U.S. DEPARTMENT OF ENERGY

Water Electrolyzers and Fuel Cells Supply Chain

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, “America’s Supply Chains”

February 24, 2022

(This page intentionally left blank)

About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the capstone policy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- carbon capture materials,
- electric grid including transformers and high voltage direct current (HVDC),
- energy storage,
- fuel cells and electrolyzers,
- hydropower including pumped storage hydropower (PSH),
- neodymium magnets,
- nuclear energy,
- platinum group metals and other catalysts,
- semiconductors,
- solar photovoltaics (PV), and
- wind

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- commercialization and competitiveness, and
- cybersecurity and digital components.
- More information can be found at www.energy.gov/policy/supplychains.

Acknowledgments

The U.S. Department of Energy (DOE) acknowledges all stakeholders that contributed input used in the development of this report – including but not limited to federal agencies, state and local governments, U.S. industry, national labs, researchers, academia, non-governmental organizations, and other experts and individuals. The authors appreciate input and guidance from the organizers of the overall effort: Tsisilile Igogo and Colin Cunliff of the DOE Office of Policy.

Principal Authors
Badgett, Alex, Decision Support Analysis Researcher, National Renewable Energy Laboratory
Brauch, Joe, Decision Support Analysis Researcher, National Renewable Energy Laboratory
Buchheit, Kyle, Support Contractor, National Energy Technology Laboratory
Hackett, Gregory, Energy Process Analyst, National Energy Technology Laboratory
Li, Yijin, Decision Support Analysis Researcher, National Renewable Energy Laboratory
Melaina, Marc, Senior Analyst, DOE Hydrogen and Fuel Cell Technology Office
Ruth, Mark, Group Manager, National Renewable Energy Laboratory
Sandor, Debra, Project Manager, National Renewable Energy Laboratory
Summers, Morgan, Energy Systems Analyst, National Energy Technology Laboratory
Upasani, Shubhankar, Decision Support Analysis Researcher, National Renewable Energy Laboratory

Contributors
Breazeale, Liz, Writer/Editor/Web Content, National Renewable Energy Laboratory
Cramer, Lisa, Business Support Professional, National Renewable Energy Laboratory
Dolan, Connor, Director of External Affairs, Fuel Cell and Hydrogen Energy Association
Engel-Cox, Jill, Research Advisor, National Renewable Energy Laboratory
Gore, Colin, Fellow, DOE Hydrogen and Fuel Cell Technology Office
Graziano, Diane, Chemical Engineer, Argonne National Laboratory
Kleen, Gregory, General Engineer, DOE Hydrogen and Fuel Cell Technology Office
Meshek, Mike, Project Manager and Editor, National Renewable Energy Laboratory
Papageorgopoulos, Dimitrios, Supervisory Scientist, DOE Hydrogen and Fuel Cell Technology Office
Smith, Braeton, Principal Energy Economist, Argonne National Laboratory
Stetson, Ned, Supervisory Scientist, Hydrogen and Fuel Cell Technology Office
Ulsh, Michael, Group Manager, National Renewable Energy Laboratory
Wipke, Keith, Laboratory Program Manager, National Renewable Energy Laboratory

Reviewers
Crisostomo, Noel, Physical Scientist, Office of Policy
Cunliff, Colin, Physical Scientist, Office of Policy
Gilman, Patrick, Supervisory Management and Program Analyst, Wind Energy Technology Office
Igogo, Tsisilile, Lead Supply Chain Coordinator, Office of Policy [Detailee]
Satyapal, Sunita, Office Director, Hydrogen and Fuel Cell Technology Office
Speakes-Backman, Kelly, Acting Assistant Secretary, Energy Efficiency and Renewable Energy
Unel, Burcin, Energy Policy Director, Institute for Policy Integrity
Vaidyanthan, Kavita, Deputy Assistant General Counsel, Fossil Energy and Carbon Management
Veeder, Christy, Senior Advisor, Office of Energy Jobs
Whiting, Amelia, Attorney-Advisor, Office of General Counsel

Nomenclature

AEMEC	anion exchange membrane electrolysis cell
AEMFC	anion exchange membrane fuel cell
BNEF	Bloomberg New Energy Finance
BPP	bipolar plates
DOE	U.S. Department of Energy
ESIB	Energy Sector Industrial Base
FCEV	fuel cell electric vehicle
GDL	gas diffusion layer
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kg	kilogram
kWh	kilowatt-hour
LSC	doped lanthanum chromate ($La_{0.8}5Sr_{0.15}CrO_3$)
LSCF	lanthanum strontium cobalt ferrite
LSM	lanthanum strontium manganite
MEA	membrane electrode assembly
MMT	million metric tonnes
PEM	polymer electrolyte membrane
PEMEC	polymer electrolyte membrane electrolyzer cell
PEMFC	polymer electrolyte membrane fuel cell
PFSA	perfluorosulfonic acid
PGM	platinum group metals
PTFE	polytetrafluoroethylene
R&D	research and development
SMR	steam methane reforming
SOC	solid oxide cell
SOEC	solid oxide electrolyzer cell
SOFC	solid oxide fuel cell

TW	terawatts
W	watts
yr	year
YSZ	yttria-stabilized zirconia

Executive Summary

This report is one of a series that supports the analysis of the energy industrial base called for in Executive Order 14017 on America's supply chains (Exec. Order No. 14017, 2021). Specifically, it provides a review of the supply chain for water electrolyzers and fuel cells with a focus on polymer electrolyte membrane electrolyzer cells (PEMEC), polymer electrolyte membrane fuel cells (PEMFC), solid oxide electrolyzer cells (SOEC), and solid oxide fuel cells (SOFC). Water electrolysis and fuel cells are a nascent industry with little prior information related to supply chain needs and constraints. This report provides a preliminary assessment; further industry peer review and revisions are expected.

The market basis for this effort is founded on hydrogen market sizes because electrolyzers produce hydrogen, and fuel cells use hydrogen (H_2). Today's hydrogen market is approximately 10 million metric tonnes per year (MMT/yr) in the United States and 65–100 MMT/yr globally. However, almost none of that hydrogen is electrolytic (i.e., is produced using electrolyzers). To achieve U.S. decarbonization goals, electrolytic hydrogen will be necessary, although there will likely be a role for hydrogen produced using thermal conversion processes such as today's common technology—steam methane reforming (SMR)—along with carbon capture and storage (CCS). Thus, the electrolytic hydrogen market will need to grow substantially to meet potential future demands and provide decarbonization opportunities for difficult-to-abate sectors, including synthetic fuels for air and marine transport, long-distance transport via heavy and medium duty vehicles, energy storage, and high-temperature heat. For the end point in this analysis, we build upon the *U.S. Long-Term Strategy: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* and use the Princeton Net-Zero America E+RE+ scenario's U.S. market estimate of just over 100 MMT H_2/yr in 2050, which provides a more granular technology resolution. We also use the International Energy Agency's global market estimate of just over 500 MMT H_2/yr in 2050 to provide a global comparison.

To meet that U.S. market size, estimates of electrolyzer capacity required range up to 1,000 GW to meet new capacity deployments and replace existing capacity at the end of its lifetime. This is a large increase over the approximately 0.17 GW of capacity currently installed or planned in the United States and result in an approximately 20% compound annual growth rate from 2021 to 2050. We also estimate a total domestic fuel cell capacity of over 50 GW and a maximum annual manufacturing rate as high as 3 GW/yr will be needed for heavy-duty vehicles, medium-duty vehicles, and electricity generation.

The current and future electrolyzer and fuel cell supply chains include five segments: extracting the raw materials, generating processed materials, manufacturing subcomponents, manufacturing components, and recovering materials at the end-of-life. This report summarizes findings across those segments for today's supply chain and identifies key considerations for the development of supply chains to meet a 100 MMT/yr electrolytic hydrogen market.

Currently, the United States has sufficient domestic resources and imports to meet the materials demand. The United States also currently has manufacturing capabilities in most of the necessary key processed materials and subcomponent manufacturing for both polymer electrolyte and solid oxide technologies. Likewise, the United States has relatively well-positioned end product manufacturing capabilities for both technologies.

To meet the needs of a 100 MMT/yr hydrogen market, large increases in extraction and refining of many materials would be needed, with many key materials currently being addressed primarily (and exclusively, for some) by imports. Especially of concern are several materials that have both (1) larger projected electrolyzer and fuel cell demands than their current availability and (2) a currently high percentage of total market being met via imports with no specific plans for domestic production. Those include iridium, yttrium, platinum, strontium, and graphite. The platinum group metals (PGM) catalyst report that is part of this series ("Supply Chain Review: Platinum Metal Group Catalysts" 2021) provides additional information on those metals, including vulnerabilities and opportunities. The United States appears to have sufficient resources and supply chains for many of the other key materials, including stainless steel, titanium, zirconium, and nickel.

It is difficult to exactly predict manufacturing challenges because of the extraordinary growth required in the electrolytic hydrogen market and thus the electrolyzer and fuel cell markets. Key processed materials for polymer electrolyte technologies include perfluorosulfonic acids, catalysts, graphite composites, and titanium meshes. Key processed materials for solid oxide technologies include air electrode materials, fuel electrode materials, and the electrolyte. How and where manufacturing capacity along the supply chain may grow are unknown. Thus, government support may be needed to support those industries and meet cost reduction, growth, decarbonization, and supply chain security objectives.

Key vulnerabilities in developing an electrolytic hydrogen market and the supply chains needed for that market include:

- Immature technologies that are not currently cost-competitive for both electrolytic hydrogen production and utilization
- Lack of sufficient emission reduction incentives
- Insufficient codes and standards
- Insufficient electricity generation capacity
- Electrolyzers not being compensated sufficiently in the electricity market
- Insufficient infrastructure to support hydrogen markets at their potential
- Availability of key raw materials
- Growth requirements of manufacturing capacity and supply chains
- Energy justice issues
- Environmental justice issues
- Mismatch in demand and supply of domestic workforce
- Consistent and equal standards for hydrogen production around the world.

While the United States has technology development targets and an RD&D plan, it does not currently have hydrogen deployment targets or a national plan, unlike other countries. However, the United States is developing a national plan as required by Section 40314 of the Infrastructure Investment and Jobs Act (Infrastructure Investment and Jobs Act 2021).

The overarching opportunity for electrolytic hydrogen within the United States is to capture the high value-added links of the electrolytic hydrogen supply chain for the potential market of over 100 MMT/yr for applications across the industrial, transportation, and power sectors (Department of Energy (DOE) 2020). Key opportunities to enable the growth of electrolytic hydrogen and fuel cell markets to meet the overarching opportunity include:

- Reducing cost and increasing commercialization of electrolytic hydrogen production
- Developing economically competitive applications
- Leading development of codes and standards

- Expanding the U.S. electric grid capacity
- Developing and managing bulk hydrogen storage
- Utilizing of the natural gas infrastructure for hydrogen transport and storage
- Developing domestic material supplies, including recycling and PGM-free catalysts
- Developing electrolyzer and fuel cell manufacturing capacity
- Leading energy and environmental justice issues for a new industry
- Potentially exporting hydrogen.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

Table of Contents

List of Figures

List of Tables

1. Introduction

This report supports the analysis of the energy industrial base sector called for in Section (4)(a)(iv) of Executive Order 14017 on America's Supply Chains, which requires the Secretary of Energy, in consultation with the heads of appropriate agencies, to "submit a report on supply chains for the energy sector industrial base (as determined by the Secretary of Energy)" (Exec. Order No. 14017, 2021). The Secretary of Energy selected 11 specific technology areas for reporting, with electrolyzers and fuel cells being one of them. To meet the requirements in the executive order, this report considers supply chains and critical materials for electrolyzers, which split water into hydrogen and oxygen, and fuel cells, which consume hydrogen to generate electricity. Multiple electrolyzer and fuel cell systems are available, each having a different architecture, relying on different materials, and offering unique system integration opportunities; thus, the supply chains for these systems and how and where they might be deployed vary.

This section of the report summarizes the potential roles of hydrogen, electrolyzers, and fuel cells in the future, provides a technology overview, and summarizes a market size and resource requirement estimate to 2050. The next section maps supply chains for polymer electrolyte and solid oxide technologies. Then, a risk assessment is reported, and it lists key vulnerabilities. The report concludes with a section on opportunities and challenges.

1.1 Potential Roles of Hydrogen, Electrolyzers, and Fuel Cells in the Future Energy System

Hydrogen has been identified as a key energy intermediate to enable full decarbonization of the energy system because it can temporally decouple carbon-free energy production (e.g., variable renewable energy and nuclear energy) from its utilization and it can be a feedstock for independent and dispatchable energy applications and chemical processes. However, to meet that potential, new hydrogen production, transportation, storage, and utilization supply chains need to be developed and the components that support those supply chains need to be manufactured and operated. This report focuses on two critical components of this supply chain: electrolyzers and fuel cells.

