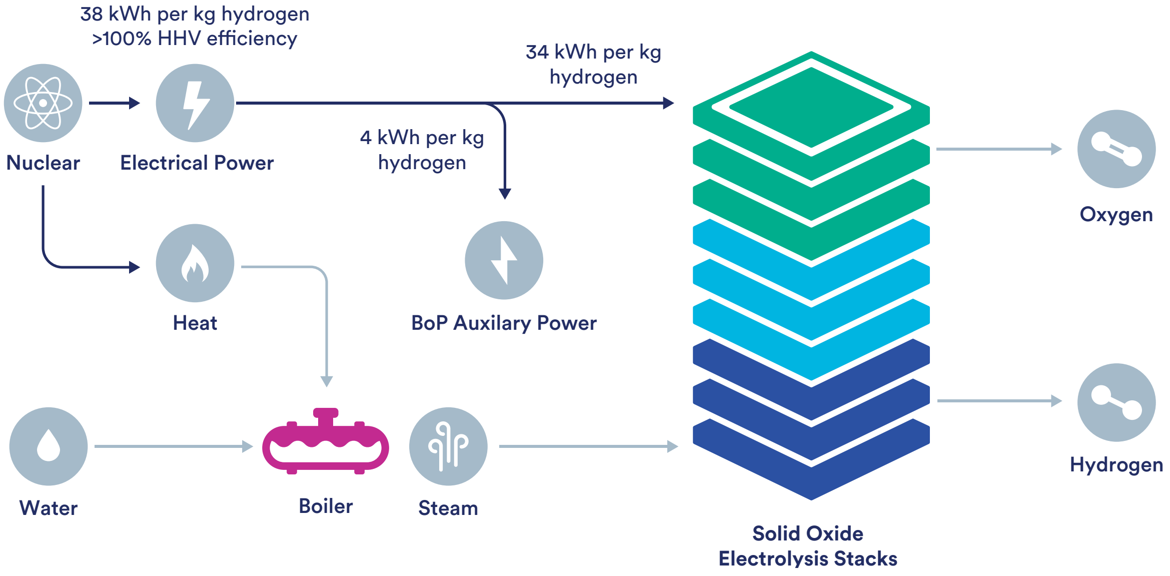


Figure 16: FuelCell Energy's Flow Diagram of an SOEC Electrolyzer Coupled with a Nuclear Power Plant[32]



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[31] All About SOEC For PtX – TOPSOE

[32] Leo, T. (2023, January 12). *Low-cost hydrogen production from nuclear energy.* FuellCell Energy. https://www.fuelcellenergy.com/blog/low-cost-hydrogen-production-from-nuclear-energy

Table 3: Energy Consumption of Specific Components of a Solid Oxide Electrolyzer System[33]

Component	kWh/kgH$_2$
Electric heating feed	1.2
Electric heating air	1.8
H2 compressor	2.2
SOEC stack (DC)	34.6
Total LHV (with steam import)	39.8
Steam generation (if required)	7.9
Total HHV (with internal steam generation)	47.7

Results from another feasibility study that estimated the energy consumption of BoP sub-component are summarized in Table 3.

3.2 Technology Challenges for High Temperature Electrolysis

One of the biggest hurdles to commercializing solid oxide technology is shaking its reputation for poor durability. A literature review that includes data up to 2020 put the average degradation rate for SOEC systems at under 1% per 1,000 hours of operation. Taking performance at 80% of nameplate capacity as the industry cut-off for stack replacement, a 1% degradation rate would imply a stack lifetime of around 2.5 years at full load, which, while up from less than half a year a decade ago, is still four to eight times shorter than the typical expected lifetimes for PEM and alkaline technologies.

However, extrapolating electrolyzer lifetime purely from observed degradation rates can be misleading. Solid oxide stacks can compensate for loss of performance by operating at a higher temperature and thereby increasing their conductivity. The increased energy demand required to supply the extra heat will not exceed an extra kWh per kg H_2 produced. Higher temperatures increase viable running hours beyond what degradation rates would suggest without sacrificing meaningful performance. Most solid oxide manufacturers build this functionality within their stacks.

Still, compensating with increased temperature does add to overall thermal stress, and increases the risk of stack failure – most commonly as a result of electrolyte cracking or seal breakage, which opens the possibility of gas crossover, and which demands immediate shutdown and replacement. At higher temperature, the operator might not observe much performance degradation for several years, until one day, the stack fails. Manufacturers typically have enough test data to be able to quantify and guarantee stack lifetime, provided the stack is operated within given parameters.

Nevertheless, most modern solid oxide stacks will fail before PEM or alkaline stacks. High temperature operation is thus a double-edged sword: it increases efficiency but increases the probability of accelerated stack failure. Figure 18 summarizes the main mechanisms of SOEC degradation caused by high temperature operation. The most consequential are nickel migration and nickel sintering. Both lead to gradual loss of active sites on the anode side and increase electrolyte resistance, which is the main driver of the observed 1% degradation rate.

As already noted, interconnects and seals are also susceptible to thermal stress. For instance, metallic interconnects and piping can require special coatings, sometimes involving cobalt, to decrease the risk of chromium evaporation which could poison the electrode. The need to prevent seals from failing has also been a major obstacle to SOEC commercialization. The problem is that seals and solid oxide cells have different thermal coefficients, which can cause mechanical failures as a temperature gradient develops across the stack. Temperature gradients can be prevented by heating the very stack slowly, or by simply maintaining it at a constant temperature. Thus, solid oxide systems will typically require several hours for a cold start, so that all system elements heat evenly to the requisite temperature. The problem of temperature gradients also explains why solid oxide systems degrade more during frequent cycling. This can make it much preferable to keep the stack in a hot 'standby' mode. Compared with PEM or alkaline systems, solid oxide systems require a lower minimal load (3% for SOEC vs. more than 10% for PEM/ALK/AEM) to be on standby.

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[33] Institute for Sustainable Process Technology. (2023). Next Level Solid Oxide Electrolysis. https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf

Figure 17: Historical Improvements to Solid Oxide Electrolysis

(A) Cumulative Stack Test Duration, (B) Observed Degradation Rate and (C) Largest Plant Size by Year[34]

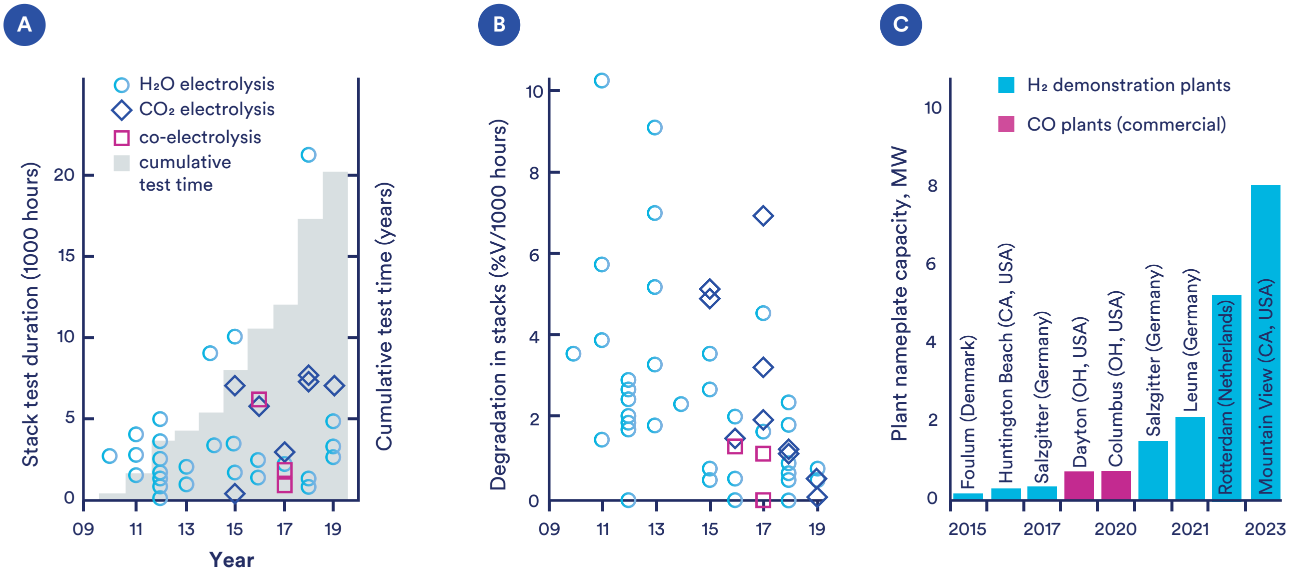


Figure 18: Known Mechanisms of SOEC Degradation[35]

1 Cathode degradation

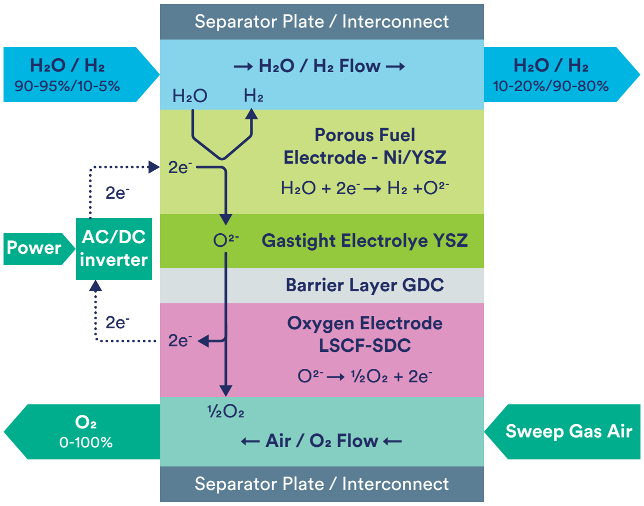
- Ni coarsening /sintering
- Ni oxidation
- Ni mobility

Leads to reduced triple point dispersion and activity and delamination from electrolyte; Results in decreased e^- conduction

2 Dense electrolyte degradation

- YSZ composition changes
- Zr reduction/ NiZr alloying

Results in decreased $O^=$ ion conduction



3 GDC barrier degradation

- Gd exsolution
- New Gd containing phases
- Coarsening
- Interfacial void formation

4 Anode degradation

- Interfacial void formation
- Sr reaction with Zr, $SrZrO_3$

Lead to increased pO_2 & delamination

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[34] Hauch, A., Küngas, R., Blennow, P., Hansen, A. B., Hansen, J. B., Mathiesen, B. V., & Mogensen, M. B. (2020a). Recent advances in solid oxide cell technology for electrolysis. *Science,* 370(6513). https://doi.org/10.1126/science.aba6118

[35] *Hydrogen from Next-generation Electrolyzers of Water (H2NEW).* H2NEW. (n.d.). https://h2new.energy.gov/home

Finally, solid oxide electrolyzers, much like PEM, AEM, and alkaline electrolyzers, require desalinated and deionised water, as some impurities can poison the catalysts. SOECs are particularly prone to poisoning by sulphur and silicon, as well as by amines, ammonia, and oxides of nitrogen (NOx). However, quality control of BoP systems, and the addition of a water deioniser will significantly reduce the risk of poisoning. Most cell-level degradation mechanisms can be largely avoided by assuring quality control during manufacturing or by operating the stack within design parameters.

3.3 Strategies for Maximizing Stack Durability

Technology choices and manufacturing experience can extend the longevity of SOEC stacks. Selecting materials that minimize the activation energy of the electrolyte, for example, will allow for lower operating temperatures, which in turn ensures that the electrolyzer experiences less thermal stress to start with and enables the use of cheaper materials. Thus, minimizing activation energy confers a technological advantage. Since operating temperatures for most SOEC materials are still above 500°C, however, this approach offers, at most, incremental gains rather than a step change in electrolyzer efficiency and durability.

Operating and manufacturing experience will also greatly impact stack durability. More data on electrolyzer performance under real-world conditions will give manufacturers a better idea of when and under what conditions a stack might be expected to fail. Manufacturers can either address these problems through design iteration or by providing preventive maintenance. For any chemical plant, an unplanned outage will be infinitely more costly than a planned stack replacement. Since SOEC manufacturers are aware of their technology's shorter stack lifespan compared with alkaline and PEM technologies, they design their stack-modules to be easily accessible in case of failure. A 'hot-box' can be replaced in as little as an hour after it has cooled.