Electrolyzers use electricity to split water into hydrogen and oxygen. If nuclear or renewable-generated electricity is used, the resulting hydrogen has minimal related carbon emissions. Today, electrolysis is not a common method of hydrogen production because the cost of hydrogen produced from electrolysis is greater than it is from conventional means which involve hydrocarbon reforming such as steam methane reforming (SMR). However, the U.S. Department of Energy's (DOE's) Hydrogen Shot initiative is targeting a production cost ($1/kg) that is lower than SMR within the next decade (Department of Energy 2021).

Electrolyzers have the potential to support the energy system both by producing hydrogen for use elsewhere and at other times and by providing a controllable load for the grid. If the electrolyzer capital costs are sufficiently low, hydrogen can be produced at a lower cost by reducing or stopping production when electricity prices are high and increasing production up to the maximum load when electricity prices are low, instead of operating at all times (Badgett, Ruth, and Pivovar 2022).

Fuel cells are essentially the opposite of electrolyzers. They react hydrogen and oxygen to generate electricity with water as a byproduct. Like electrolyzers, there are both low-temperature and high-temperature fuel cells. However, the only low-temperature fuel cells with strong development support right now are polymer electrolyte membrane fuel cells (PEMFCs) also known as proton exchange membrane fuel cells. PEMFCs are expected to be used primarily for transportation applications (e.g., heavy, medium, and light-duty vehicles; material handling equipment; and trains), and they have the potential to be used to generate electricity both as a backup power source and as a dispatchable generator for the grid. PEMFCs can produce electricity exclusively or as combined heat and power when the heat can be used. For high temperatures, solid oxide fuel cells (SOFCs) are commercialized and continue to be developed, as are molten carbonate fuel cells. Some high-temperature fuel cells can reform methane within the fuel cells and thus, use natural gas directly. High-temperature fuel cells are primarily considered for power for microgrids and the grid.

Because electrolyzers produce hydrogen and fuel cells consume it, they can be used in combination to provide energy storage for the grid where low-cost hydrogen storage is available. One benefit of hydrogen storage is that, unlike conventional batteries, the amount of stored energy can be decoupled from charging and discharging power. Thus, hydrogen storage is likely more economic for long-duration energy storage than batteries (Hunter et al. 2021). Some studies that have analyzed what would be required to reach 100% renewables on the grid have concluded dispatchable electricity generation (including long-duration storage) is required to achieve that objective (Cochran et al. 2021; Pearre and Swan 2020; Denholm et al. 2021; Kroposki et al. 2017).

1.2 Technology Overview

Several electrolysis and fuel cell technologies exist or are under development (Table 1, page 3). Electrolyzers that use electricity exclusively are referred to as low-temperature electrolyzers because they operate at temperatures lower than the boiling point of water (100°C at sea level). Low-temperature electrolyzer technologies include traditional alkaline electrolyzers, polymer electrolyte membrane electrolyzer cells (PEMECs), and anion exchange membrane electrolyzer cells (AEMECs). PEMECs are less mature than alkaline electrolyzers, but they exhibit significant potential for cost reductions and large-scale deployment. AEMECs are in early development stages, but have the potential to cost less than PEMECs while having similar performance attributes. Due to the low maturity of AEMECs, they are not considered in this analysis. PEMECs can ramp operation up and down at faster rates than traditional alkaline electrolyzers (International Energy Agency "The Future of Hydrogen - Analysis" 2019), making them favorable for directly coupling them to variable renewable energy sources such as wind or solar—one reason they could be developed at large scales.

Electrolysis technologies that use both heat and electricity and are commonly referred to as high-temperature steam electrolyzers because steam exists within their stacks. Those solid oxide cells (SOC) use high-temperature oxide-conducting ceramics as the ion-conducting membrane. SOCs are attractive for their ability to produce hydrogen at much higher efficiencies than other technologies, which they can do because the high temperatures they operate at (generally 650–800˚C) reduce the minimum voltage of the water-splitting reaction (Hauch et al. 2020). Solid oxide electrolyzer cells (SOECs) have been shown to have the potential to ramp operation up and down similar to PEMECs, but they require some heat and electricity to be held in hot standby due to issues with thermal inertia (Badgett, Ruth, and Pivovar 2022).

Two types of fuel cells are considered in this analysis: PEMFC and SOFC. These systems are largely similar to their electrolyzer counterparts but have slight variations in materials used and system designs. Like SOECs, SOFCs are more efficient than their low-temperature counterparts; they can achieve 70% efficiencies when fueled with hydrogen or natural gas. PEMFCs are favorable for use in transportation applications, as they operate variably. Both systems could be developed in energy storage applications, using hydrogen generated from electrolyzers to produce electricity when needed.

Key characteristics of the electrochemical systems that are considered in this work are summarized in Table 1 (Badgett, Ruth, and Pivovar 2022). Further information regarding performance and material use assumptions for each technology considered in this analysis can be found in Appendix A.

Table 1. Summary of Material and Performance Characteristics of Electrochemical Technologies Considered in This Analysis

System	Summary of Materials and Performance
PEMEC	PEMEC uses platinum and iridium oxide as catalysts and perfluorosulfonic acid (PFSA) as a proton conductor and binder. Membrane electrode assemblies are separated by a titanium bipolar plate coated with a thin layer of platinum. The system operates at lower efficiencies than SOEC, but operation can be ramped up and down quickly, making PEMEC favorable for integration with variable renewable generation, such as wind and solar photovoltaics. Current systems exhibit moderate lifetimes and can operate at high current densities at moderate cell potentials.
SOEC	SOEC uses oxide ion-conducting electrolyte materials, such as yttria-stabilized zirconia (YSZ) that allow for ion transport at high temperatures and generally operate at temperatures near 600˚C. High-temperature operation significantly increases the system efficiency, but it poses challenges for system durability and frequent on-off cycling.
Alkaline electrolyzers	Alkaline electrolyzers use nickel-based catalysts in an alkaline electrolyte solution such as potassium hydroxide and a diaphragm to separate electrodes and transport hydroxide ions. Alkaline systems operate at lower efficiencies than other electrolysis architectures, but they have longer lifetimes and have been deployed in large-capacity systems. Materials for alkaline electrolyte solutions are not considered in this analysis.
AEMEC	AEMEC uses an anion exchange membrane separated by nickel and nickel alloy catalysts to produce hydrogen. These systems operate at similar voltages, but lower current densities than to PEMEC systems. AEMEC systems are at a lower technology maturity level than PEMECs and alkaline electrolyzers (Miller et al. 2020).
PEMFC	PEMFC uses materials and designs that are similar to those used by PEMEC. PEMFC uses platinum and platinum-based alloys as cathode catalysts and PFSA as a proton conductor and binder. Membrane electrode assemblies are separated by a metal or carbon bipolar plate.
SOFC	SOFC uses materials, designs, and operating strategies that are similar to those of SOEC.
AEMFC	Anion exchange membrane fuel cells (AEMFCs) use an alkaline anion exchange membrane electrolyte and avoid the use of platinum catalysts that are required for PEMFCs. Similarly to their AEMEC counterparts, AEMFCs are at a lower technology maturity and are not considered in this analysis.

This report focuses on the supply chains for two electrolysis technologies (PEMEC and SOEC) and two fuel cell technologies (PEMFC and SOFC). These technologies are anticipated to hold the largest share in the global electrolyzer/fuel cell market overall. Traditional alkaline electrolyzer cells are included in installed electrolyzer capacity estimates because they are the most mature electrolyzer technology, having been operated for years in the chemical industry and are likely to be deployed across some hydrogen applications. Though AEMECs hold potential for future applications, these systems are not included in this analysis because of their low technical maturity; thus, critical materials for alkaline and AEMEC systems are beyond the scope of this analysis.

The basic components of electrolyzers and fuel cells are illustrated in Figure 1. All fuel cell and electrolyzer systems require anode and cathode catalysts for the two half reactions occurring on either side of the cell, with the desired catalytic materials varying depending on the system architecture. These catalysts are generally supported on diffusion media such as carbon paper to facilitate liquid and gas transport to and from the catalyst layer. Anode and cathode catalysts are separated by ion exchange media, the type of which varies by system. PEMFC and PEMEC systems transport hydrogen ions through a polymer electrolyte membrane, and solid oxide systems use oxide ion-conducting ceramic materials. To form large-scale electrochemical stacks, repeat units of catalysts, support, and ion conductors are separated by bipolar plates (BPPs), which facilitate product and reactant flows and act as current collectors for the system.

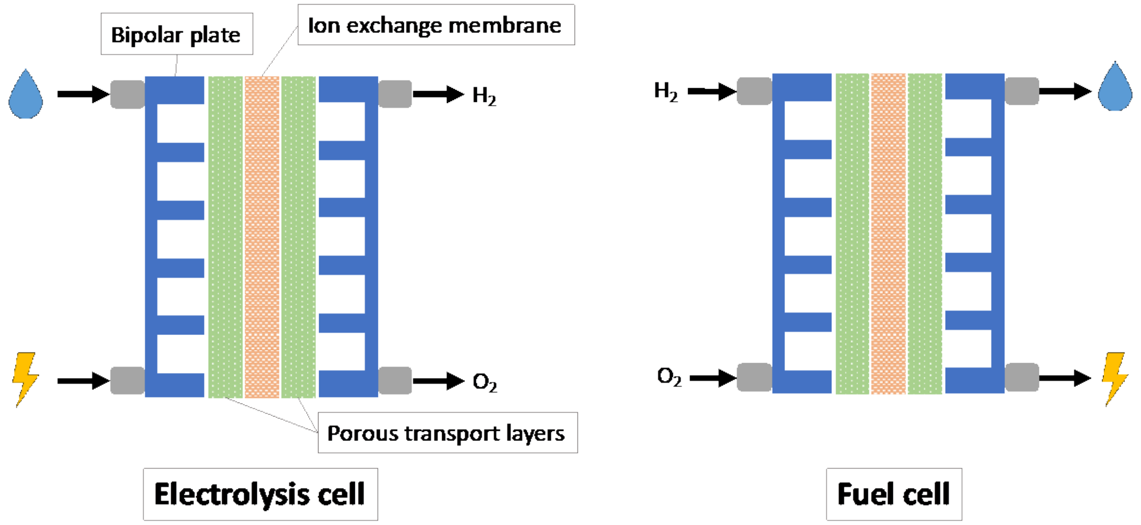


Figure 1. Key components of electrolyzers and fuel cells (Original work)

The heart of a PEMFC or a PEMEC is the membrane electrode assembly (MEA), which includes the membrane, the catalyst layers, and the porous transport layers. Hardware components used to incorporate an MEA include gaskets, which provide a seal around the MEA to prevent leakage of gases, and BPPs, which are used to assemble individual cells into a fuel cell stack and provide channels for the gaseous fuel and air (DOE n.d.). The PEMEC and associated materials and subcomponents are largely similar to those of the PEMFC. Due to higher voltages on the anode side, corrosion-resistant materials like titanium, titanium alloys, and coated stainless steel are used, instead of the carbon materials commonly used in PEMFCs (e.g., for porous transport layers and BPPs). PEMEC anode catalyst compositions are different from PEMFCs, with PEMECs using iridium for the oxygen evolution reaction (HyTechCycling 2019; E4Tech 2019), while PEMFCs use platinum for both anode and cathode catalysts.

Solid oxide stacks are composed of approximately 40–60 individual ceramic cells that produce nearly 25 W each in fuel cell operations, interconnected into a single module (Bloom Energy 2019). Material sets for solid oxide electrolyzers and fuel cells are identical or very similar. Each cell is comprised of layers of different ceramo-metallic materials allowing for efficient ionic species and electrical charge transport at high temperature (600–1,000°C). The most prominent cell geometry (planar) involves a thicker, fuel electrode providing support with the electrolyte deposited and sintered followed by the air electrode layers. Completed cells are connected in series or in parallel with appropriate separators, spacers, and flow fields to keep the fuel and oxygen carriers separate inside the final stack frame. Stacks can then be connected in parallel to produce a desired nominal output of electricity or fuels in a modular or fully integrated fashion for a given application.

1.3 Electrolyzer and Fuel Cell Market Size Estimates

The current domestic hydrogen market is approximately 10 MMT/yr and global hydrogen production is 65–100 MMT/yr (Connelly, Elgowainy, and Ruth 2019). Nearly all of this hydrogen is produced via conventional means, especially SMR. SMR uses natural gas as a feedstock, and the carbon dioxide that results from this reaction is usually released to the atmosphere and not captured. As a result, hydrogen production is responsible for 830 MMT/yr of carbon dioxide emissions (IEA 2019), and thus is a key contributor to total global carbon emissions. Currently, the primary applications for hydrogen are hydrocracking and hydrodesulfurization in crude oil refining and ammonia production via the Haber Bosch process (Connelly, Elgowainy, and Ruth 2019). The current U.S. hydrogen market revenue is approximately $17.6 billion/yr (Fuel Cell and Hydrogen Energy Association 2021). The current hydrogen market includes both captive (which is hydrogen produced at the point of consumption for internal use) and merchant hydrogen (which is hydrogen sold to consumers). Approximately, 50%-75% of the current market is captive (Connelly, Elgowainy, and Ruth 2019).

With only 0.172 GW of electrolysis capacity currently installed or planned in the United States (Arjona and Buddhavarapu 2021), the maximum electrolytic hydrogen currently produced in the United States is less than 0.025 MMT/yr. Thus, the electrolytic hydrogen market is in its infancy.

To meet decarbonization goals, carbon capture and sequestration would need to be added to SMR or electrolytic hydrogen would need to displace SMR production. As of this writing, electrolyzers and fuel cells have been mostly deployed only in niche applications in the transportation and industrial chemical sectors. However, if a clean hydrogen market develops, electrolyzer and fuel cell markets will also develop.

Original work in this report estimated domestic and global electrolyzer and fuel cell market sizes for this analysis using data from recent modeling work that depicts deep decarbonization across domestic and global economies. In November 2021, the U.S. Department of State and U.S. White House released *The Long-Term Strategy of the United States*, which lays out how the United States can reach its goal of net-zero emissions no later than 2050 and was submitted to the United Nations Framework Convention on Climate Change (UNFCCC) at the 26th Conference of the Parties.[1] The LTS illustrates many plausible pathways through 2050 to achieve a net-zero emissions economy, and offers insights into what the overall energy system for the United States could look like between now and 2050 under a range of assumptions about the evolution of technological costs, economic growth, and other drivers to 2050. The International Energy Agency estimates global hydrogen market demand could exceed 500 MMT/yr by 2050 (IEA 2021b) and the Princeton Net-Zero America analysis (Larson et al. 2021) estimates U.S. hydrogen demand could exceed 100 MMT/yr by 2050 in the E+RE+ scenario, which we used in the analysis reported here because it extends the U.S. Long-Term Strategy (United States Department of State and United States Executive Office of the President 2021) by providing a more granular technology resolution. Figure 2a and b (page 7) show the potential global and domestic hydrogen market growth between now and 2050 based on data from IEA and Princeton University analyses. The 2020 Princeton NZA market size estimate of 5 MMT/y used in this analysis varies from the 10 MMT/yr current domestic market estimated (Connelly, Elgowainy, and Ruth 2019) due to variations in data gathering as well as conversion factors used to generate hydrogen market sizes in MMT/yr based on energy consumption data from NZA scenarios. We estimate that around 5000 TWh/yr of electricity would be required to produce 100 MMT/yr.

---

[1] https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

Key results of the original analysis work conducted for this report are shown in Figures 2-6 and Figure 9. These results show possible trajectories for the growth of hydrogen markets, illustrating accompanying increases in deployment of fuel cells and electrolyzers. These projections can inform possible material requirements to produce these systems, helping to identify where raw material demands could significantly exceed current production and consumption. Assumptions and methodologies used to develop these estimates can be found in Appendix A.

The current U.S. hydrogen market revenue is estimated at $17.6 billion/yr (Fuel Cell and Hydrogen Energy Association 2021). Assuming a current (2020) hydrogen market price of $2/kg and hydrogen demand of approximately 5 MMT/yr from values calculated in this work, the current size of today's hydrogen market could be $10 billion/yr. Variation between the market sizes of $17.6 and $10 billion/yr are subject to the same variability discussed in the prior paragraph. Assuming the Hydrogen Shot initiative meets the target of $1/kg clean hydrogen by 2030 (Department of Energy 2021) and using the market size estimates calculated here, revenue in domestic hydrogen markets changes to $8.6 billion/yr at 2030 and $ 105 billion/yr in 2050 at a hydrogen price of $1/kg.

We did not estimate impacts on U.S. jobs, but the "Road Map to a US Hydrogen Economy" estimated that if the U.S. hydrogen market grows to 17 MMT/yr by 2030, it would support 700,000 jobs and if it grows to 74 MMT/yr by 2050, it would support 3,400,000 jobs (Fuel Cell and Hydrogen Energy Association 2021).

Neither analysis provides details about the production of hydrogen to meet global and U.S. demand by sector. Therefore, we developed estimates for our analysis that estimate the amount of hydrogen and installed electrolyzer capacity by sector. We assumed the conventional technology (i.e., primarily SMR) will meet existing and near-term hydrogen demand from now to 2025 (Figure 3, c and d, page 8) and that after 2025, hydrogen market demand increases will be met by electrolyzer deployments. We also assumed that from 2030 to 2050 conventional technologies will be phased out and replaced with electrolysis, with no hydrogen being generated via conventional generation technologies by 2050.

Because the future market involves more consumers and a smaller share of industrial users, the merchant market's share in the future is likely to be similar to today's share. Assuming that 75% of new feedstock, synfuels, chemicals and existing feedstock, and energy storage are captive and the remaining applications are served by merchant hydrogen, the market share for captive hydrogen changes from the current value of 50%-75% (Connelly, Elgowainy, and Ruth 2019) to approximately 68% in 2030 and 67% in 2050.

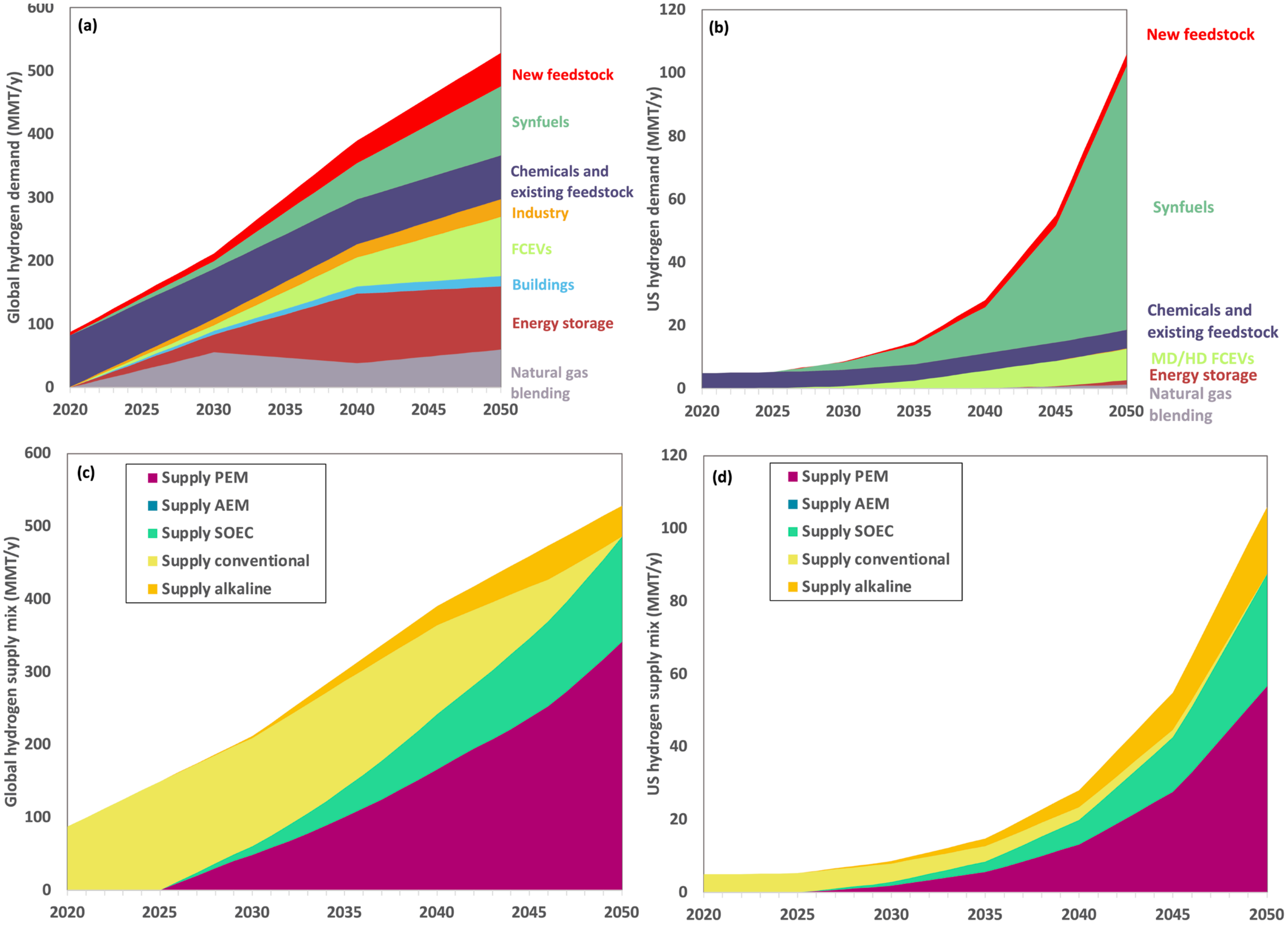


Figure 2. Estimated global (a) and U.S. (b) hydrogen demands by economic sector from 2020 to 2050. Sources of hydrogen by type for global (c) and U.S. (d) (Original work)

> *Conventional supply sources include SMR. Domestic hydrogen demand is from the E+RE+ scenario in the Princeton Net-Zero America analysis. The 2020 Princeton NZA market size estimate of 5 MMT/yr used in this analysis varies from the 10 MMT/yr current domestic market estimated (Connelly, Elgowainy, and Ruth 2019) due to variations in data gathering as well as conversion factors used to generate hydrogen market sizes in MMT/yr based on energy consumption data from NZA scenarios.*
>
> *Global data source: IEA 2021; U.S. data source: Larson et al. 2021*

The combination of increasing hydrogen demands and phasing out conventional technologies including SMR requires many electrolyzers to be manufactured and deployed. Our estimates of cumulative (Figure 3, a and b) and annual (Figure 3, c and d) installed electrolyzer capacity are shown in Figure 3. The manufactured capacity estimates shown here include estimates resulting from both new deployment of electrolyzers and the replacement of retired systems at their end-of-life. We estimate that up to 1,000 GW of electrolyzer capacity is manufactured by 2050 to meet new capacity deployments and replacement of existing capacity at the end of its lifetime. This is a large increase over the approximately 0.172 GW of capacity currently installed or planned in the United States (Arjona and Buddhavarapu 2021). These installed capacities result in an estimated compound annual growth rate from 2021 to 2050 of 22% for PEMECs and 19% for SOECs in the United States (see Appendix A).