Interestingly, relevant experience for successful SOEC manufacture and operation does not necessarily need to come from solid oxide electrolyzers specifically. Because solid oxide fuel cells are practically identical in design to electrolyzers, learnings from SOFC manufacturing and operation can be translated to SOEC manufacturing. The major differences between fuel cells and electrolyzers occur at the balance-of-plant configuration, rather than at the cell level. Therefore, while the current academic literature implies an average operating life of 2.5 years for solid oxide electrolyzers, experience from the historical deployment of solid oxide fuel cells suggests that solid oxide stacks can operate as long as 80,000 hours, or nearly 9 years at full capacity.

Operating parameters other than temperature will also play a role in longevity. Higher operating pressure, for example, is helpful for kinetics and mass transport in the electrodes. However, at pressures greater than 3 barg, the performance improvement is small. Meanwhile, high pressure can cause mechanical problems, particularly to the thin and brittle electrolyte.[36] This is why the output mixture of hydrogen and steam produced by most solid oxide systems leaves the electrolyzer at a pressure of only 0–2 barg, thus necessitating further pressurization to be suitable for most industrial applications. Using an external compressor to pressurize the hydrogen to 30 barg will increase the energy demand of the overall system by around 2 kWh per kg of hydrogen output; compression to 200 barg roughly doubles that requirement, to around 4 kWh per kg of hydrogen (Figure 19).

To sum up, the operating life of a solid oxide stack will depend on the experience that goes into its design and manufacture, choices about technology and materials, and the operator's ability to stay within design limits. A conservative assumption would put the average life of a solid oxide electrolyzer *stack* today at 2.5 years; an optimistic assumption would be 5 years. By 2030 or before, it would be fair to expect the technology to achieve an expected operating life of 7–8 years at full load.

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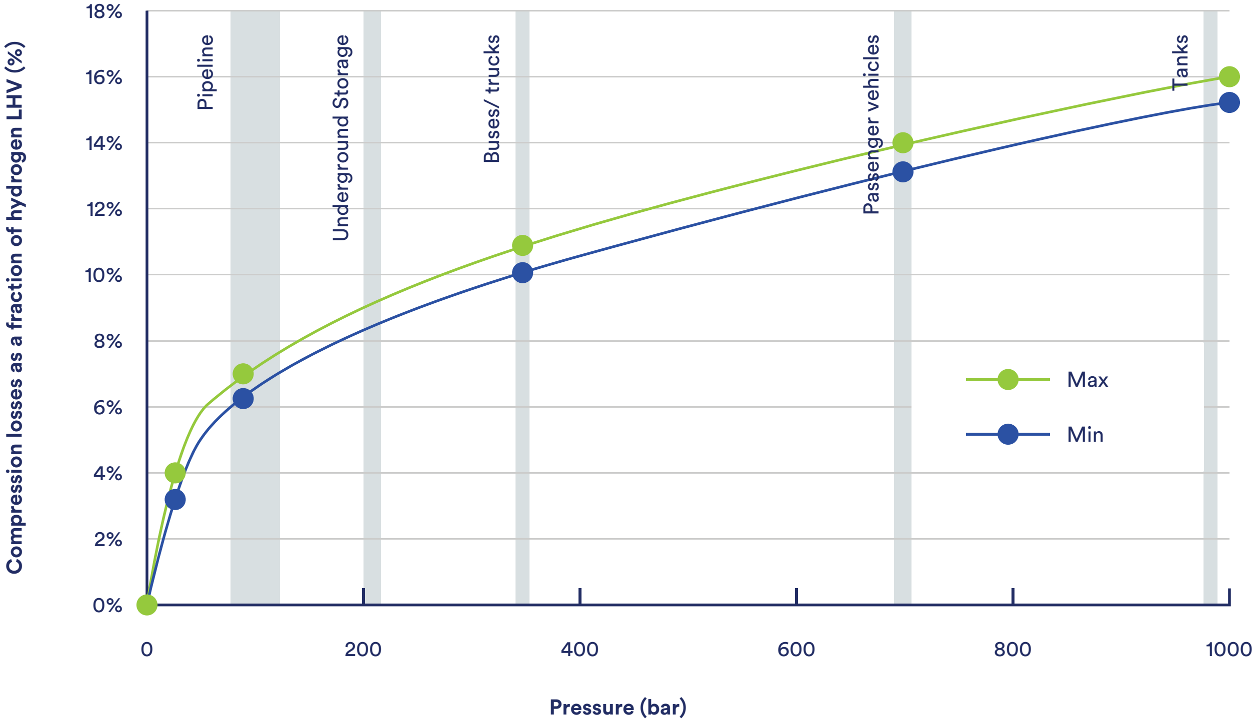
[36] Zhang, M., Wang, E., Mao, J., Wang, H., Ouyang, M., & Hu, H. (2022). Performance analysis of a metal-supported intermediate-temperature solid oxide electrolysis cell. *Frontiers in Energy Research,* 10. https://doi.org/10.3389/fenrg.2022.888787

Figure 19: Energy Losses for the Multi-Stage Mechanical Compression of Hydrogen[37]



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[37] Institute for Sustainable Process Technology. (2023). Next Level Solid Oxide Electrolysis. https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf

Next Generation Solid Oxide Technologies

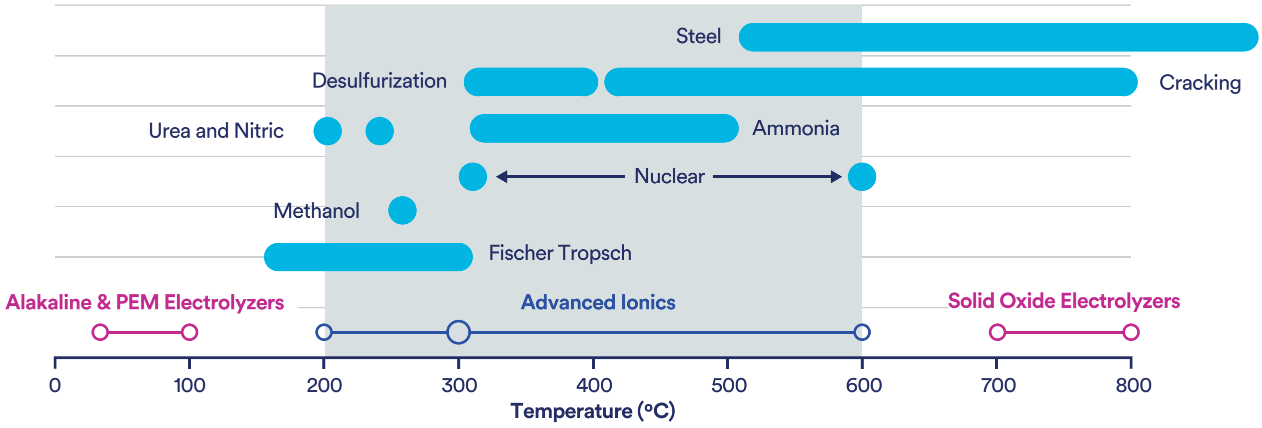
Proton conducting solid oxide electrolytes. To this point, the discussion has focused on oxygen ion conducting solid oxide electrolytes (O-SOEC). However, there are also solid oxides that can conduct protons (H-SOEC). These ionic conductors exhibit higher ion conductivity at much lower temperatures (350°C–600°C), reflecting the relatively low activation energy required for proton migration. Lower operating temperature means less thermal stress, which addresses many of the challenges faced by O-SOEC.

However, the mechanisms behind H-SOEC are still poorly understood: many studies note significant current leakage, and the electrical efficiencies of H-SOEC designs are still far below those of O-SOECs.[38]

New materials and manufacturing approaches. Some SOEC start-ups have chosen to completely reinvent the process for manufacturing the solid oxide stack. With the help of new materials and dry power pressing additive methods, they claim to be able to produce a monolithic, seal-free design with internal gas routing channels. This innovation allows for a marked increase in the operating pressure range and consequently the power density of the cell, while also removing potential failure mechanisms associated with seals and interconnects.

Novel ionically conductive materials. An up-and-coming company called Advanced Ionics claims to have created a hybrid design which conducts oxygen ions between electrodes but does not feature a brittle ceramic membrane. This innovation allows the electrolyzer to operate at a lower temperature range (200°C–600°C) than with a conventional solid oxide. Lower operating temperature translates into less thermal stress, all the while improving the efficiency of integration with an external source of low-temperature process heat. This is important because most industrial facilities operate at temperatures well below the range needed for conventional SOEC operation (Figure 20).

Figure 20: Operating Temperature Ranges of Electrolyzers and the Typical Process Temperature of Various Industrial and Power Generation Processes[39]



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[38] Lei, L., Zhang, J., Yuan, Z., Liu, J., Ni, M., & Chen, F. (2019). Progress report on Proton conducting solid oxide electrolysis cells. *Advanced Functional Materials*, 29(37). https://doi.org/10.1002/adfm.201903805

[39] Source: Advanced Ionics pitch deck.

3.4 Comparing SOEC with other electrolyzer architectures

Table 4 summarizes the key advantages and drawbacks of solid oxide electrolyzers relative to other prominent electrolyzer architectures, specifically: alkaline, polymer electrolyte membrane (PEM), and anion exchange membrane (AEM). Table 5 summarizes operational characteristics.

Table 4: Advantages and Drawbacks of SOEC Relative to other Types of Electrolyzers

Alkaline	PEM	AEM	Solid Oxide
Advantages			
■ Mature technology with GWs of historical deployment ■ Multi-MW stacks enable systems with large capacities already today ■ Potential to use earth abundant and inexpensive materials	■ High-power densities exceeding 2A/cm^2, enabling compact designs and small physical footprint ■ Fast cold start-up time and fast load changing capabilities ■ Relatively mature, with MWs ■ High intrinsic product gas purity ■ Can exceed its rated power for brief periods giving a broader range of flexibility	■ No expensive or critical minerals ■ Compact designs and small footprint like PEM ■ Suitable for high pressure (>30 barg) operation ■ Potential to use earth abundant and inexpensive materials	■ Lowest standby load ■ Intrinsic high efficiency due to fast kinetics and high conductivity at elevated temperatures ■ Option to leverage external sources of heat to attain stack electrical efficiencies over 100% ■ Some designs can operate reversibly as fuel cells and electrolyzers ■ Can electrolyse carbon-based molecules and co-electrolyse them with water ■ Potential to use earth abundant and inexpensive materials
Disadvantages			
■ High material effort on system level by using highly alkaline liquid as electrolyte ■ Low power densities and large footprint ■ Additional effort for gas purity required ■ Slow cold start-up time ■ High minimal load due to gas permeability of the membrane	■ Use of expensive materials as titanium and critical platinum group metals (PGM) on cell level ■ Long-term stability needs to be proven at MW scale ■ Current generation reliant on 'forever chemicals' such as PFAS which don't occur in nature, and hardly degrade in the natural environment	■ Available stack sizes are in the low kWs, driving up balance of plant costs. ■ Shorter stack lifetimes than for alkaline and PEM due to membrane degradation	■ Highest physical footprint, 1/3rd more than alkaline and AEM and 3.5x more than PEM ■ High operating temperatures cause thermally accelerated aging ■ Produced hydrogen needs to be separated from steam and purified ■ Low output pressure requiring external compression ■ Cold starts take several hours ■ Historical reputation for poor durability

Table 5: Operational Characteristics of Different Electrolyzer Architectures[40]

Technology	Alkaline	PEM	AEM	SOEC
Development stage	>1 GW deployed	>100 MW deployed	<10 MW deployed	>1 GW deployed (fuel cell) <10 MW deployed (electrolyser)
Electrolyte	Liquid: 25 – 40% KOH	Solid: proton exchange membrane (Nafion)	Liquid-solid hybrid: 1% KOH/anion exchange membrane	Solid: ceramic – zirconia or ceria based
Operating temperature (°C)	70 – 90	50 – 80	40 – 80	500 – 900
Operating pressure (bar)	Conventional: atmospheric Modern: up to 30 bar (50 among startups)	Up to 80 (350 among startups)	Up to 35 with potential for much higher in the future	0 – 2 bar
Typical current densities today (A/cm2)	0.4 – 1.0	0.2 – 4.0	0.2 – 2.0	0.5 – 1.5
System energy consumption (kWh/kg H_2)	50 – 78	50 – 83	57 – 69	38 (with steam import) 48 (without steam import)
Stack cost (2020 $/kW)	270 – 450	400 – 870	200	250 – 2,000
Electrolyzer system cost with BoP (2020 $/kW)	800 – 1,500	1,400 – 2,100	3,333	917 – 4,000
Stack lifetime (full load hours)	60,000 – 100,000	50,000 – 90,000	5,000 – 40,000	20,000 – 50,000
Degradation (% / 1000 hours)	0.13	0.25	0.4	0.55 – 1%
Ramp up time hot idle to nominal power	60s	10s	30 minutes	10 minutes
Cold ramp up time	30 – 60 minutes	5 minutes	20 minutes	>600 minutes
Minimum load	10 – 40%	5 – 10%	10 – 20	>3%

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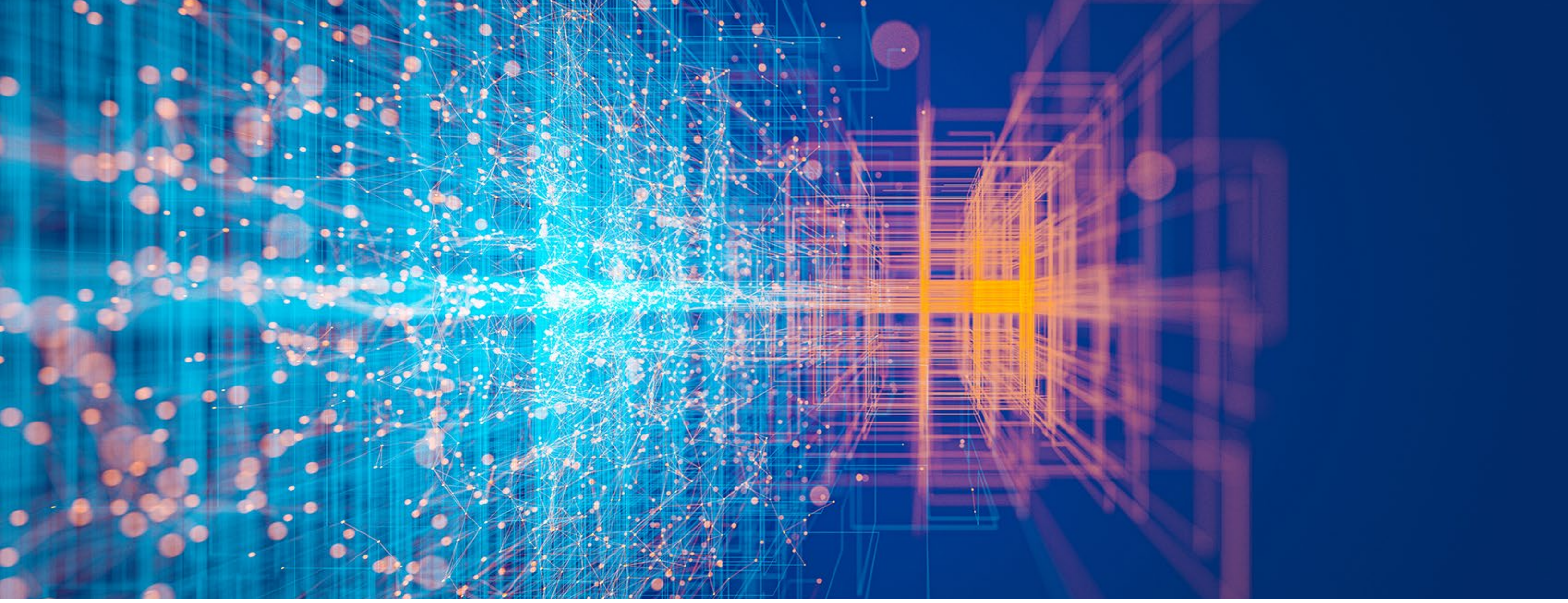
[40] Zheng, Y., Chen, Z. & Zhang, J. (2021). Solid Oxide Electrolysis of H_2O and CO_2 to Produce Hydrogen and Low-Carbon Fuels. Electrochem. Energ. Rev. 4, 508–517. https://doi.org/10.1007/s41918-021-00097-4 ; Wang, J. (2020, October 20). *AEM water electrolysis: How it works.* Enapter. https://www.enapter.com/newsroom/aem-water-electrolysis-how-it-works ; European Commission, Joint Research Centre, Davies, J., Dolci, F., Weidner, E. (2021). Historical analysis of FCH 2 JU electrolyser projects : evaluation of contributions towards advancing the state of the art, Publications Office. https://data.europa.eu/doi/10.2760/951902 ; *Pem Electrolyser*. Nel Hydrogen. (2022, December 16). https://nelhydrogen.com/product/m-series-3/ ; The Oxford Institute for Energy Studies. (2022). Cost-competitive green hydrogen: how to lower the cost of electrolysers?. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/01/Cost-competitive-green-hydrogen-how-to-lower-the-cost-of-electrolysers-EL47.pdf ; Department of Energy. (2016). Hydrogen Production Cost from Solid Oxide Electrolysis. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/16014_h2_production_cost_solid_oxide_electrolysis.pdf ; Wang, L., Chen, M., Küngas, R., Lin, T.-E., Diethelm, S., Maréchal, F., & Van herle, J. (2019). Power-to-fuels via solid-oxide electrolyzer: Operating window and Techno-Economics. Renewable and Sustainable Energy Reviews, 110, 174–187. https://doi.org/10.1016/j.rser.2019.04.071 ; Institute for Sustainable Process Technology. (2023). Next Level Solid Oxide Electrolysis. https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf ; Fraunhofer ISE. (2021). Cost Forecast for Low-Temperature Electrolysis. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/presseinformationen/2022/2021-11-17_CATF_Report_Electrolysis_final.pdf ; Sunfire. (n.d.). Renewable Hydrogen for Industrial Applications Sunfire-Hylink SOEC. Dresden, Germany; Sunfire GmbH. Retrieved from https://www.sunfire.de/files/sunfire/images/content/Sunfire.de%20(neu)/Sunfire-Factsheet-HyLink-SOEC-20210303.pdf.



SECTION 4

Assessing SOEC Technology Readiness Based on Flagship deployments

This section reviews recent deployments of SOEC technology in various industrial applications. Experience from these deployments is helpful in assessing the technology readiness of solid oxide electrolysis as an option for hydrogen production. Throughout, the discussion references "technology readiness level" (TRL), which is a metric commonly used to describe the maturity of a new technology. Originally developed by the National Aeronautics and Space Administration (NASA) and now widely used by the U.S. Department of Energy (DOE) and other government agencies, the TRL system assigns a number, on a scale of 1 to 9, based on the development milestones a new technology has reached.[41]

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[41] For a description of how different U.S. government agencies assign TRLs, see: https://www.gao.gov/assets/gao-20-48g.pdf.

Chemical Industry – Carbon Monoxide Production
TRL: 8

Since 2020, U.S.-based DeLille Oxygen Company has used two commercially available, 750-kW Topsoe eCOs™ units for the on-site production of ‘clean’ carbon monoxide via solid oxide electrolysis.

Figure 21: Topsoe eCOs™ Electrolyzers at a DeLille Oxygen Co. Site[42,43]

Chemical Industry – Hydrogen Production
TRL: 7

Sunfire began testing a 1-MW electrolyzer for use in methanol synthesis at the Hydrogen Lab Leuna, in Germany, in 2021. Various operational studies were carried out at the lab, in close cooperation with Sunfire, to evaluate likely system performance when connected to an intermittent renewable electricity supply.[44]

Another MW-scale Sunfire project, MultiPLHY, involves the first commercial-scale use of high temperature solid oxide electrolyzers at Neste’s biofuel refinery in Rotterdam. A 2.6-MW electrolyzer was installed in April 2023 and was scheduled to start operations by the end of 2023. If this project meets performance targets by the time it concludes (expected by end of 2024), the Sunfire technology should reach TRL 8.

Figure 22: One of Sunfire’s SOEC Modules at the MultiPLHY Site[45]

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[42] Ravn, S. (2019, May 29). *Delille Oxygen Co. leases two ECOSTM Units for cost-competitive onsite co production.* Topsoe. https://www.topsoe.com/blog/delille-oxygen-co.-leases-two-ecos-units-for-cost-competitive-onsite-co-production

[43] Wix Christian (2022) Solid Oxide Electrolysis Explained [PowerPoint Slides]. TOPSOE. https://fortesmedia.com/files/files/Doc_Pack/Hydrogen_%26_P2X/Christian_Wix_Topsoe.pdf

[44] Junghans, U., & Rasch, C. (2023, August 8). *E-CO₂Met – Electricity & CO₂ to methanol*. Fraunhofer Center for Chemical-Biotechnological Processes CBP. https://www.igb.fraunhofer.de/content/cbp/en/reference-projects/e-co2met.html

[45] European Commission. (2021). Multimegawatt high-temperature electrolyser to generate green hydrogen for production of high-quality biofuels. https://doi.org/10.3030/875123

Steelmaking
TRL: 7

The benefits of coupling SOEC with a steel plant are similar to those of coupling SOEC with a nuclear plant, in that industrial process heat can be reused in the SOEC to increase the overall electrical efficiency of hydrogen production. In this configuration, a SOEC system will require less low-carbon electricity than PEM or alkaline electrolyzers to produce the same quantity of hydrogen.

In the first large-scale project to test this concept, called GrinHy 1.0, the German company Salzgitter AG installed a 140-kW Sunfire SOEC system at one of its steelmaking plants. The project proved that heat from a steel plant could be used with a solid oxide electrolyzer to produce hydrogen at the purity required for low-carbon steelmaking. In the first phase of the GrinHy project, however, hydrogen was turned back to electricity using the reversibility of solid oxide technology, rather than being used in steelmaking.[46]

Figure 23: The GrinHy 2.0 720-kW Sunfire Electrolyzer at Salzgitter's Site[47]

GrinHy 1.0 was succeeded by GrinHy 2.0, which involves a substantially larger, 720-kW SOEC system. This prototype also recycles process heat from steelmaking but has been further integrated into Salzgitter's steelmaking operations in that it supplies hydrogen for the annealing process. By the end of 2022, stack performance had been proved for 20,000 hours of operation, producing a total of around 100 tons of high purity 'green' hydrogen at an electrical efficiency of minimum 84% (measured at the lower heating value (LHV) of hydrogen), and proving the technology at TRL level 7. In the next phase, the electrolyzer will supply hydrogen for the reduction of iron ore, which will reduce CO_2 emissions from this step of the steelmaking process by 95% and prove the technology at TRL 8.

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[46] European Commission. (2016). Green Industrial Hydrogen via Reversible High-Temperature Electrolysis. https://doi.org/10.3030/700300

[47] *Grinhy2.0.* SALCOS®. (n.d.). https://salcos.salzgitter-ag.com/en/grinhy-20.html

Synthetic Fuels
TRL: 5 – 6

Because a solid oxide electrolyte can conduct oxygen ions, SOEC technology can be used to electrolyze molecules such as CO_2. The resulting product in this case would be carbon monoxide (CO).

When carbonated water is fed to a solid oxide electrolyzer, both water and CO_2 can be electrolyzed simultaneously – this process is called co-electrolysis. Co-electrolysis produces a mixture of carbon monoxide and hydrogen, also known as synthetic gas or 'syngas', alongside steam and CO_2. Syngas can be used to produce a range of synthetic hydrocarbons, including fuels and materials.

Sunfire has demonstrated a 150-kW co-electrolyzer for methanol production through its SynLink project, putting the technology at TLR 6.[48] In parallel, Sunfire has also validated a 10-kW module to produce synthetic fuels through its Kopernikus PtX project.