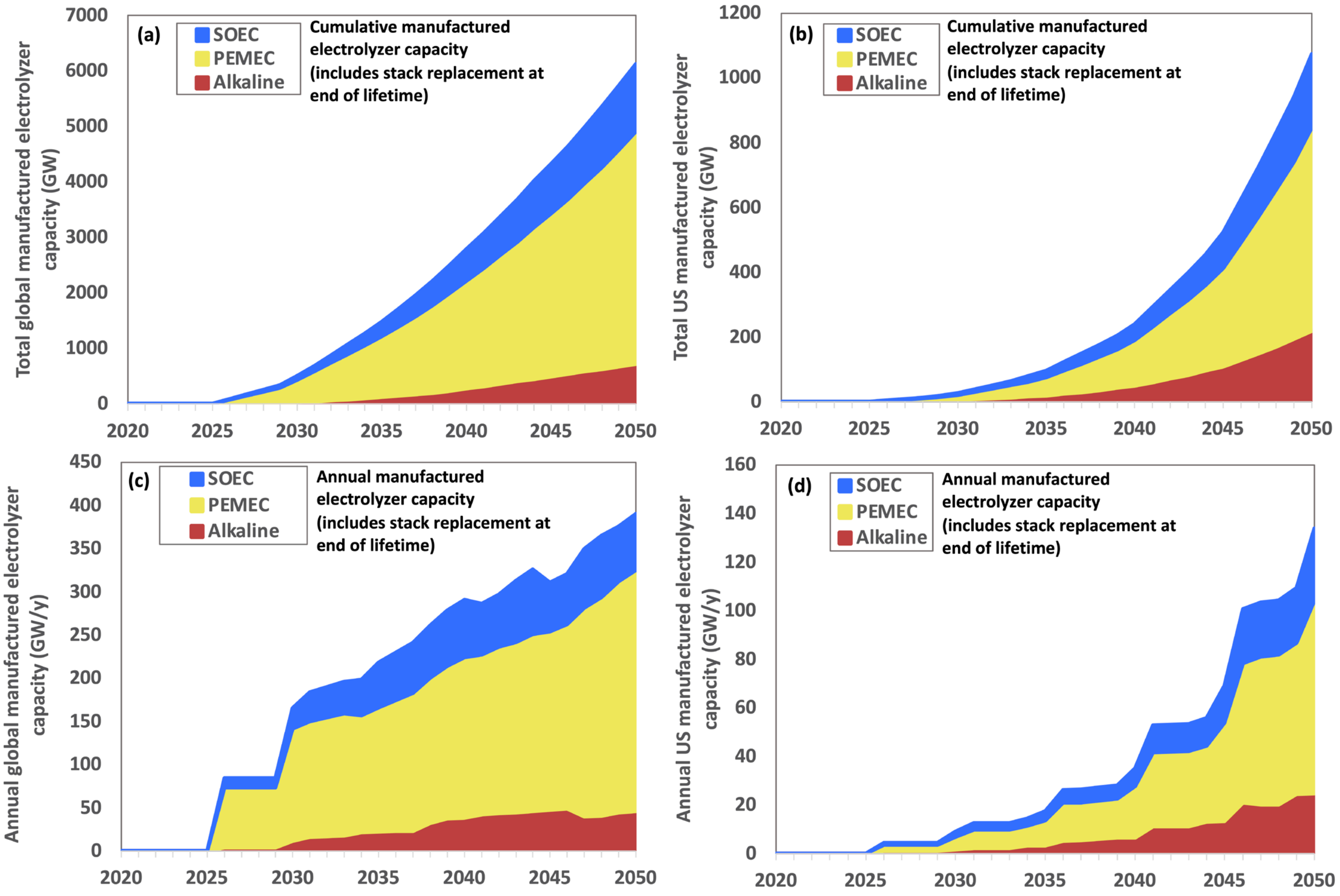


Figure 3. Estimated cumulative global (a) and U.S. (b) manufactured capacity of electrolyzers by type. Estimated annual global (c)[a] and U.S. (d) manufactured capacity of electrolyzers by type (Original work)

Values include replacement systems manufactured to replace those at end-of-life.

[a] *The global manufacturing rate of electrolyzers decreases from 2025 to 2030 in Figure 3c because of how this work assumed electrolyzers phase in to the hydrogen markets and assumptions about growth in hydrogen market size. The linear hydrogen market growth for global markets creates a jump in required manufacturing capacity of electrolyzers, which slows in its rate of growth from 2025 to 2030. It is worth noting that in Figure 3c, although the capacity decreases from 2025 to 2030, the total installed capacity of the electrolyzers continues to increase and just the rate of change (derivative) is lower here than what was required to phase the electrolyzers into the market*

Fuel cell manufacturing is also projected to increase both domestically and globally from current levels to 2050 (Figure 4). Most of the growth in deployment of fuel cells in these analyses is driven by applications in the transportation sector, mainly from heavy and medium duty fuel cell electric vehicles. This work also assumes fuel cells are deployed in energy storage applications for electric grid decarbonization, taking electrolytic hydrogen and generating electricity that is supplied to the power sector. In the Princeton NZA E+RE+ scenario, hydrogen for energy storage is predominantly used in combustion turbines and small portions in fuel cells. The estimated amount of fuel cell capacity for energy storage is sensitive to assumptions for combustion turbines versus fuel cells for energy storage applications.

This analysis estimated materials, subcomponents, and components needed for the construction of the fuel cell and electrolyzer stack itself, but it did not estimate any balance-of-plant material or equipment requirements.

Though balance-of-plant material usage is not insignificant, the materials used for these subsystems are generally less critical than the specialty materials used in the stack itself. Additionally, power electronics used to control and condition power supplied to the system are considered in other reports that are part of this series ("Semiconductor Supply Chain Deep Dive Assessment" 2022)

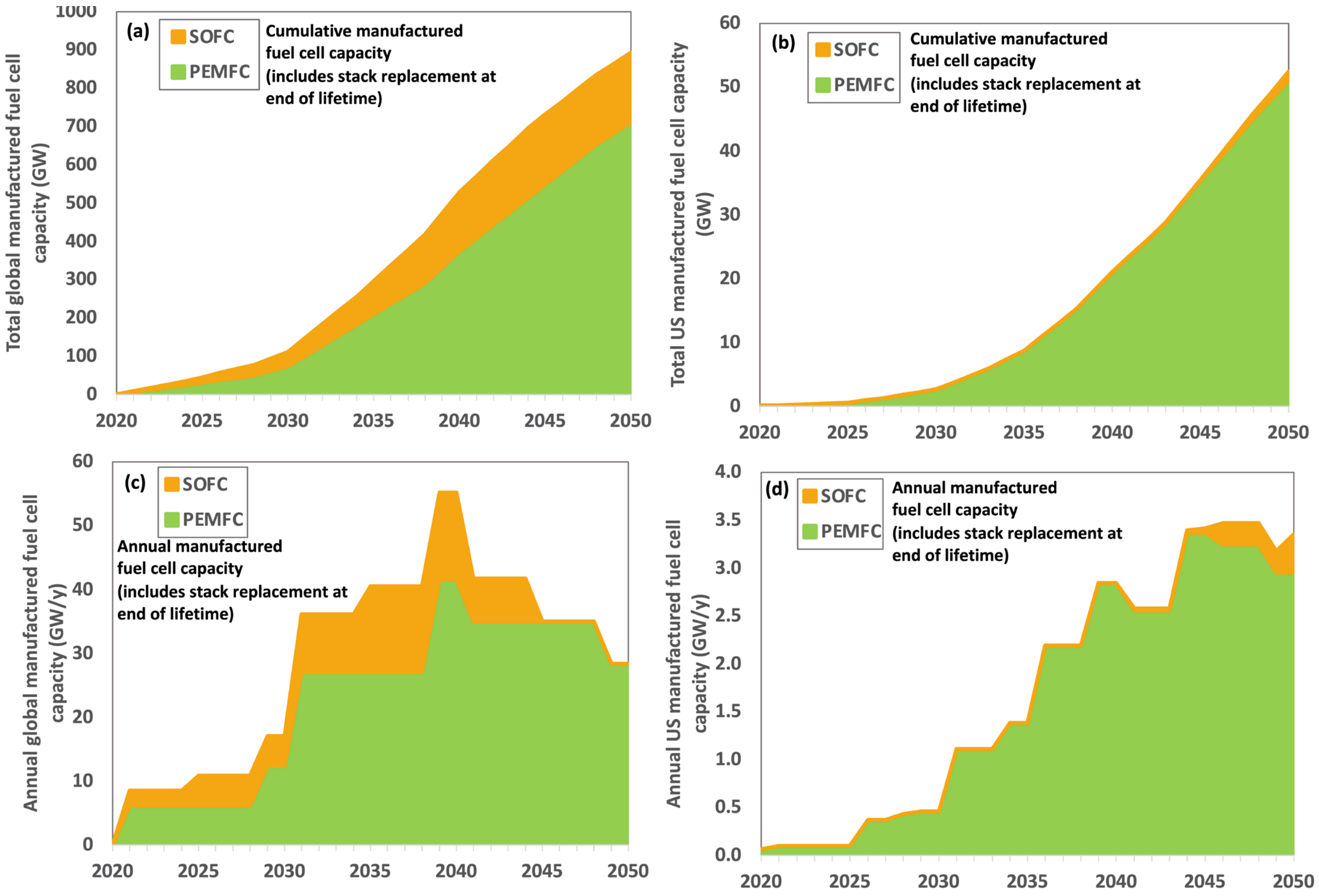


Figure 4. Estimated cumulative global (a) and U.S. (b) manufactured capacity of fuel cells by type. Estimated annual global (c) and U.S. (d) manufactured capacity of fuel cells by type (Original work)

Values include replacement systems manufactured to replace those at end-of-life. Replacing existing capacity at the end-of-life drives some of the variability and peaks in annual manufacturing rates shown in Figures c and d.

As reported above, the market for these technologies is anticipated to increase through 2050, thereby increasing the demand for materials of construction. Cumulative material requirements by 2050 are shown in Figure 5, illustrating the significant number and amount of materials required to produce the electrolyzer and fuel cell systems shown in Figure 4. The large amounts of stainless steel and titanium are driven by the use of these materials in bipolar plates in PEMECs and SOECs. Bipolar plates are thicker than other components and are composed of pure metal, making the amount of material per megawatt of system capacity higher than that of other components.

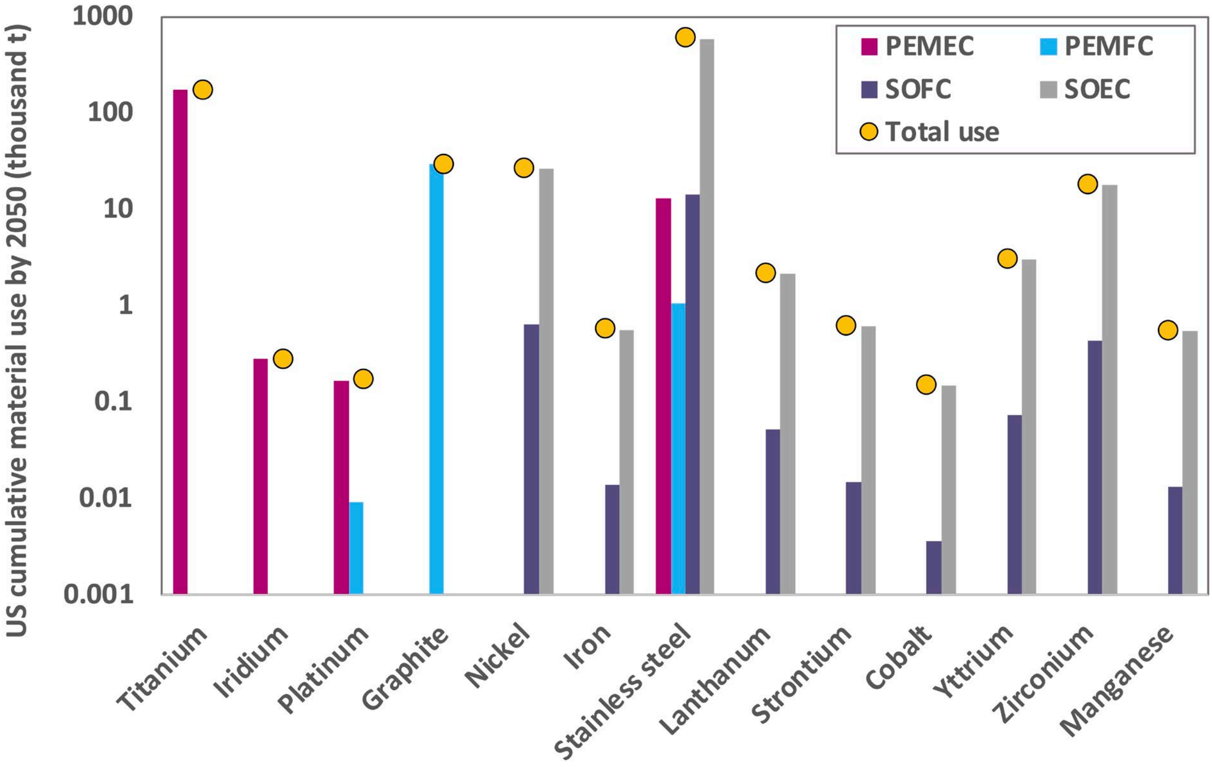


Figure 5. U.S. cumulative 2050 use by material. Total use of each material across technologies is shown in yellow points.(Original work)

The y-axis of this chart is on a log-scale. For many materials, the smaller use rate is negligible compared to the larger one so the difference between the total use and the larger use may not be noticeable.

Though titanium and stainless steel are used in the highest quantities, they are not necessarily the more important materials of those shown. Both high and low-temperature systems rely on more-exotic materials, such as iridium and yttrium in their construction. Though the total amounts of these materials required are lower, they are also less abundant, and mines that produce them are more likely to be located outside the United States. These external factors, which influence the "criticality" of various materials, are discussed in detail in the following sections.

In addition to preliminary estimates of raw materials required for catalyst and supporting components of the electrolyzer stack, the amount of polymer electrolyte membrane material required by PEMFC and PEMEC systems is estimated (Figure 6). The polymer electrolyte membranes used in these systems is based on PFSA ionomers that allow for transport of protons and acting as an electrical insulator and barrier to oxygen and hydrogen. The production of PFSA membranes uses solution casting technology, where a PFSA polymer dispersion is applied to a base film that then undergoes quality control inspection and packaging (Curtin et al. 2004). This analysis uses of PFSA-based ion exchange membranes given the significant increase in demand for these materials suggested by Figure 6 and the few suppliers currently meeting the small demand; along with possible environmental concerns associated with their production warrant additional consideration (Lohmann et al. 2020; Cousins et al. 2019).