Another solid oxide cell manufacturer, Estonia-based Elcogen, has partnered with French energy company Engie SA on a pilot project to produce dimethyl ether (DME), a synthetic alternative to diesel fuel for transport applications. The project, called C2 Fuels is deploying a small solid oxide system, with electrical capacity in the single-digit kWs, in Dunkirk, France.[49]

Figure 24: Sunfire Co-Electrolyzer Module as Part of the Kopernikus PtX Project

The next challenge for co-electrolysis technology is demonstration on a MW scale. To that end, the European Union is co-funding an ongoing project, called MegaSyn, to demonstrate syngas production by co-electrolysis in an industrial environment. The aim is to lift the solid oxide co-electrolysis technology to TRL 7 by 2025.[50]

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[48] *SynLink – Synthetic E-fuels as key enabler for sector linking.* Fraunhofer Center for Chemical-Biotechnological Processes CBP. (2023, August 9). https://www.cbp.fraunhofer.de/en/reference-projects/synlink.html

[49] Elcogen takes a new step for c2fuel! | C2FUEL. (n.d.). https://c2fuel-project.eu/elcogen-takes-a-new-step-for-c2fuel/ ; Lehtinen, T., & Noponen, M. (2021). Solid oxide electrolyser demonstrator development at Elcogen. *ECS Meeting Abstracts, MA2021-03*(1), 285–285. https://doi.org/10.1149/ma2021-031285mtgabs

[50] Hansen, K. V. (n.d.). MEGASYN – Power-to-X Project in MEGAWATT-SCALE. https://www.megasyn.eu. https://www.megasyn.eu/highlights/megasyn-start

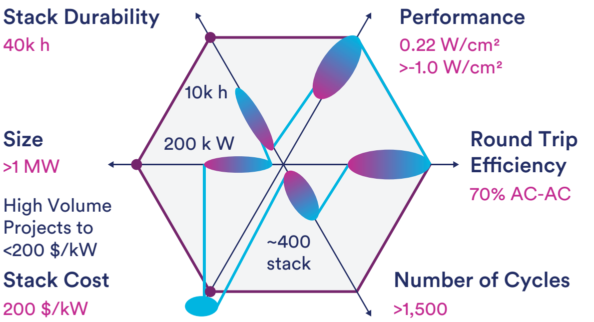
Energy Storage
TRL: 5 – 6

Another practical application of reversible SOEC technology would be clean energy storage: water could be electrolyzed at times when clean sources of power are abundant, the resulting clean hydrogen could then be stored and turned back to electricity using the same device at times when clean power supply is low. This approach would benefit from lower capital expenditures and reduced space requirements because it avoids the need to purchase and install electrolyzers and fuel cells separately.

Reversible SOEC/SOFC technology has already been demonstrated in large-area stacks. For instance, FuelCell Energy (FCE) has a reversible SOFC (rSOFC) technology that is currently at TRL 5 and expected to reach TRL 6 due to concurrent work supported by DOE’s National Energy Technology Laboratory (NETL) (project award number DE-FE0031974). The aim of this work is to validate and verify engineering/pilot-scale rSOFC technology in a relevant environment. FCE has been open about the outstanding challenges that need to be solved before its rSOEC technology is commercial, including challenges with respect to stack-module size, durability, and number of cycles. In fact, improvements in these three areas are recurring themes for most SOEC manufacturers.

European firms are also conducting trials of reversible SOEC: for example, Elcogen is currently testing its rSOEC technology at Finland’s VTT Technical Research Centre. This project is due to wrap up in the summer of 2023, with the aim of reaching TRL 6.[52] Sunfire has already validated a small, 140-kW rSOEC system through its GrinHy project at the Salzgitter steel plant, which puts its technology at TRL level 6.[53,54]

Figure 25: FCE rSOFC Targets and Current Capability[51]



RSOFC is at low TRL building off significant prior SOFC & SOEC core technology and system demonstrations.

— Commercialization Target

— Current Capability Range

Figure 26: Sunfire’s GrinHy 1.0 Reversible SOEC[55]

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[51] Ghezel-Ayagh, Hossein. *Reversible Solid Oxide Fuel Cell Systems for Energy Storage and Hydrogen Production.* United States. https://doi.org/10.2172/1874500

[52] European Commission. (2023). Reversible solid oxide Electrolyzer and Fuel cell for optimized Local Energy miX. https://doi.org/10.3030/779577

[53] Di Molfetta, R. (2022, April 5). Strategies for regional deployment of hydrogen infrastructure: The case of North Rhine-Westphalia, Germany. http://kth.diva-portal.org/smash/get/diva2:1652006/FULLTEXT01.pdf

[54] Wulf, C., Linßen, J., & Zapp, P. (2018). Review of Power-to-Gas Projects in Europe. Energy Procedia, 155, 367-378. https://doi.org/10.1016/j.egypro.2018.11.041

[55] European Commission. (2019). Green industrial hydrogen production powering Europe along the road to a decarbonised future. https://doi.org/10.3030/700300

Nuclear
TRL: 3 – 4

The benefits of pairing SOEC with a nuclear plant go both ways: the electrolyzer gets access to high-grade process heat (300°C–500°C) while the nuclear plant gains the option to switch between feeding electricity to the grid or using it to produce hydrogen. In a system with high penetration of wind and solar generators, this optionality would allow the nuclear plant to keep a steady electricity generation profile, without having to ramp up and down in response to fluctuating output from low-cost renewable generation. This could be particularly important for integrating nuclear with high-renewable-energy systems.

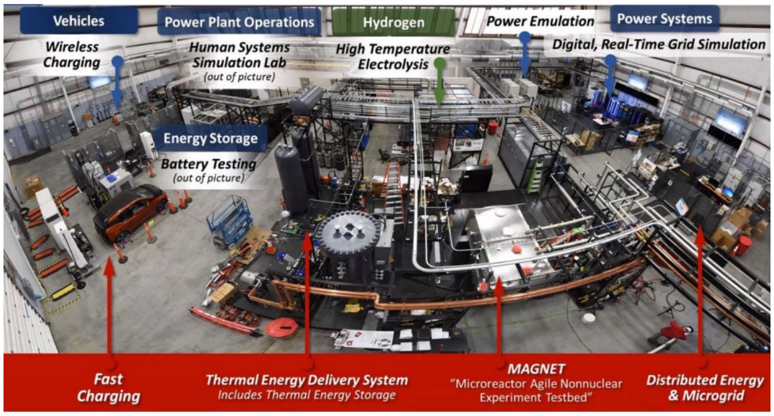
Researchers at Idaho National Lab (INL) in the United States have been conducting a variety of tests on Bloom Energy's solid oxide electrolyzer at the Dynamic Energy Testing and Integration Laboratory. These tests include physical steam and load simulations that replicate nuclear power station conditions, an important step in validating full compatibility with a nuclear facility. Early tests at high temperatures and high nuclear plant availability revealed that Bloom Energy's electrolyzer could produce hydrogen at 37.7 kWh per kilogram of hydrogen and with 88.5% electrical efficiency (with respect to LHV of hydrogen and conversion to direct current (DC)).[56] FuelCell Energy has also deployed a 250- kW electrolysis module at INL (Figure 27).

Actually harnessing nuclear process heat from an existing reactor for electrolysis is a lot more complicated than conducting a simulation. For instance, tapping into a boiling water reactor's steam system would require adding a radiation-shielded heat exchanger loop. This could quickly turn into a permitting nightmare, given the regulatory and safety requirements placed on nuclear plants, particularly in the United States. However in other regions like the UK regulators are willing to allow small modifications to plants without re-licensing. For pressurised water or gas cooled reactors which have a shielded loop, coupling with SOEC becomes a little easier, and indeed EDF has embarked on such a project. However, EDF has described three big limitations facing similar retrofits:

1. Steam harnessing potential is limited to low-pressure tap-off, significantly limiting the size of the electrolyser to double digit MWs
2. This site had an onsite alkaline electrolyser as part of the original design and license
3. The electrolyser had to be sited at least several hundred meters from the reactor for safety reasons, limiting the quality of heat that can be transferred to the SOEC to about 200C.

Thus, it is unlikely that SOEC will be deployed in 100s of MW scale at existing nuclear plants. If we are to see any big rollout of SOEC at greenfield nuclear plants, it's imperative that these plants are designed, engineered, and licensed with solid oxide electrolyser optionality from the get-go.

Figure 27: FCE Electrolyzer Module at the INL Testing Facility



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[56] Idaho National Lab and Bloom Energy Produce Hydrogen at Record-Setting Efficiencies. (2022, August 9). Retrieved from https://investor.bloomenergy.com/press-releases/press-release-details/2022/Idaho-National-Lab-and-Bloom-Energy-Produce-Hydrogen-at-Record-Setting-Efficiencies/default.aspx.

4.1 Overall Summary of Applications

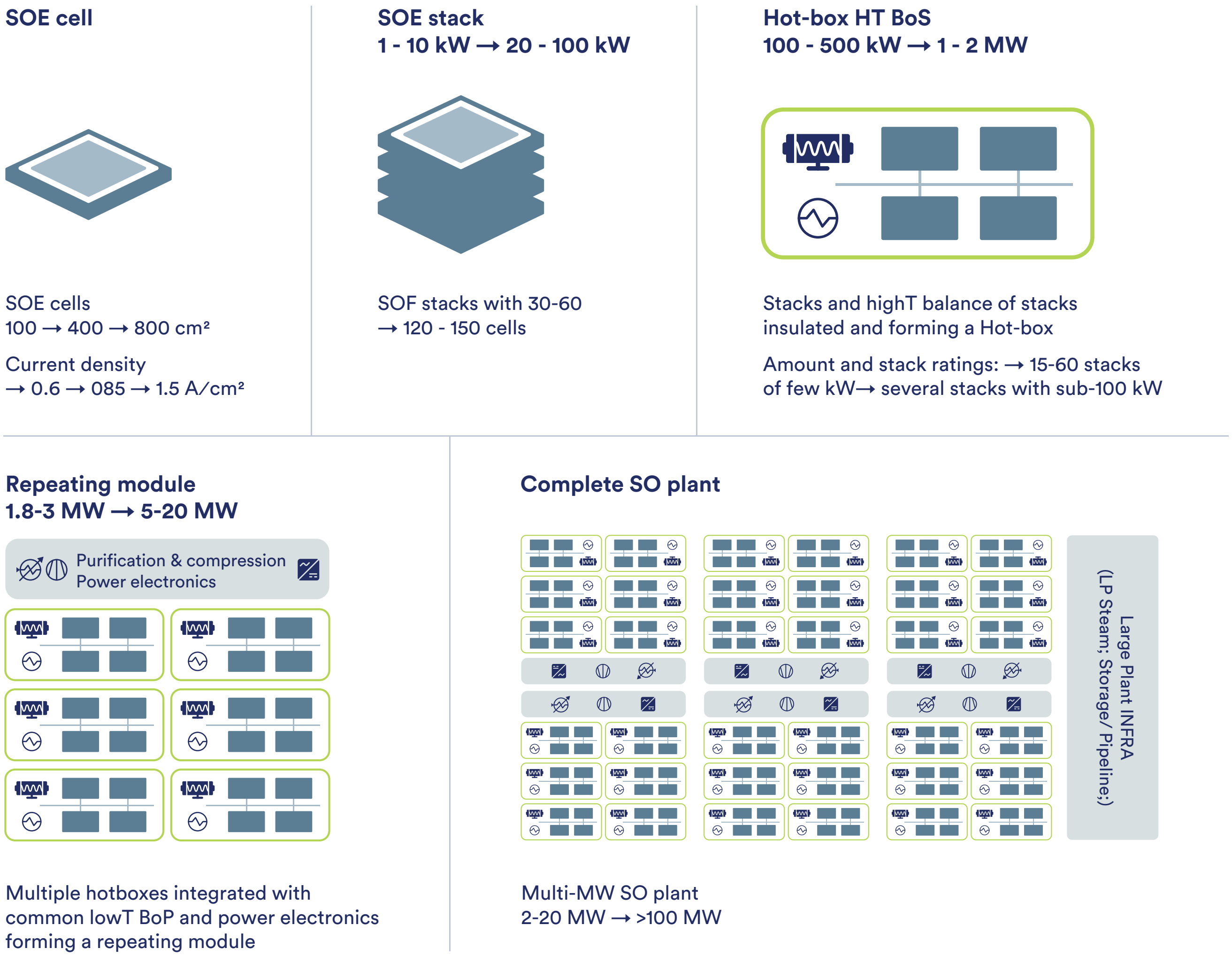
At first glance, flagship deployments of SOEC technology across different applications show mixed results: For applications in the chemical industry, SOEC has recently been demonstrated at a commercially relevant scale. In steelmaking, the technology is nearly there. Further work is needed to prove the commercial viability of co-electrolysis for energy storage and synthetic fuel production, especially with regard to issues of durability and scale.