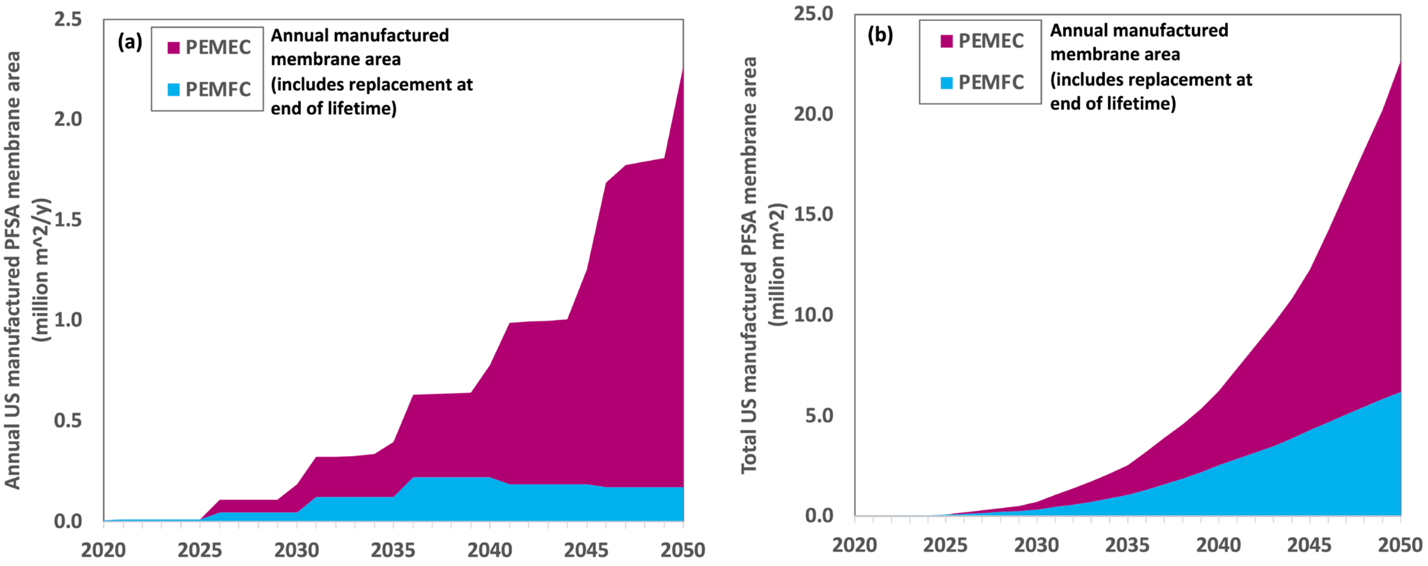


Figure 6. U.S. annual (a) and cumulative (b) use of PFSA polymer electrolyte membrane in PEMFC and PEMEC systems from current to 2050 (Original work)

Advances in the design of electrolyzers and fuel cells could reduce material use. Changes in several performance and design characteristics of these systems could result in lower material demand per kilogram of hydrogen produced. The loading rates (mg/cm^2) of catalyst materials represent a key opportunity to reduce the rate at which these catalysts are used in electrochemical systems. Additionally, ensuring systems can operate over longer lifetimes reduces the need for their replacement and requires less materials. Finally, higher efficiency electrolyzers that produce more hydrogen per kilowatt-hour (kWh) of energy consumed will more effectively meet hydrogen demand, and in turn require fewer systems and materials. This analysis assumes constant system performance and catalyst loading rates, but changes in these factors can significantly impact the materials required to manufacture a system. Because reducing or even eliminating use of critical materials generally reduces capital costs as well, doing so is the subject of significant ongoing research.

In addition to advances in the technology itself, progress in recyclability and recycling infrastructure for electrochemical systems could reduce demand for new mines and materials. The ability to recycle critical materials at high recovery rates is a key opportunity to address increasing material needs as demand for these systems increases. Realizing this goal requires systems that are designed for recycling and avoid the use of coatings or designs that reduce the recovery rate of critical materials; for example, the recycling process of metal bipolar plates that are coated in a thin layer of platinum/gold requires more equipment and is likely to be more difficult than recycling plates without the coating.

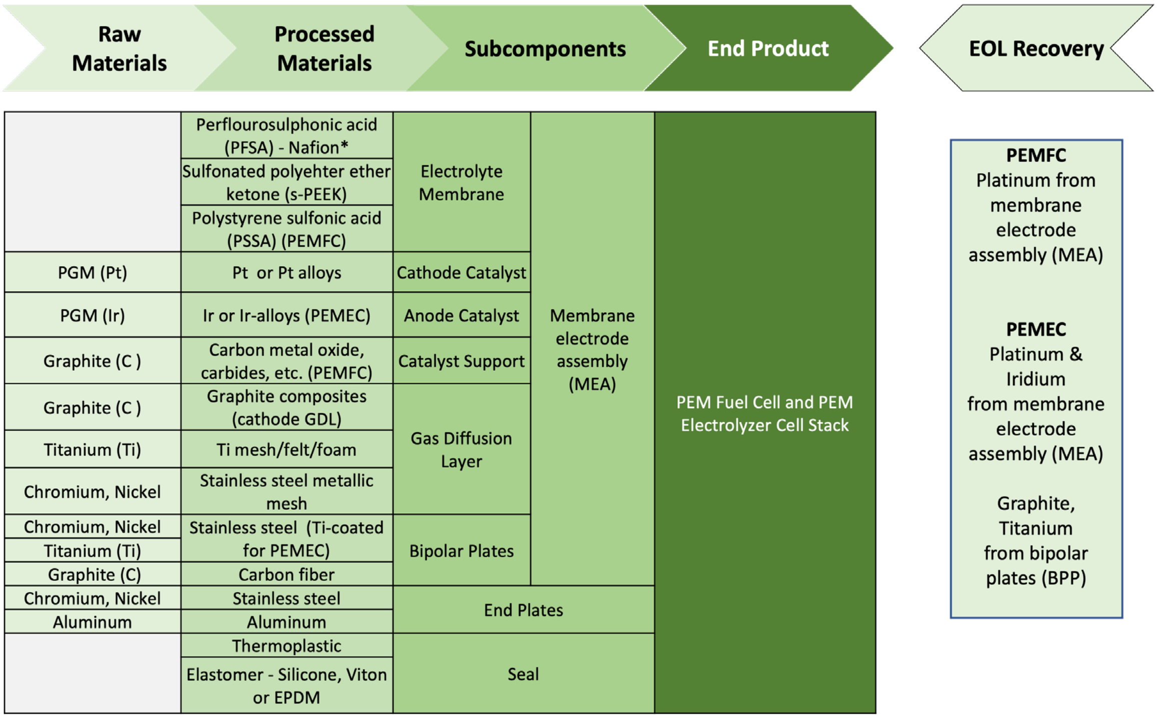
2. Supply Chain Mapping

Because PEM and SOC are developing technologies, supply chains for them have yet to be established. Nonetheless, assessing the current state of supply chain elements helps identify the potential constraints and opportunities for the United States as these supply chains build up to support increased demand. For each technology, we describe the supply chain and industry structure at a high level and provide insight into current U.S. resilience and competitiveness. We also discuss recycling opportunities and current national policies and incentives.

2.1 PEMEC and PEMFC Systems

2.1.1 Supply Chain Overview by Segment

The key elements of the PEM fuel cell and PEM electrolyzer manufacturing supply chains—raw materials, processed materials, subcomponents, and end products, along with end-of-life material recovery opportunities—are highlighted in Figure 7.



Raw Materials	Processed Materials	Subcomponents		End Product
	Perflourosulphonic acid (PFSA) - Nafion*	Electrolyte Membrane	Membrane electrode assembly (MEA)	PEM Fuel Cell and PEM Electrolyzer Cell Stack
	Sulfonated polyehter ether ketone (s-PEEK)			
	Polystyrene sulfonic acid (PSSA) (PEMFC)			
PGM (Pt)	Pt or Pt alloys	Cathode Catalyst		
PGM (Ir)	Ir or Ir-alloys (PEMEC)	Anode Catalyst		
Graphite (C)	Carbon metal oxide, carbides, etc. (PEMFC)	Catalyst Support		
Graphite (C)	Graphite composites (cathode GDL)	Gas Diffusion Layer		
Titanium (Ti)	Ti mesh/felt/foam			
Chromium, Nickel	Stainless steel metallic mesh			
Chromium, Nickel	Stainless steel (Ti-coated for PEMEC)	Bipolar Plates		
Titanium (Ti)				
Graphite (C)	Carbon fiber			
Chromium, Nickel	Stainless steel	End Plates		
Aluminum	Aluminum			
	Thermoplastic	Seal		
	Elastomer - Silicone, Viton or EPDM			

EOL Recovery

PEMFC
Platinum from membrane electrode assembly (MEA)

PEMEC
Platinum & Iridium from membrane electrode assembly (MEA)

Graphite, Titanium from bipolar plates (BPP)

Figure 7. Key elements of PEMFC and PEMEC supply chains

EOL is end-of-life.

2.1.1.1 Industry Structure

Today's nascent PEMFC and PEMEC industry is made up of fairly few suppliers across the supply chain (James et al. 2018). Many key players are large companies (e.g., 3M, DuPont, and Cummins), but the fuel cell/electrolyzer business is only a small portion of their business profiles (BNEF 2021). One of the largest PEMFC manufacturers, Ballard Power, produces most of the subcomponents (i.e., bipolar plates, gas diffusion layer, and electrolyte membrane) in-house. Other suppliers typically produce one or two subcomponents in the supply chain (Table 4 on page 16 and Appendix B), but none currently has the capacity to produce fuel cell systems and components at high manufacturing rates (James et al. 2018). To a large extent, the PEMEC industry has benefited from progress in PEMFC R&D and it expects to be able to leverage PEMFC manufacturing supply chains as they develop.

2.1.2 Current U.S. Resilience

Because these technologies are nascent and markets have yet to grow, global demand for PEMECs and PEMFCs is fairly low. Consequently, global manufacturing capacity for these technologies is low and supply chains to support manufacturing have not yet developed as is discussed in the Electrolyzer and Fuel Cell Market Size Estimates section above. The United States has the potential to build domestic capacity as demand for hydrogen and subcomponents technologies grows. Current U.S. resilience is summarized in Table 2 in terms of strengths and weaknesses in production capabilities, innovation and technology, workforce, policy, and infrastructure. Since water electrolysis and fuel cells are a nascent industry, the table focuses on the current status and will change as the industry evolves and policies and initiatives are established. The table will need to be updated as those occur.

Table 2. Current U.S. Resilience (Strengths and Weaknesses) of PEMFC and PEMEC Supply Chain

	Strengths	Weaknesses
Existing U.S. production capabilities	Sufficient U.S. manufacturing capacity to meet current demand for PEM electrolyzers and fuel cells, catalyst, membrane, gas diffusion layer (GDL), and bipolar plate subcomponents	U.S. manufacturing capacity may not be sufficient to meet growing demands. Reliance on imports of key materials especially platinum, iridium, and graphite. High manufacturing cost for fuel cell/electrolyzer components and lack of high-throughput assembly processes
Emerging U.S. production capabilities	Presence of high-technology domestic industries including automotive, electrolysis, and chemical processing	Reliance on imports platinum, iridium, and graphite Meeting expanded demand for PEM electrolyzer and fuel cell manufacturing in the United States requires technical advancements, capital investment, and demonstration of higher production volumes of fuel cells, electrolyzers and subcomponents. Growth in Asian markets is likely to outpace the rest of the world. Demand will most likely be met by Asian suppliers, who can leverage manufacturing economies of scale to outcompete U.S. suppliers. European investment and targets (e.g., 40 GW of electrolysis) are driving investment in several GW-scale manufacturing plants in Europe, including by U.S. companies.
Innovation and technology	United States' leadership in innovation and strong innovation ecosystem Robust R&D funding at national laboratories and academia (often	Increasing R&D investments outside the United States. However, the United States is involved in international collaborations including the International Partnership for Hydrogen and Fuel Cells in the Economy

	Strengths	Weaknesses
	in partnership with private industry)	(https://www.iphe.net/) and European Collaborations to leverage international knowledge and support partnerships.
Workforce	Skilled labor Access to educated workforce	Limited pool of trained workers with expertise in hydrogen and fuel cell technologies
U.S. policy	Import/export policies (no tariffs) Buy America incentivizes domestic components Support from federal and state programs including development of a National Hydrogen Strategy and Roadmap as required by section 40314 of the Infrastructure Investment and Jobs Act (Infrastructure Investment and Jobs Act 2021)	Lack of coordinated incentives/facilitation Lack of tax liability and reduced value of tax credits for emerging industry Without coordinated implementation of domestic manufacturing content requirements, insufficient access to domestic industrial supplies may increase costs and reduce competitiveness in global markets
U.S. infrastructure	Reliable low-cost electricity supply and growth of renewables U.S. road, rail, and coastal port infrastructure for moving freight	Lack of U.S. hydrogen infrastructure Limited dedicated hydrogen transmission and storage infrastructure including interregional connections
Sources: (Mayyas and Mann 2019); (Fullenkamp et al. 2017)		

2.1.3 U.S. Competitiveness

Available information on PEMECs is limited due to the nascent markets and the focus on fuel cells during recent decades. Thus, we expect the U.S. status with electrolyzers to be similar to that of fuel cells.