TRL status notwithstanding, all SOEC applications still share at least one hurdle to clear: Even in applications where the technology has been demonstrated at a small commercial scale, the challenge of engineering systems at the hundreds-of-megawatts scale.

The Final Frontier: Upscaling SOEC to Meet the Requirements of Industrial Users

The path to upscaling SOEC is relatively straightforward: cell area and current density need to increase, and more cells need to be packed into a stack. These improvements would uprate the hotbox to single-digit megawatts; multiple hotboxes could then be packed into double-digit megawatt blocks (also referred to as modules in Figure 28). Large blocks would avoid over duplicating balance-of-plant requirements, allowing the capital costs of SOEC systems to become competitive with those of large PEM and alkaline systems.

Figure 28: SOEC Scale Up Towards a Multi-MW Plant[57]



SOE cell

SOE cells
100 → 400 → 800 cm²

Current density
→ 0.6 → 085 → 1.5 A/cm²

SOE stack
1 - 10 kW → 20 - 100 kW

SOF stacks with 30-60
→ 120 - 150 cells

Hot-box HT BoS
100 - 500 kW → 1 - 2 MW

Stacks and highT balance of stacks
insulated and forming a Hot-box

Amount and stack ratings: → 15-60 stacks
of few kW→ several stacks with sub-100 kW

Repeating module
1.8-3 MW → 5-20 MW

Multiple hotboxes integrated with
common lowT BoP and power electronics
forming a repeating module

Complete SO plant

Multi-MW SO plant
2-20 MW → >100 MW

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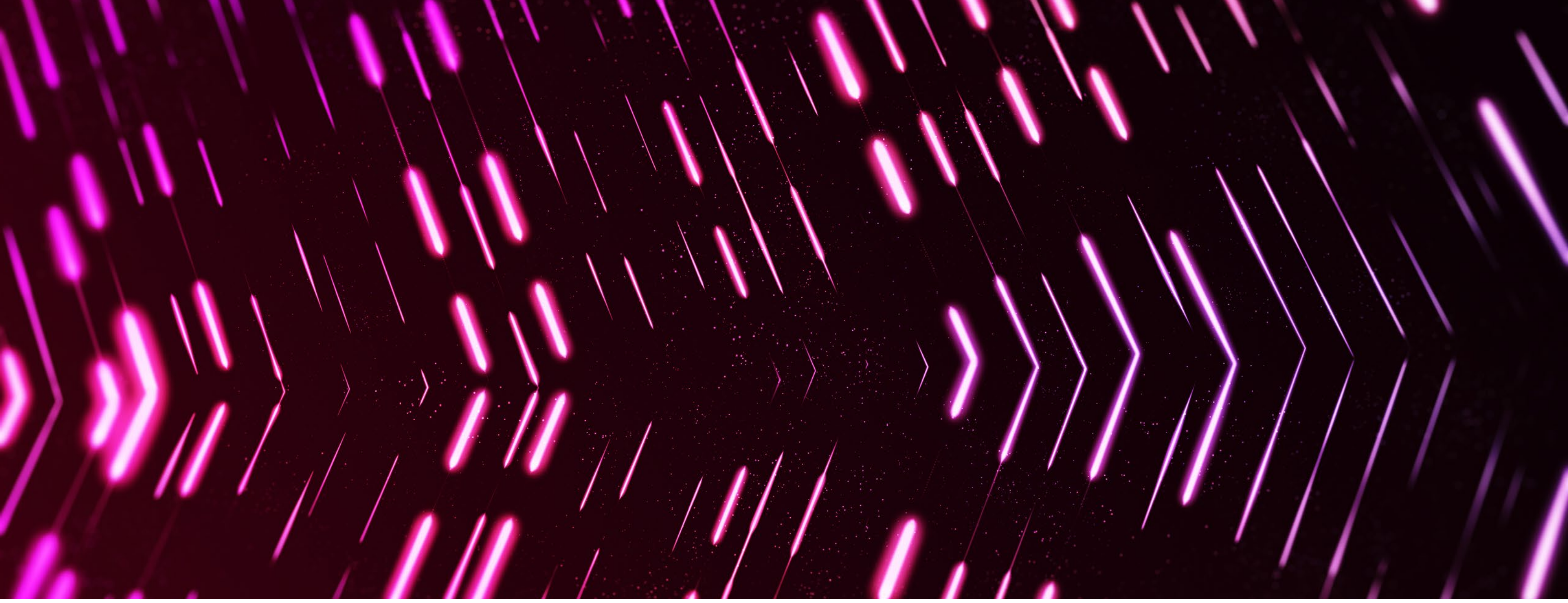
[57] Institute for Sustainable Process Technology. (2023). Next Level Solid Oxide Electrolysis. https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf



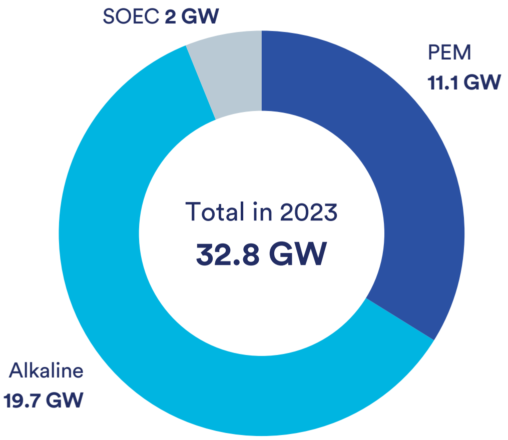
SECTION 5

Market Considerations and Commercialization Challenges

5.1 An Overview of SOEC Manufacturers and Technology Developers

Table 6 on pages 35-37 summarizes information about current SOEC manufacturers and technology developers, based on primary research into the state of the industry and interviews with industry leaders. The table provides information on key technology characteristics, R&D efforts, manufacturing capacities, and upcoming projects.

Figure 29: Global Nameplate Electrolyzer Manufacturing Capacity[58]



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[58] *A breakneck growth pivot nears for green hydrogen* (2022) BloombergNEF. Available at: https://about.bnef.com/blog/a-breakneck-growth-pivot-nears-for-green-hydrogen/ (Accessed: 02 November 2023); Clean Air Task Force

Table 6: Summary of Key Solid Oxide Technology Developers and Manufacturers

Bloomenergy

Brief description	Electrolyzer mfg capacity per year[59]	Technology	Upcoming electrolyzer projects
US based manufacturer of solid oxide systems. Spun-out in 2001 from NASA tech to create fuel and oxygen using Martian water. Bloom has deployed over 1 GW of solid oxide fuel cells worldwide and has recently returned to providing an electrolyzer product. They had recently built, installed, and operationalised the largest solid oxide electrolyzer in the world – 4 MW – all in a span of two months	Today: 2GW	■ Electrode-supported manufacturing. ■ Built a 2 GW electrolyser/1 GW fuel cell factory in less than two years. ■ Operational temperature above 800°C. ■ Current modules of 120 kW can be combined to form 2 MW blocks. ■ Above-industry average stack lifetimes exceeding 5 years and even reaching 8 years. ■ R&D focussed on increasing power density and further automating manufacturing	■ 10 MW electrolyzer with LSB Industries. ■ Westinghouse and Bloom Energy signed a letter of intent to accelerate large-scale hydrogen production in the nuclear industry. ■ Bloom announced plans to install a 240 kW electrolyzer at Xcel Energy's Prairie Island nuclear plant in Minnesota. Power-on expected in early 2024.[60] ■ Bloom is also expected to provide stacks for a nuclear-powered hydrogen micro hub in South Korea.[61]

ceres

Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
Ceres is a UK based solid oxide technology developer. The company traces its roots to research at Imperial College London and has been spun out in 2001.	Ceres is a technology developer and licenses out its tech for other companies to manufacture.	■ Gadolinium-doped ceria (GDC) electrolyte allows lower temperature operation (500°C– 600°C) which improves durability and allows the use of standard automotive gaskets and stainless steel, as the temperature is below the evaporation point of chromium, a strong poison to SOEC. ■ The trade-off with using GDC is lower current density at a given temperature. ■ Metal supported manufacturing.	■ Ceres had signed an agreement with Shell to deliver a 1 MW solid oxide electrolyzer demonstrator in 2023 in Bangalore, India. ■ Another 1 MW demonstrator is scheduled for deployment and testing by 2024 with Bosch and Linde Engineering.

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[59] Note: solid oxide manufacturing lines for fuel cells and electrolyzers are interchangeable, but electrolytic capacity is roughly twice that of fuel cell capacity adjusted for efficiency.

[60] Xcel Energy and Bloom Energy to Produce Zero-Carbon Hydrogen at Nuclear Facility. (2022, September 19). Retrieved from https://www.bloomenergy.com/news/xcel-energy-and-bloom-energy-to-produce-zero-carbon-hydrogen-at-nuclear-facility/.

[61] Patel, S. (2023, April 27). *South Korean companies snap up opportunities to advance floating nuclear, nuclear hydrogen, smrs.* POWER Magazine. https://www.powermag.com/south-korean-companies-snap-up-opportunities-to-advance-floating-nuclear-nuclear-hydrogen-smrs/

Table 6: Summary of Key Solid Oxide Technology Developers and Manufacturers – continued

Fuel cell technology
elcogen

Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
Elcogen is an Estonia based solid-oxide technology developer and manufacturer. The company has been operating since 2001.	Today: 1 to 10 MW Soon: 100 to 200 MW	■ Anode supported manufacturing, enabling a thin electrolyte that operates at 650°C which improves conductivity. ■ Current R&D focussed on automating stack assembly process – cell printing already takes single digit seconds. ■ Focussed on scaling manufacturing.	■ Elcogen's system integrator partner – Convion – is collaborating with Shell to deploy a 1 MW demonstrator system out of four 250kW stacks at Shell's Energy Transition campus in Amsterdam.

FuelCell Energy

Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
Originally founded in 1969 Connecticut and called Energy Research Corporation. In 1992 renamed to FuelCell Energy and demonstrated first product – the molten carbonate fuel cell. As of 2011, FuelCell Energy is also in the business of developing solid oxide technology.	Today: 10 to 100 MW GW scale by 2030	■ Stacks are 95% recyclable. ■ Current R&D efforts to increase stack lifetime to five years, and beyond. ■ Opted for disc shape to reduce manufacturing costs by repurposing DVD production machinery. ■ Have recently announced they are taking commercial orders for electrolyzers. ■ Also working on a reversible solid oxide stack product.	■ FuelCell Energy has an agreement with Malaysia and Marine Heavy Engineering Holdings (MHB) to collaborate on development of large-scale electrolyzers in Asia, Australia, and New Zealand. ■ FCE is also partnering with Idaho National Lab to explore coupling of SOEC with nuclear energy to leverage process heat for steam imports, and to extend the life of nuclear plants. The 250-kW module is meant to enter operation in 2023.

Table 6: Summary of Key Solid Oxide Technology Developers and Manufacturers – continued

sunfire®

Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
Sunfire was founded in Germany in 2010 and originally focussed exclusively on solid oxide technologies. As of 2021, Sunfire had also expanded into the alkaline electrolysis market by acquiring Industrie Haute Technologie.	Today: 1 – 10 MW	■ Electrolyte supported manufacturing. ■ Operational temperature of 850°C. ■ Co-electrolysis capability is a unique selling point, positioning the company well for the emerging PtL market. ■ The company is planning for a pre-commercial 10 MW pilot to reach TRL level 8 in the next five years, focussing on proving longevity of over 10 years.	■ Norsk e-fuels plans to commission a PtL (power to liquids) plant running on a mixture of alkaline and SOEC electrolyzers from Sunfire in 2024.[62]

TOPSOE

Brief description	Electrolyzer mfg capacity per year	Technology	Upcoming electrolyzer projects
Topsoe is a Danish company founded in 1940 which specialises in catalysis and process technology in chemical and hydro processing. Topsoe has been active in solid oxide development since 2004. From 2014 the company has focussed on developing electrolysis systems for the production of hydrogen, synthesis gas, and pure carbon monoxide. Topsoe has 80+ years of experience in catalysis utilized in SOEC development.	500 MW by 2025 with optionality to expand to 5 GW	■ Anode supported manufacturing. ■ Operates at 750°C. ■ Current 2nd Generation lifetime of 4 years. ■ 3rd Generation coming in second half of this decade will feature improvements to lifetime, cost, and a new geometry. ■ Focused on coupling their electrolyzer product to ammonia and methanol production, where they have complementary expertise through their catalyst business.	■ First Ammonia signed a capacity reservation agreement with Topsoe for 500MW with the option to increase to 5GW to produce green ammonia as fuel for transportation, power storage & generation, and fertilizer.[63]

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[62] Sunfire. (2022, February 28). GREEN KEROSINE FROM 2024: NORSK E-FUEL PRESENTS ITS PLANS. Retrieved from https://www.sunfire.de/en/news/detail/green-kerosine-from-2024-norsk-e-fuel-presents-its-plans.

[63] *TOPSOE and first ammonia to launch green ammonia production.* F&L Asia. (2022, September 16). https://www.fuelsandlubes.com/flo-article/topsoe-and-first-ammonia-to-launch-green-ammonia-production/#:~:text=Topsoe%20and%20First%20Ammonia%20have,storage%20and%20generation%2C%20and%20fertilizer

5.2 Manufacturing Cost Outlook

Before discussing details, it is important to note that solid oxide manufacturing will look largely the same whether the end product is electrolytic cells or fuel cells. In fact, the manufacturing process, and the machinery it requires, will be shared and switched between the two products depending on the order book. Switching over from fuel cell production to electrolytic cell production and vice versa will take less than several hours.

First Step: the Substrate

Solid oxide cell manufacturing starts with a substrate, on which other cell elements will be deposited in layers. The substrate can be thought of as the bread to a sandwich. The choice of substrate will vary by electrolyzer design and manufacturing method, but the substrate is an integral element of the cell, like the electrolyte, the electrode, or the interconnect. Older solid oxide designs rely on electrolyte-supported manufacturing, while newer designs are electrode- or even metal-supported.

The choice of substrate has implications for the operational characteristics of the cell, and for the cost of stack manufacturing. Electrolyte-supported manufacturing arose because of the difficulty of depositing thin layers of yttria-stabilized zirconium (YSZ) electrolyte, which typically needs to be laid in thicker layers (>10 micrometers or μm) to prevent cracking. Newer ceria-based electrolytes can be deposited in thinner layers, which opens the possibility of electrode- or metal-supported manufacturing.

Thinner electrolytes mean better conductivity at lower temperatures, but they also have manufacturing advantages such as lower material costs and lower heat input requirements for sintering. Heat treatment steps are usually the costliest element of the manufacturing process for SOEC cells and will account for approximately 40% of the stack's manufacturing cost.[64]

Building the Electrolyzer 'Sandwich'

Once the substrate has been selected, the layers of the electrolyzer 'sandwich' can be assembled. This layering of cell elements can be done in several ways, but the three most common industrial methods are tape casting, screen printing, and vapor deposition.

Vapor deposition is the slowest of these three options because it is often done manually. This method is widely used in early-stage factories and labs because it does not cause mechanical stress and the capital requirements are relatively light. In contrast, screen printing and tape casting are more capital intensive but allow for far greater throughput and automation. Still, because screen printing is a batch process, it is typically slower than tape casting, which is a continuous process.

Nonetheless, most solid oxide manufacturers currently prefer screen printing as it is easier to control and perfect than tape casting. This leads to more consistent quality which is paramount during high-temperature operation when even the slightest imperfections compound. Screen printing is also cheaper and easier to set up at smaller manufacturing scales (megawatts to single-digit gigawatts).

Factories might employ a mix of these methods at different stages of manufacturing. For instance, a factory might tape cast the solid oxide electrolyte substrate, and then apply electrodes using screen printing. The optimization problem in this respect has different solutions depending on the manufacturer's experience, throughput, choice of materials, and choice of substrate.

Figure 31 and Figure 32 show how the process might change between electrolyte- and electrode-supported manufacturing.

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[64] James, B.D., Prosser, J.H., & Das S. (2022) HTE Stack Manufacturing Cost Analysis [PowerPoint slides]. Strategic Analysis. https://www.energy.gov/sites/default/files/2022-03/HTE%20Workshop-Strategic%20Analysis.pdf

Figure 30: Substrate Types for Electrolyzer Manufacturing[65]

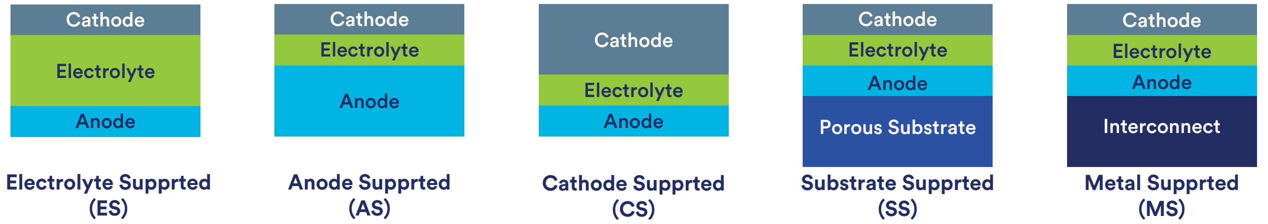
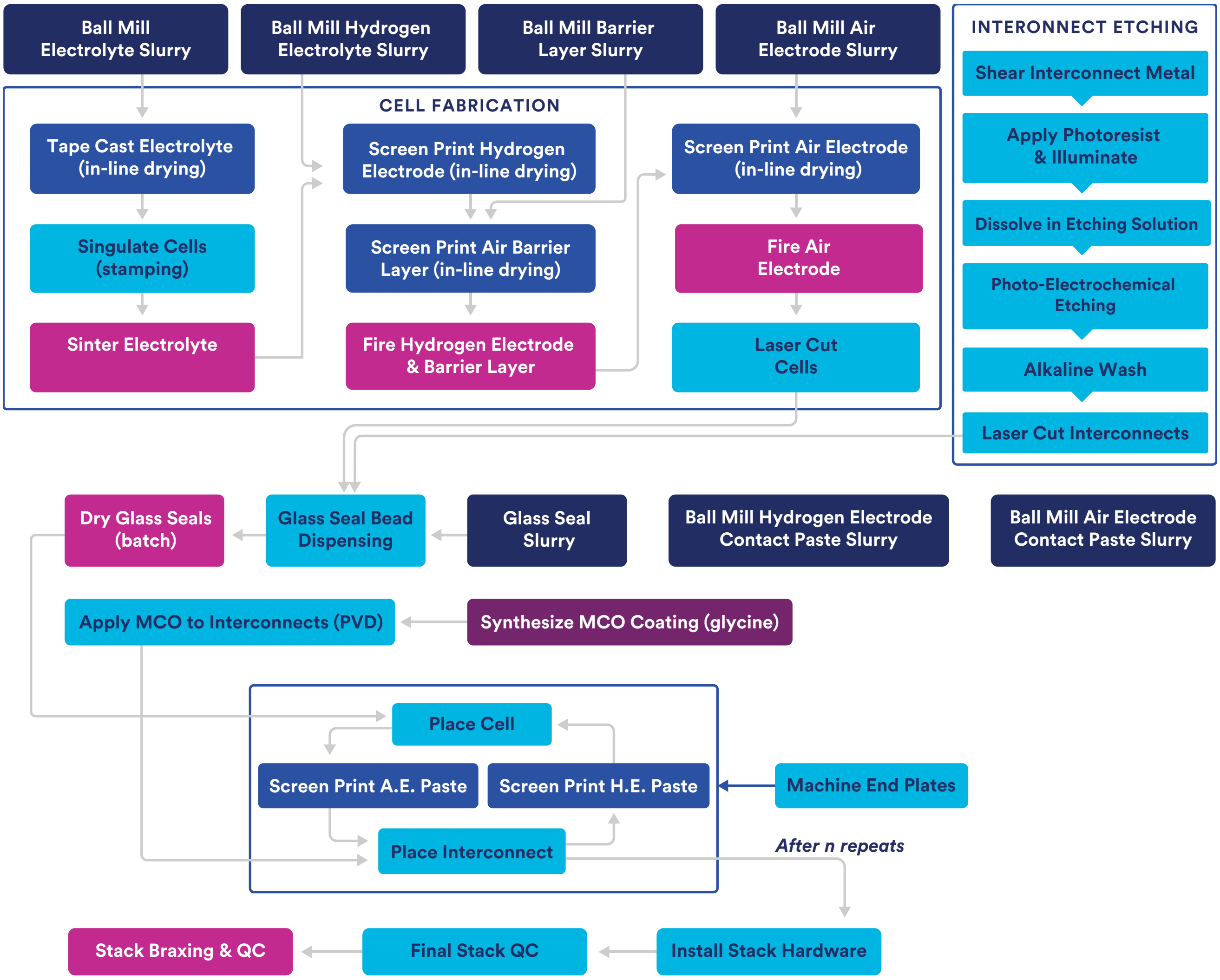


Figure 31: Process Flow Diagram of a 'Generic' SOEC Stack Fabrication Using Electrolyte Supported Cells[66]



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[65] Kuterbekov, K. A., Nikonov, A. V., Bekmyrza, K. Zh., Pavzderin, N. B., Kabyshev, A. M., Kubenova, M. M., Kabdrakhimova, G. D., et al. (2022). Classification of Solid Oxide Fuel Cells. Nanomaterials, 12(7), 1059. MDPI AG. Retrieved from http://dx.doi.org/10.3390/nano12071059

[66] James, B.D., Prosser, J.H., & Das S. (2022) HTE Stack Manufacturing Cost Analysis [PowerPoint slides]. Strategic Analysis. https://www.energy.gov/sites/default/files/2022-03/HTE%20Workshop-Strategic%20Analysis.pdf

Figure 32: Process Flow Diagram for a 'Generic' SOEC Stack Fabrication Using Electrode-Supported Cells