Based on a recent EU fuel cell supply chain assessment of all fuel cell types (European Commission 2020), the United States and Asia are the current leaders in fuel cell and fuel cell subcomponent manufacturing. Moving up the supply chain, manufacturing is less concentrated. For processed materials, the United States is relatively well-positioned. However, the United States depends almost completely on other countries for raw materials used to manufacture fuel cells. A related study by the European Commission Joint Research Centre (Blagoeva et al. 2020) provided details on some key processed materials in the current fuel cell supply chain in the Directorate-General assessment. This JRC analysis shows that the United States is a global supplier for some portion of the fuel cell processed materials: 60% of ionomer (Nafion) (for electrolyte membrane); 20% of carbon cloth/paper (for GDLs); and 27% of stainless steel and 30% of carbon fiber (for bipolar plates). Unlike China, which relies on imports across the supply chain, the United States and Japan can currently supply most of their fuel cell subcomponents with domestic manufacturing (Xun et al. 2021). As discussed in the Market Size Estimate section above, the market is likely to grow dramatically. Thus, the supply chain in the future may differ from the current supply chain; the current status may no longer be applicable and the United States may become increasingly dependent upon imported systems, subcomponents, processed materials, and/or raw materials. Policies may need to evolve rapidly to support manufacturing capacity as the market grows.

2.1.3.1 Key Manufacturers

Key global players—major companies and their locations (both headquarters and manufacturing locations if known)—in the PEMEC and PEMFC manufacturing supply chains are summarized in Table 3 and Table 4, respectively. Unlike mature solar technology, PEMEC and PEMFC are not yet widely commercialized and do not have established manufacturing supply chains which are tracked in industry market reports that provide standardized information on manufacturing locations and capacities. However, by cross referencing (1) information found on company websites, reports, and press releases with (2) high-level market highlight webpages with information from Bloomberg New Energy Finance (BNEF), we identified major manufacturers of systems and components. Public information on PEMEC manufacturing is limited and provides little insight into upstream manufacturing of components, although many of the fuel cell supply chain companies also offer components for electrolyzers. These tables identify key sellers of the end product and specific components. Some companies are vertically integrated, at least to a certain extent, and produce many of the components but sell only the end product. Intermediate components are not listed for those companies except where noted. An expanded list of manufacturers and estimates of company manufacturing capacities are provided in Appendix B. Not all companies are listed and the data represents only one snapshot in time. Given the rapid pace of growth and the number of acquisitions, emerging companies, and joint ventures in numerous countries, the data in these tables will change frequently.

Table 3. Select PEMEC Manufacturers

Company	Headquarters	Manufacturing Location	Product
Elogen (subsidiary of GTT, recently rebranded from Areva H2Gen) (“GTT Group”; “Elogen”)	Les Ulis, France	France	PEMEC
Hydrogenics – subsidiary of Cummins (Cummins 2019)	Mississauga, Ontario, Canada	Ontario, Canada; Indiana and California, US	PEMEC
Ion Power	New Castle, DE, US	Delaware and Pennsylvania, US	Membrane
ITM	Sheffield, UK	UK	PEMEC
Kobelco Eco-solutions	Kobe, Japan	Japan	PEMEC
Nel ASA (Løkke 2021)	Oslo, Norway	Connecticut, US; Norway; Denmark	PEMEC
Plug Power (“Plug Power | Green Hydrogen & Fuel Cell Solutions”)	Latham, NY, US	New York, US	PEMEC
Siemens Energy (Siemens Energy 2020)	Munich, Germany	Unavailable	PEMEC

Included companies were mentioned either by at least three market reports or by two market reports and BNEF. Companies for which the electrolyzer type is unavailable are not included (see Appendix B for details). Note that manufacturing locations listed are specifically for PEMECs, and the list may not be a complete for a given company. Details, select capacities/upcoming developments, and citations are in Appendix B.

Table 4. Select PEMFC and Component Manufacturers

Company	Headquarters	Manufacturing Locations	Products
3M	St. Paul, MN, US	Minnesota and Wisconsin, US	Membrane, Ionomer
Advent	Athens, Greece; Boston, MA, US	Greece; MA, US	Membrane, MEA
Ballard Power Systems	Burnaby, British Columbia, Canada	British Columbia, Canada; Denmark	PEMFC, MEA*, BPP*
BASF	Ludwigshafen, Germany	Germany	MEA, Catalyst
Chemours	Wilmington, DE, US	South Carolina, US	Membrane, Ionomer
Horizon Fuel Cell	Singapore	Singapore; China	PEMFC
Hydrogenics – subsidiary of Cummins (Cummins 2019)	Mississauga, Ontario, Canada	Ontario, Canada	PEMFC
Intelligent Energy	Loughborough, UK	UK	PEMFC
Ion Power	New Castle, DE, US	Delaware and Pennsylvania, US	MEA
Johnson Matthey	London, UK	Pennsylvania, US; UK	MEA, Catalyst
Plug Power, Inc. (“Plug Power | Green Hydrogen & Fuel Cell Solutions”)	Latham, NY, US	New York, US	PEMFC, MEA*
Solvay	Brussels, Belgium	NJ, US; Italy	Membrane, Ionomer
TANAKA	Tokyo, Japan	Japan	Catalyst
Umicore	Brussels, Belgium	China, US, Germany, Denmark and Korea	Catalyst
W. L. Gore	Newark, DE, US	Delaware, US; Japan	Membrane

Included companies were mentioned by at least four market reports and could be found in the BNEF database, and/or they are known to the DOE’s Hydrogen and Fuel Cell Technologies Office as a manufacturer of fuel cell components. Note that manufacturing locations listed are specifically for fuel cell components, and the list may not be complete for a given company. Details, select capacities/upcoming developments, and citations are in Appendix B.

*Component is produced for use in company end-products but is not sold directly.

2.1.3.2 U.S. Position: U.S. Competitiveness in PEMFC Subcomponents

The DOE Hydrogen and Fuel Cell Technologies Office funded a PEMFC supply chain study (Fullenkamp et al. 2017) that reviewed U.S. competitiveness for key subcomponents in the MEA. Findings from that study, which was published in 2017, are summarized here in alphabetical order:

Bipolar Plates: Because the BPP component is ultimately expected to be manufactured close to the fuel cell system assembly site, BPPs are expected to be produced in the United States as long as demand continues. Currently, Europe and Asia hold the lead in BPP technology. However, there is a substantial opportunity for the United States to innovate in plate formation, coatings, and joining.

Catalyst: Europe (Umicore, Johnson Matthey) and Asia (Tanaka) are currently the world leaders in fuel cell catalyst technology. Given the long development lead time and other barriers to market entry, this is likely to continue for many years. Overall prospects for U.S. catalyst production competitiveness are low in the near term and low to moderate in the far term. U.S. innovation competitiveness is moderate.

GDL: Four main competitors predominate and are located in Europe (SGL, Freudenberg), Asia (Toray), and the United States (AvCarb). The United States does not seem to enjoy any clear advantages over other regions.

Membrane: The United States currently holds the global lead in membrane technology and will likely continue to innovate. The ionomer is likely to be produced in the future in large quantities at foreign sites (probably China). U.S.-based W.L. Gore Inc. is currently the world leader in expanded polytetrafluoroethylene (ePTFE) membrane support, although fuel cell membrane production currently occurs in Japan for the Asian market. Other U.S.-based companies (e.g., 3M and Giner) have development efforts in non-ePTFE supports. Roll-to-roll/casting membrane fabrication techniques are expected to be used in the future. Though the United States is competitive in this general field, Europe and Asia are also strong. Additionally, localized production of the catalyst-coated membrane/MEA may be favored over remote centralized production with shipping of value-added components.

Additional information on key global players and their expansion plans is provided in Appendix B although the information reported there will change often and thus it may be inaccurate.

2.2 Solid Oxide Electrolysis and Fuel Cells

2.2.1 Supply Chain Overview by Segment

The supply chain for solid oxide electrolysis and fuel cells consists of five key segments: the necessary raw materials, processed functional materials, subcomponents, the end product, and end-of-life recovery. Figure 8 highlights the function of each of the critical materials in the production of SOC cells and stacks as well as end-of-life material recovery opportunities.

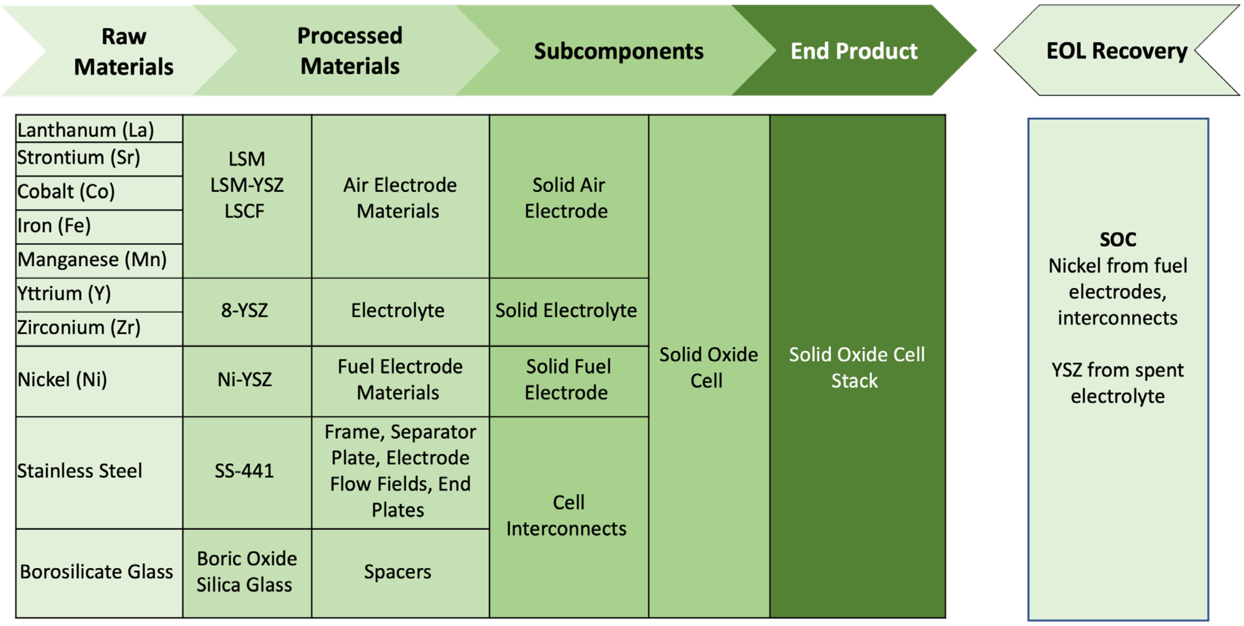


Figure 8. Key elements of the SOC supply chain

2.2.1.1 Industry Structure

The current industry structure for development of SOC-processed materials, subcomponents, and end products is centered on a select few commercial developers. Several materials in solid oxide systems, including yttrium, strontium, and manganese, come entirely from imports, and these are typically obtained directly by developers as needed. Other SOC critical materials of which a significant portion are obtained as imports include nickel and cobalt. The typical cell geometry is fuel electrode supported, with the fuel electrode being comprised of Ni-YSZ. The air electrode of the cell relies on the availability of materials such as lanthanum, strontium, cobalt, manganese, and iron, which are needed in significantly lower quantities. The U.S. Geological Survey's "Mineral Commodity Summaries 2021" discusses the production and current use of several of these materials (USGS "Mineral Commodity Summaries 2021" 2021).