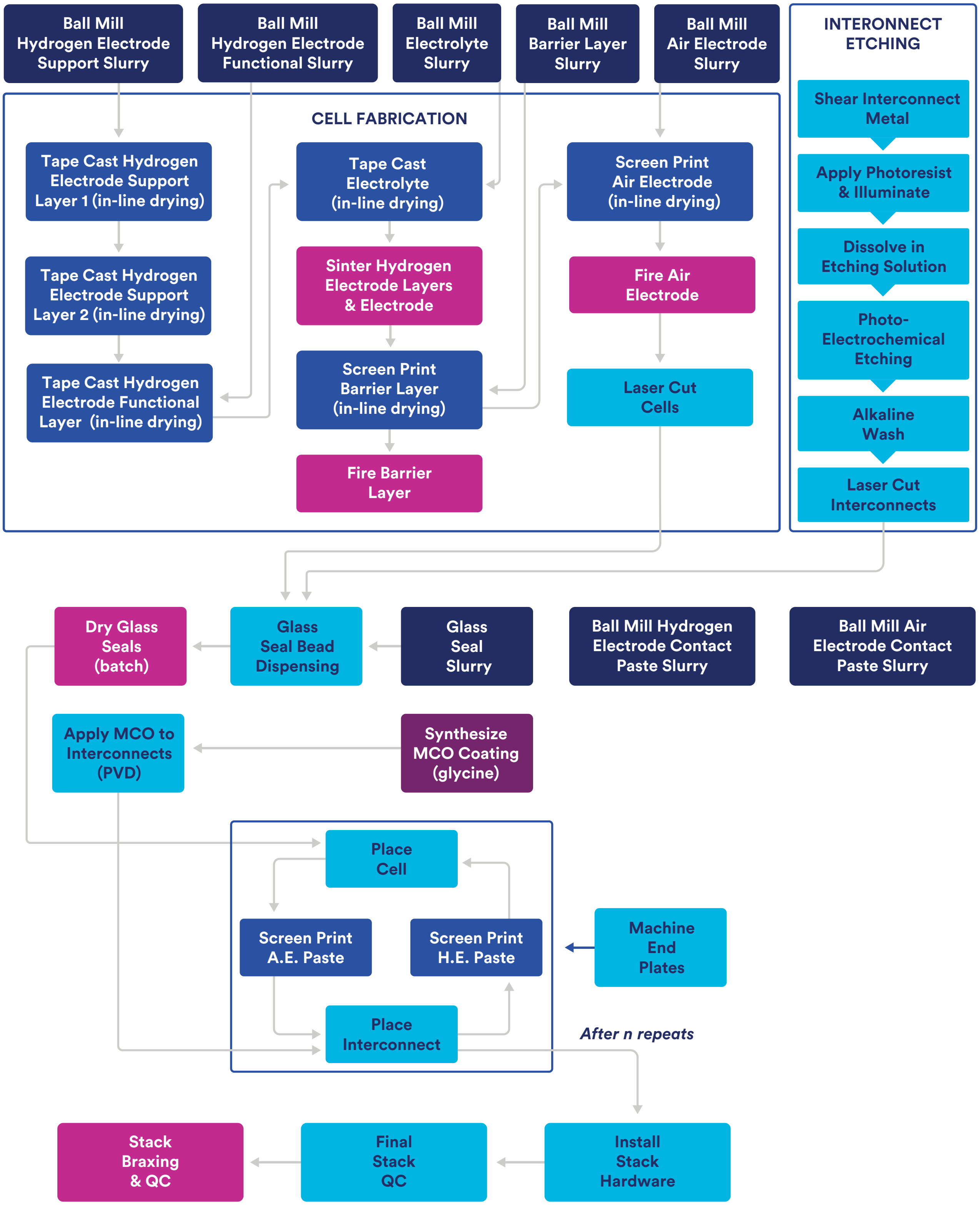
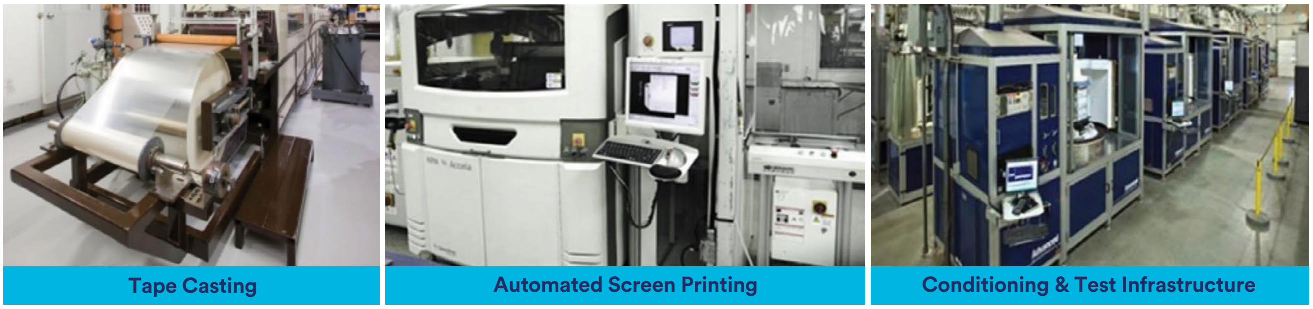


Figure 33: Solid Oxide Cell Fabrication Processes and Robots[67]



Tape Casting

Automated Screen Printing

Conditioning & Test Infrastructure

Sintering

Automated QC / Stacking

3000 m² facility with pilot cell / stack production, R&D and extensive 33 test stand capability (Calgary, AB)

Once the electrode or electrolyte layers are printed, they are sintered in ovens to make a solid oxide cell 'sandwich.' Cells are then joined to make a stack, which involves first coating the cells with a sealing material to prevent gas leakage and then encasing them with a current-conducting interconnect to join the cells. The stack is then pressed together, dried, fitted with any extra hardware like piping, if needed, and subjected to a final quality control process.

Manufacturers will probably deviate slightly from flow sheets by, for instance, outsourcing some steps such as interconnect etching. Flow sheets also don't list all the quality control steps that are taken at factories. These quality controls are critical to ensure that the stack will not fail before its intended lifetime. Most of these steps in the manufacturing process can be automated, using analytical methods involving lasers and x-rays and robotics (Figure 33).

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[67] Ghezel-Ayaagh, H. (2021). Protonic Ceramics for Energy Storage and Electricity Generation Using Ammonia [PowerPoint slides]. Fuelcellenergy. https://www.energy.gov/sites/default/files/2021-08/12-proton-ceramics-using-ammonia.pdf

Cost Reductions From Scaling Manufacturing

When goods are mass manufactured, their costs tend to come down, owing to learning-by-doing, and economies of scale. In the case of solid oxide stacks, scaling production from megawatts to gigawatts drives drastic reductions in manufacturing and materials costs. Resulting savings in total stack cost range from 67% (from $355/kW to $115/kW) to 77% (from $335/kW to $78/kW) for electrolyte- and electrode-supported processes respectively (Figure 34). Furthermore, at gigawatt scale, electrode-supported stacks are estimated to be one-third cheaper to manufacture than electrolyte-supported stacks. Once manufacturing reaches the gigawatt scale, the rate of cost savings tapers off.

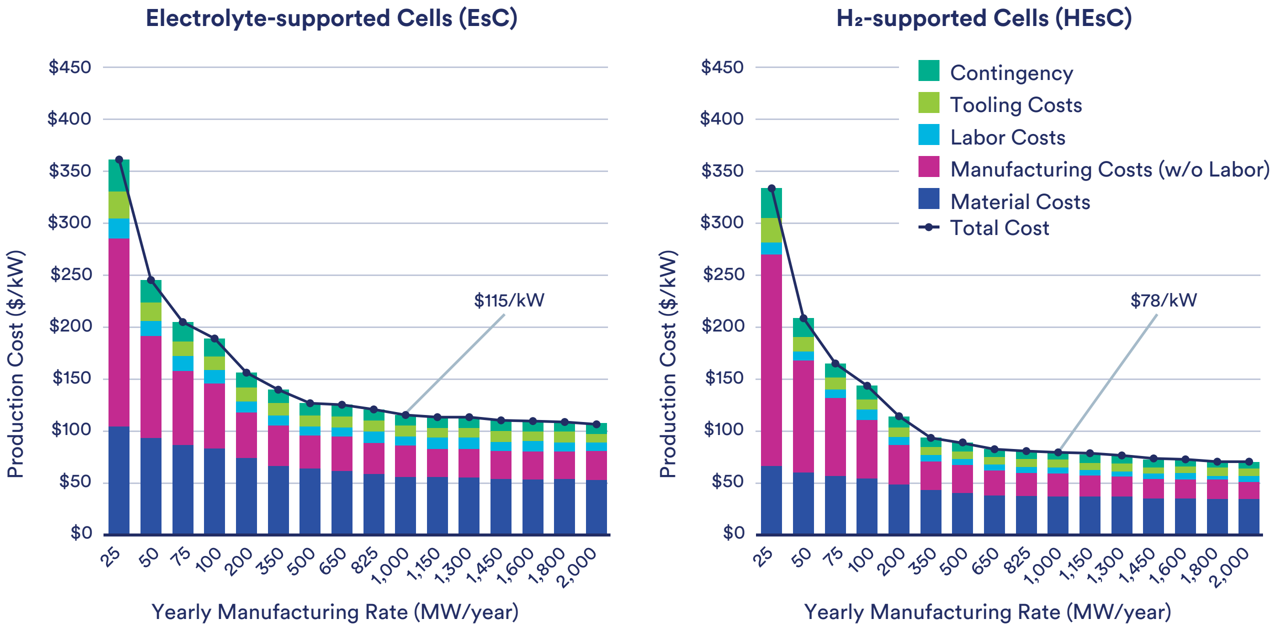
Costs for stack manufacture, however, are only part of the final cost of the electrolyzer. A typical stand-alone solid oxide electrolyzer system also integrates many stacks inside an insulated hotbox and includes mechanical equipment (pumps, compressors) as well as electrical balance-of-plant components.

A 2016 study by the Technical University of Denmark (DTU) outlined how BoP costs decline with module size, based on component costs from existing chemical plants.[69] Today, solid oxide electrolyzers are typically packaged and sold in modules of hundreds of kilowatts.

Thus, according to the DTU study, typical BoP costs would be around $688/kW. Other sources put current BoP costs at $700/kW[70] or even $1,000/kW.[71]

Nevertheless, BoP costs can fall, driven by economies of scale as BoP is shared by a larger block of SOEC modules. Estimates of future BoP costs predict a decline of 60%–75%.

Figure 34: SOEC Stack Production Costs by Manufacturing Method[68]



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[68] https://www.energy.gov/sites/default/files/2022-03/HTE%20Workshop-Strategic%20Analysis.pdf

[69] James, B.D., Prosser, J.H., & Das S. (2022) HTE Stack Manufacturing Cost Analysis [PowerPoint slides]. Strategic Analysis. https://www.energy.gov/sites/default/files/2022-03/HTE%20Workshop-Strategic%20Analysis.pdf

[70] James, B.D., Prosser, J.H., & Das S. (2022) HTE Stack Manufacturing Cost Analysis [PowerPoint slides]. Strategic Analysis. https://www.energy.gov/sites/default/files/2022-03/HTE%20Workshop-Strategic%20Analysis.pdf

[71] FuelCell Energy. (2022). Reversible Solid Oxide Fuel Cell Systems for Energy Storage and Hydrogen Production. https://www.osti.gov/servlets/purl/1874500

Estimates of total direct cost for a solid oxide electrolyzer are scant and vary widely. Table 8 presents estimates from a leading SOEC manufacturer, Bloom Energy, and from the Dutch independent research organization TNO (Netherlands Organisation for Applied Scientific Research), which recently concluded a cost study with leading SOEC manufacturers. Of course, developers of SOEC projects would also need to account for additional, indirect costs such as engineering, procurement, and construction (EPC) costs and contingency costs. These indirect costs could double the final, installed cost for an SOEC plant.

5.3 Operations and Maintenance Costs

Due to their higher operating temperatures and shorter stack lifetimes, SOEC systems tend to have higher maintenance costs than PEM and alkaline electroyzers. Bloom Energy has developed cost estimates for its own SOEC technology and competitor products. Another study, by Idaho National Laboratory, estimated annual operations and maintenance (O&M) cost for an SOEC coupled directly to a nuclear plant at $39.5 per kW.

Table 7: SOEC Balance of Plant Cost Estimates

	2022 – Cost of SOEC BoP (2022 $/kW)			2030 – Cost of SOEC BoP (2022 $/kW)		
Source	**DTU[67]**	**Strategic Analysis[68]**	**FuelCell Energy[69]**	**DTU[67]**	**Strategic Analysis[68]**	**FuelCell Energy[69]**
Heat Exchanger	66	–	–	16	–	–
Rectifier	456	–	–	115	–	–
Compressor	122	–	–	30	–	–
Other BoP	44	–	–	11	–	–
Total BoP	688[72]	700	$1,000[73]	172[74]	–	400[75]

Table 8: Estimates of Electrolyzer System Direct Costs

Direct System Cost – Electrolyzer Plus Installation ($/kW)		
	Bloom Energy[76]	**ISPT[77]**
2020	1,302	3,006
2030	359	738

Table 9: O&M Cost Estimates for an SOEC System

O&M Annual Cost Excl. Stack Replacement ($/kW/yr)				
	Bloom Energy[78]			**INL[79]**
Technology	**ALK**	**PEM**	**SOEC**	**SOEC**
2020	36	61	69	39.5
2030	15	17	17	39.5

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[72] Based on plant size of 0.1 MW.

[73] Based on a manufacturing capacity of 20 MW/year.

[74] Based on plant size of 10 MW.

[75] Based on a manufacturing capacity of 500 MW/year.

[76] Bloom Energy. (2022). The Role of Solid Oxide Technology in the Hydrogen Economy: A Primer. https://f.hubspotusercontent30.net/hubfs/5242085/BE21_22%20Hydrogen-white-paper_D.pdf

[77] Institute for Sustainable Process Technology. (2023). Next Level Solid Oxide Electrolysis. https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf

[78] Bloom Energy. (2022). The Role of Solid Oxide Technology in the Hydrogen Economy: A Primer. https://f.hubspotusercontent30.net/hubfs/5242085/BE21_22%20Hydrogen-white-paper_D.pdf

[79] Idaho National Lab. 2019. *Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest.* https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_18785.pdf

5.4 Key Input Materials and Potential Supply Chain Bottlenecks

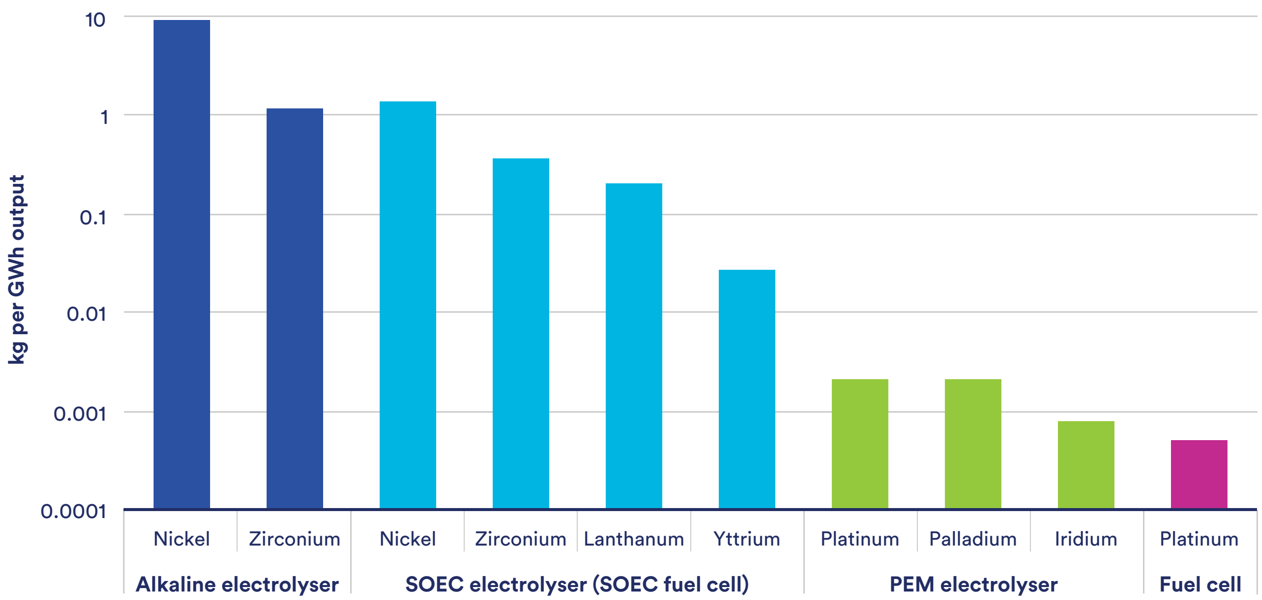
Input materials are an important driver of manufacturing cost for SOECs. Per megawatt, a 'generic' SOEC will require 150–200 kg of nickel, approximately 40 kg of zirconium, approximately 20 kg of lanthanum, and up to 5 kg of yttrium.

Some SOEC designs may also require tens of kilograms of ceria and smaller quantities (single-digit kilograms) of scandium and gadolinium. Overall, the IEA expects that these materials requirements could be halved through design improvements over the next decade, with technical potential to reduce nickel content to below 10 kg per MW.

Compared with alkaline electrolyzers, SOECs require an order of magnitude less nickel. With nickel demand set to soar due to rapid growth in global battery manufacture, solid oxide electrolyzers are less exposed to nickel price volatility than alkaline electrolyzers. At the current nickel price of $22,000 per tonne,[80] this metal accounts for only $4.4/kW of the cost to manufacture a SOEC. Since the mining of nickel is geographically dispersed, overall supply chain risk from this element is low.

An important advantage of SOEC technology is that it avoids the use of platinum and iridium – rare earth metals for which the supply chain is concentrated and known reserves are relatively low. Nonetheless, SOEC supply chains are not risk free, because these electrolyzers do require other rare earth metals such as zirconium, lanthanum, yttrium, and scandium. Until relatively recently, supply chains for some of these elements were very concentrated in China. But since 2016, substantial new production has surfaced – chiefly in the United States, Myanmar, and Australia. While the mining of rare earth metals is still relatively concentrated globally, the small quantities of these elements required for SOEC manufacture mean that alternative supplies can likely be found if needed. Some SOEC manufacturers have already had to adjust as a result of supply chain problems with scandium but managed to find alternative sources without affecting their ability to deliver.

Figure 35: Estimated Levelized Demand for the Main Minerals in Electrolyzers and Fuel Cells Today[81]



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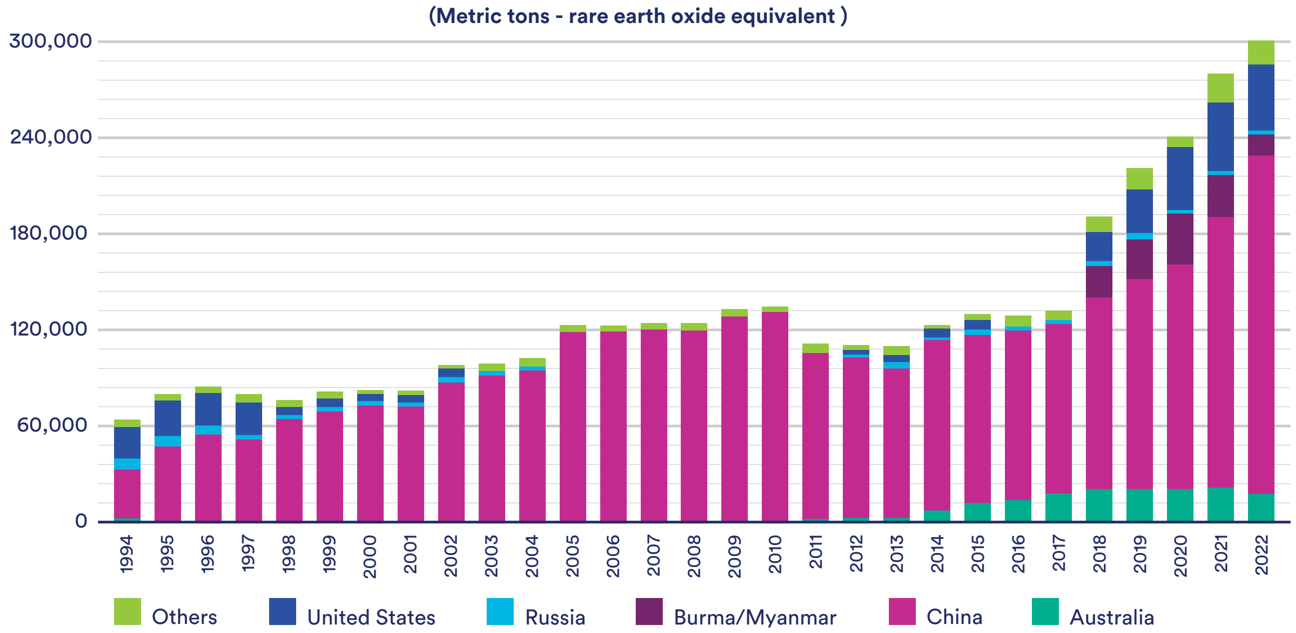
[80] Lme Nickel | London Metal Exchange. (n.d.). https://www.lme.com/en/metals/non-ferrous/lme-nickel

[81] IEA (2022). The Role of Critical Minerals in Clean Energy Transitions Sector. https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf

Figure 36: Global Production of Rare-Earth Oxides[82]



To illustrate why it should be relatively easy to accommodate rare-earth demand from SOEC manufacture, it is instructive to consider the market for lanthanum. In 2019, around 50,000 tonnes[83] of lanthanum oxide, containing 42,500 tonnes of elemental lanthanum, were mined globally. Producing 1,000 MWh of hydrogen using SOECs requires 0.2 kg of lanthanum. Thus, just one year's global supply of lanthanum would be enough to produce 212.5 billion MWh of hydrogen (assuming 50,000 GW of SOEC running at 50% capacity factor).

5.5 Non-Technological Risks to SOEC Scaleup

To successfully scale SOEC technology, several additional, non-technological risks will need to be overcome. These include financial risks, operational risks, and obsolescence risk. Examples of financial risk include the possibility that banks would be unwilling to finance an unfamiliar technology or that project developers would prioritize cheaper upfront costs and select alkaline and PEM technologies. An example of operational risk is the possibility that an SOEC system might be run outside the manufacturer's design parameters (e.g., with frequent cold starts or without maintaining optimal temperature conditions). This could cause equipment failures and entrench the perception that the technology remains underdeveloped. Other external developments, meanwhile, can create obsolescence risk – for example if the electrification of industrial processes vastly reduces sources of process heat for SOEC systems to tap into.

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[82] King, H. M. (n.d.). *REE - Rare Earth Elements and their Uses. Geology.* https://geology.com/articles/rare-earth-elements/

[83] Davis, S. (2020, July 29). *Rare Earth Elements Supply Uncertain for IC Fabs.* Semiconductor Digest. https://www.semiconductor-digest.com/rare-earth-elements-supply-uncertain-for-ic-fabs/

SECTION 6

Conclusion and Outlook

Solid oxide electrolyzer technology is at a higher readiness level than many give it credit for. Most of the companies that are pursuing SOEC development have already completed pilot projects, and even put their technology into commercial operation with industrial partners. One manufacturer – Bloom Energy – leads the pack as it has already deployed more than 1 GW of solid oxide systems worldwide.

Scaling SOEC manufacturing to meet the world's growing appetite for electrolyzers will not be a bottleneck. Experienced manufacturers with a track record can build a large, gigawatt-scale factory in less than two years and navigate supply chain risks for raw materials. The industry leader in SOEC manufacturing leader is again Bloom Energy: its 2 GW/year stack manufacturing capacity already exceeds that of most alkaline, PEM, and AEM electrolyzer companies. Other solid oxide developers are planning to catch up: the runner up is Topsoe, which has started building a 500-MW electrolyzer factory that is due to come online in 2025. Elcogen and FuelCell Energy have also indicated they will be expanding production into the hundreds of MWs.

The main advantage of SOEC technology is the step change improvement in efficiency it offers when integrated with an external process that can provide high-purity steam. This makes SOEC a perfect fit for industrial sites with enough unused low-grade process heat to evaporate water. Ammonia, chemical, and steel plants, as well as refineries, would be particularly well suited for SOEC integration. Geothermal plants are another option. Some have proposed that SOEC systems could tap into other sources of process heat, such as from a nuclear power plant, but this approach is only scalable for new nuclear plants rather than for retrofits of existing assets or those currently under construction. This will also require new regulatory approaches to nuclear licensing and permitting.

Looking forward, SOEC manufacturers still have one critical technology hurdle to clear: they must successfully scale their product from current modules, which – though they qualify as commercial – are still relatively small, to large systems (in the hundreds of megawatts) that match the size and the output of a typical industrial plant. If they succeed, SOEC is well positioned to be the preferred hydrogen generation technology at industrial sites with available process steam.