Nexceris is a primary producer of processed material that is either sold commercially or used internally to produce individual cells and stacks. Developers, such as Bloom Energy, FuelCell Energy, and Cummins, typically purchase or generate their own processed materials as part of their cell, stack, and system development process. As part of that process, stainless steel materials are used for bipolar plate material, borosilicate glass is used for spacers, and other similar materials are used as needed based on particular designs. Bloom Energy and FuelCell Energy are currently the largest suppliers of end-product SOC technology in the United States, and several smaller companies are working to increase production.

2.2.2 Current U.S. Resilience

The U.S. commercial development structure is organized for converting critical materials into processed materials, individual cells, cell stacks, and finally the system through a tailored manufacturing process. The process begins with combining the critical materials into processed materials to make the appropriate subcomponents. The cell electrodes and electrolyte processed material, which is produced by each developer, is tailored to meet specific composition and microstructure requirements. Processed materials such as LSM and LSCF are used to reduce oxygen molecules supplied from air into oxygen ions in SOC electrodes. The electrolyte, which is typically a YSZ material, transports the oxygen ions to active reaction sites. The fuel electrode is typically Ni-YSZ, which serves as a catalyst and electron transport material for the electron exchange reaction.

Industry has developed advanced manufacturing methods for producing the needed quantity of SOCs, stacks, and systems (including incorporation of balance-of-plant equipment) that is tailored to their production processes, resulting in a final SOC system. Balance-of-plant equipment can include, but is not limited to air blowers, heat exchangers, fuel and product storage, and inverters. There is significant R&D investment in the development of these balance-of-plant materials specifically for solid oxide system technologies, and the investment is especially geared toward distributed generation. Current U.S. resilience is summarized in Table 5.

Table 5. Current U.S. Resilience (Strengths and Weaknesses) of Solid Oxide Electrolyzer and Fuel Cell Supply Chain

	Strengths	Weaknesses
Existing U.S. production capabilities	Sufficient production capacity to meet current demand	Significant volume expansion needed to meet anticipated demand; reliance on imports of yttrium, strontium, manganese, nickel, and cobalt High manufacturing cost for complex ceramic materials
Emerging U.S. production capabilities	U.S. development structure's focus on scaling up current manufacturing process for higher volume production of cells and stacks	Scale up in production not fully realized in United States, could be challenged due to regulations, component availability, or other unforeseen challenges U.S. production outpaced by Europe and Asia
Innovation and technology	United States' leadership in innovation and strong innovation ecosystem Robust R&D funding at national laboratories, academia, and commercial developers that is well-supported by U.S. government agencies including a Clean Hydrogen Electrolysis Program as required by section 40314 of the Infrastructure Investment and Jobs Act (Infrastructure Investment and Jobs Act 2021).	Potential commercial reliance on government funding.
Workforce	Access to educated and skilled labor from a global perspective	Limited pool of trained workers with expertise in hydrogen and fuel cell technologies
U.S. policy	Support from federal and state programs including development of a National Hydrogen Strategy and Roadmap as required by section	Expiring subsidies resulting in a high-cost solution; lack of coordinated incentives/facilitation

	Strengths	Weaknesses
	40314 of the Infrastructure Investment and Jobs Act (Infrastructure Investment and Jobs Act 2021) Localized subsidies	Lack of tax liability and reduced value of tax credits for emerging industry
U.S. infrastructure	Reliable, low-cost electricity supply Global leadership of U.S. road, rail, and coastal port infrastructure for moving freight	Limited access to excess renewable energy and nuclear/thermal sources for electrolysis operation, hydrogen fuel for fuel cell operation Limited dedicated hydrogen transmission and storage infrastructure including interregional connections
Sources: (Mayyas and Mann 2019); (Fullenkamp et al. 2017)		

2.2.3 U.S. Competitiveness

SOFC and SOEC technologies are not yet widely commercialized and do not have established manufacturing supply chains. By cross referencing (1) information found on company websites, reports, and press releases with (2) high-level market highlight webpages with information from BNEF, we identified major manufacturers of systems and components. Some information is given here, and a high-level summary is provided in Table 6 (page 21). Details are provided in Appendix B. Not all companies are listed and the data represents only one snapshot in time. Given the rapid pace of growth and the number of acquisitions, emerging companies, and joint ventures in numerous countries, the data in these tables will change frequently.

Currently, Europe is leading in solid oxide electrolysis development, and U.S. domestic commercial developers are competing with several European and Asian SOC developers (Hauch et al. 2020). Primary domestic developers include Bloom Energy, FuelCell Energy, and Cummins, and several smaller companies are increasing production to meet anticipated future demand. Their competition includes Mitsubishi Power, Kyocera, Hitachi, and SOLIDPower.

Domestic manufacturers are at a disadvantage because the global market for higher-cost, but more-efficient generators of electricity and fuel is much more prominent than the domestic market, where energy is available at lower cost. Additional information on key global players and their expansion plans is provided in Appendix B.

The United States is most competitive in the production of the processed materials needed to produce SOC components, the production of the necessary interconnect components, and the final construction of the stacks and systems (including balance-of-plant equipment). One primary developer of the processed materials is Nexceris; it sells processed materials and individual cells for commercial uses and for R&D needs. Domestic commercial developers of SOC stacks and systems either purchase processed materials from a company such as Nexceris or develop those materials in-house.

For raw material production, there is continued opportunity for the United States to be a leader in the production of stainless steels (especially SS-441), zirconium, and nickel. Borosilicate glass is another opportunity for U.S. production. Additional opportunity is available in the resumption of previous domestically produced materials for use in SOC technology, including cobalt, strontium, and manganese.

Table 6. Major Solid Oxide Fuel Cell and Solid Oxide Electrolysis Cell and Stack Manufacturers

Company	Headquarters	Manufacturing Location	Products
Bloom Energy	San Jose, CA, US	California and Delaware, US	Bloom Energy Server (SOFC)
FuelCell Energy	Danbury, CT, US	Alberta, Canada	Molten carbonate fuel cells, SOFC, SOEC
Cummins, Inc.	Columbus, IN, US	United States, Canada	PEMFC, SOFC, engines
Nexceris	Lewis Center, OH, US	United States	Processed SOC materials, SOFC, SOEC
Mitsubishi Power, Ltd.	Yokohama, Japan	Japan	SOFC, hydrogen turbines
Kyocera	Kyoto, Japan	Japan	SOFC, solar cells, advanced ceramics
SOLIDPower	Mezzolombardo, Italy	Germany	BlueGen SOFC
Hitachi	Toshiaki, Japan	Japan	SOFC, SOEC
Robert Bosch	Gerlingen, Germany	Germany	SOFC
Special Power Sources	Alliance, OH, US	United States	Tubular SOFC
Ceres Power Holdings	West Sussex, UK	UK	SOFC, SOEC
OxEon Energy	North Salt Lake, UT, US	United States	SOEC, SOFC

2.3 Recycling Potential for Electrolyzers and Fuel Cells

End-of-life strategies for fuel cells and electrolyzers focus primarily on recovery of precious metals used in the catalyst subcomponent. Improvements in the technologies currently used to recover spent catalysts (hydrometallurgical and pyrometallurgical processes) can help reduce costs and mitigate regional supply constraints associated with these materials. Other high-value and hazardous materials in fuel cells and hydrogen technology components also offer the potential for recycling, reuse, or both (HyTechCycling 2018b). Additional details on recycling platinum group metals (PGM) from fuel cells and electrolyzers is provided in Supply Chain Review: Platinum Metal Group Catalysts ("Supply Chain Review: Platinum Metal Group Catalysts" 2021).

PEMFC Recycling Opportunities include (HyTechCycling 2018a):

- **Bipolar Plates:** Alteration of the physical and chemical structure of bipolar plate materials (gold, platinum, graphite, stainless steel and carbon composites) during operation precludes reuse or recovery for the same original application. Materials recovered from bipolar plates could potentially be used as insulation raw material for electronic devices or in steel manufacturing (i.e., open-loop recycling).
- **MEA:** Existing technologies (hydrothermal and hydrometallurgical) and novel technologies (acid process, transient dissolution, and selective electrochemical dissolution) can be used to recover PGM from the electrodes along with other valuable materials, such as ionomers from the membrane or the carbon support of the noble catalyst. Alcohol dissolution can also be used as pretreatment for the recovery of ionomers from the membrane before the catalyst recovery process. The recovery of MEA's critical materials allows recycling in a closed-loop scheme, which means a potentially higher benefit with respect to open-loop recycling.

PEMEC Recycling Opportunities include (HyTechCycling 2018a):

- **Bipolar Plates:** Though titanium can generally be recovered through conventional methods based on physical separation (size reduction and magnetic separation), recovering it from the titanium alloys used for bipolar plates requires more-complex processes (e.g., hydrometallurgical processes).
- **MEA:** Similar to PEMFC stacks, novel and existing end-of-life technologies can be used to recover the critical materials of the PEMEC MEA. The anode electrocatalyst is commonly iridium (although ruthenium is being researched as an alternative), which can be recovered through existing (pyrometallurgical and hydrometallurgical processes) or novel (transient dissolution) methods. As with PEMFCs, these end-of-life technologies would facilitate closed-loop recycling schemes.

SOC Recycling Opportunities include (HyTechCycling 2018a):

- **Fuel Electrode Materials/Interconnects:** Existing end-of-life technologies (hydrothermal and hydrometallurgical technologies) are applicable for nickel recovery from the fuel electrode and interconnects.
- **Electrolyte:** YSZ can be recovered from the spent electrolyte using hydrothermal technologies for use in open-loop recycling—for example, for its application in electrical/electrochemical sectors with a lower purity requirement than the SOC fuel electrode or electrolyte. Alternatively, the ceramic composite material can—after grinding and mechanical separation—be recycled, still in an open-loop scheme, for use in construction applications.
- **Air Electrode Material/Interconnects:** For lanthanum compounds (LSM and LSCF), no recovery process is currently available and due to their hazardous nature, they are disposed in hazardous waste landfills.

Regarding stack components, no novel technologies are found to be applicable for the recovery of critical materials.

Table 7 summarizes existing and novel recovery technologies applicable to critical materials of fuel cell and electrolyzer stacks. Metals belonging to the platinum group (Pt, Ru, and Ir), whose reserves are depleting, and which are associated with high economic costs, are the materials for which most of the end-of-life technologies have been found. In contrast, information that is as detailed as it is for PGMs is unavailable for novel end-of-life technologies applicable to rare earth elements (e.g., lanthanum compounds and YSZ) and nickel-based materials.

Table 7. Materials in Fuel Cells and Electrolyzers With Recovery Potential (HyTechCycling 2018a)

Device	Component	Material	Critical Aspects	Recovery Technologies	
				Existing	Novel
PEMFC	Anode	Pt	Cost, supply risk	HMT; PMT	SED; TD; AP
	Cathode	Pt	Cost, supply risk	HMT; PMT	SED; TD; AP
	Electrolyte	Ionomer	Cost, hazard[a]	n/a	AD; AP
PEMEC	Anode	Ir; Ru	Cost, supply risk, hazard	HMT; PMT	TD
	Cathode	Pt	Cost, supply risk	HMT; PMT	SED; TD; AP
	Electrolyte	Ionomer	Cost, hazard[a]	n/a	AD; AP
	Bipolar plate	Ti	Cost	HMT	n/a
SOC	Fuel electrode	YSZ	Cost, supply risk	HDT	n/a
		Ni; NiO	Hazard	HDT; HMT	n/a
	Air Electrode	LSM, LSCF	Hazard, supply risk	n/a	n/a
	Electrolyte	YSZ	Cost, supply risk	HDT	n/a
	Interconnects	Ni; NiO	Hazard	HDT; HMT	n/a
		LSC	Hazard, supply risk	n/a	n/a

HDT: hydrothermal technology; HMT: hydrometallurgical technology; PMT: pyrometallurgical technology; TD: transient dissolution: AP: acid process; SED selective electrochemical dissolution: AD: alcohol dissolution; PEMEC: PEMWE (proton exchange membrane water electrolyzer) is the acronym used in the cited HyTechCycling Report.

[a] Concerns linked to hydrogen fluoride (HF) emissions if the membrane is incinerated

2.4 Current National Policies and Incentives for Electrolyzers and Fuel Cells

The development and deployment of hydrogen and fuel cell technologies to date has been driven primarily by government policies and incentives focused on addressing larger goals of addressing climate change, reducing emissions, and advancing clean energy technologies. A number of nations and the European Union have developed policies and strategies for the hydrogen economy. The IEA listed a number of targets and policies and their list is included in Table 8. Note that Table 8 includes nonbinding road maps, strategies, and targets as well as investments that are, in some cases, legally binding incentives. While the United States has technology development targets and an RD&D plan (Department of Energy (DOE) 2020), it does not currently have hydrogen deployment targets or a national plan, unlike other countries. However, the United States is developing a national plan as required by section 40314 of the Infrastructure Investment and Jobs Act (Infrastructure Investment and Jobs Act 2021). Appendix C lists existing U.S. policies.

Table 8. Hydrogen Targets and Policies Identified by the International Energy Agency (IEA 2021a)

Origin	Document, year	Deployment targets (2030)	Production	Uses	Public investment committed
Australia	National Hydrogen Strategy, 2019	• None specified	• Coal with CCUS • Electrolysis (renewable) • Natural gas with CCUS	• Building • Electricity • Exports • Industry • Shipping • Transport	AUD 1.3B (~USD 0.9B)
Canada	Hydrogen Strategy for Canada, 2020	• Total use: 4 MMT H_2/yr • 6.2% TFEC	• Biomass • By-product H_2 • Electrolysis • Natural Gas with CCUS • Oil with CCUS	• Buildings • Electricity • Exports • Industry • Mining • Refining • Shipping • Transport	CAD 25M by 2026[1] (~USD 19M)
Chile	National Green Hydrogen Strategy, 2020	• 25 GW electrolysis[2]	• Electrolysis (renewable)	• Buildings • Exports • Industry (chemicals) • Mining • Refining • Transport	USD 50M for 2021
Czech Republic	Hydrogen Strategy, 2021	• Low-carbon demand: 0.097 MMT H_2/yr	• Electrolysis	• Industry (chemicals) • Transport	n/a
European Union	EU Hydrogen Strategy, 2020	• 40 GW electrolysis	• Electrolysis (renewable) • Transition role of natural gas with CCUS	• Industry • Refining • Transport	EUR 3.77B by 2030 (~USD 4.3B)
France	Hydrogen Deployment Plan, 2018 National Strategy for Decarbonised Hydrogen Development, 2020	• 6.5 GW electrolysis • 20%–40% industrial H_2 decarbonized[3] • 20,000–50,000 light-duty FCEVs[3] • 800–2,000 FC heavy-duty FCEVs[3] • 400–1,000 HRSs[3]	• Electrolysis	• Industry • Refining • Transport	EUR 7.2B by 2030 (~USD 8.2B)

Origin	Document, year	Deployment targets (2030)	Production	Uses	Public investment committed
Germany	National Hydrogen Strategy, 2020	• 5 GW electrolysis	• Electrolysis (renewable)	• Aviation • Electricity • Industry • Refining • Shipping • Transport	EUR 9B by 2030 (~USD 10.3B)
Hungary	National Hydrogen Strategy, 2021	Production: • 0.02 MMT/yr of low-carbon H_2 • 240 MW electrolysis Use: • 0.034 MMT/yr of low-carbon H_2 • 4,800 FCEVs • 20 HRSs	• Electrolysis • Fossil fuels with CCUS	• Electricity • Industry • Transport	n/a
Japan	Strategic Roadmap for Hydrogen and Fuel Cells, 2019 Green Growth Strategy, 2020, 2021 (revised)	• Total use: 3 MMT H_2/yr • Supply: 420 kT low-carbon H_2 • 800,000 FCEVs • 1,200 fuel cell buses • 10,000 fuel cell forklifts • 900 HRSs • 3 MMT NH_3 fuel demand[4]	• Electrolysis • Fossil fuels with CCUS	• Buildings • Electricity • Industry (steel) • Refining • Shipping • Transport	JPY 699.9B by 2030 (~USD 6.5B)
Korea	Hydrogen Economy Roadmap, 2019	• Total use: 1.94 MMT H_2/yr • 2.9 million fuel cell cars[5] • 1,200 HRSs[5] • 80,000 fuel cell taxis[5] • 40,000 fuel cell buses[5] • 30,000 fuel cell trucks[5] • 8 GW stationary fuel cells (plus 7 GW exported)[5] • 2.1 GW of micro-cogeneration fuel cells[5]	• By-product H_2 • Electrolysis • Natural gas with CCUS	• Buildings • Electricity • Transport	KRW 2.6T in 2020 (~USD 2.2B)

Origin	Document, year	Deployment targets (2030)	Production	Uses	Public investment committed
Netherlands	National Climate Agreement, 2019 Government Strategy on Hydrogen, 2020	• 3–4 GW electrolysis • 300,000 fuel cell cars • 3,000 heavy-duty FCEVs[6]	• Electrolysis (renewables) • Natural gas with CCUS	• Aviation • Buildings • Electricity • Industry • Refining • Shipping • Transport	EUR 70M/yr (~USD 80M/yr)
Norway	Government Hydrogen Strategy, 2020 Hydrogen Roadmap, 2021	• n/a[7]	• Electrolysis (renewables) • Natural gas with CCUS	• Industry • Shipping • Transport	NOK 200M for 2021 (~USD 21M)
Portugal	National Hydrogen Strategy, 2020	• 2.0–2.5 GW electrolysis • 1.5%–2% TFEC • 1%–5% TFEC in road transport • 2%–5% TFEC in industry • 10%–15% by volume H_2 in gas grid • 3%–5% TFEC in maritime transport • 50100 HRSs	• Electrolysis (renewables)	• Electricity • Industry • Transport	EUR 900M by 2030 (~USD 1B)
Russia	Hydrogen roadmap, 2020	• Exports: 2 MMT H_2	• Electrolysis • Natural gas with CCUS	• Electricity • Industry • Refining • Exports	n/a
Spain	National Hydrogen Roadmap, 2020	• 4 GW electrolysis • 25% industrial H_2 decarbonized • 5,000–7,500 FCEVs • 150–200 fuel cell buses • 100–150 HRSs	• Electrolysis (renewables)	• Aviation • Electricity • Industry (chemicals) • Refining • Shipping • Transport	EUR 1.6B (~USD 1.8B)

Origin	Document, year	Deployment targets (2030)	Production	Uses	Public investment committed
United Kingdom	UK Hydrogen Strategy, 2021	• 5 GW low-carbon production capacity	• Natural gas with CCUS • Electrolysis	• Aviation • Buildings • Electricity • Industry • Refining • Shipping • Transport	GBP 1B (~USD 1.3B)

Note: TFEC = total final energy consumption, HRS = hydrogen refueling station. For investments, M = million, B = billion, T = trillion.

[1] In addition to CAD 25M, Canada has committed over CAD 10B to support clean energy technologies, including H_2.

[2] This target refers to projects that at least have funding committed, not to capacity installed by 2030.

[3] Target for 2028.

[4] From the interim Ammonia Roadmap.

[5] Target for 2040.

[6] Target for 2025 from the National Climate Agreement, 2019 (currently under revision).

[7] Norway's strategy defines targets for the competitiveness of hydrogen technologies and project deployment.

3. Supply Chain Risk Assessment

Because the supply chain for electrolyzers and fuel cells is still to be established as demand grows, the risk assessment we performed for this report focused on the key materials required for electrolyzers and fuel cell production and does *not* assess subcomponents. The materials required to manufacture PEMFCs and PEMECs that meet future electrolytic hydrogen demand of around 100 MMT/yr could be significantly higher than 2020 levels of apparent consumption[2] for many of these materials (Figure 3 and Figure 4, pages 8 and 9) (USGS 2021). In this report, apparent consumption is defined in a manner consistent with the USGS, where it equals primary production plus secondary production plus imports minus exports for a given material. Projected apparent consumption greater than current rates suggests that securing and expanding the supply chains for these materials is critical to enabling the high rates of deployment of electrolyzers and fuel cells shown here.

Materials whose demand is projected to increase and which are currently imported into the United States at high percentages can be considered most critical. These two parameters are plotted for key electrolyzer and fuel cell materials in Figure 9, which shows the relationship between these variables for key materials. The y-axis value in Figure 9 depends on manufactured capacity and material usage for electrolyzers and fuel cells and is reported as a range between baseline and low material use scenarios. The upper bound baseline material use scenario is consistent with the state of technology and market sizes discussed throughout this report. The low material use scenario assumes lower market penetration of electrolyzers and lower usage rates of key materials. These two scenarios provide a plausible range of demand growth for various materials, illustrating the influence of electrolyzer deployment rates and material usage on total demand. For a detailed summary of the low material use scenario assumptions please see Appendix A.

---

[2] Apparent Consumption is defined as domestic primary metal production + recovery from scrap + net import reliance (USGS 2021)

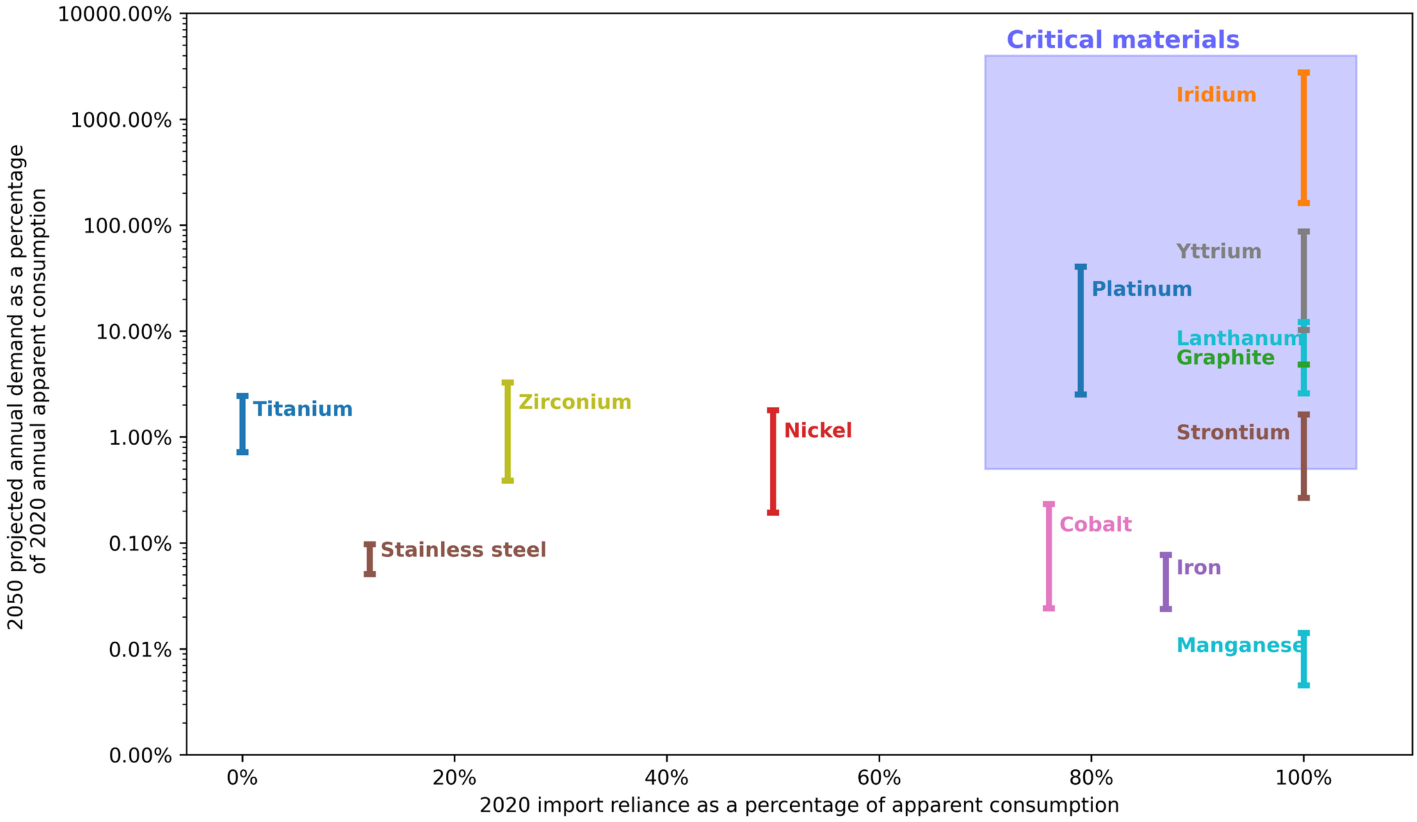


Figure 9. Ranges of projected material demand as a percentage of annual U.S. consumption and U.S. import reliance shown for key fuel cell and electrolyzer materials (Original work)

In this report, apparent consumption is defined in a manner consistent with the USGS, where apparent consumption equals primary production plus secondary production plus imports minus exports for a given material. Ranges of possible demand are shown for baseline and low material usage scenarios (see Appendix A).

Demand estimates were calculated internally based on hydrogen market sizes from (Larson et al. 2021) for baseline and low material use scenarios. Please see Appendix A for a detailed summary.

Import percentages and apparent consumption are from USGS (2021).

Some of the key risks associated with the materials required for PEM and solid oxide electrolyzers and fuel cells are highlighted here. They include U.S. import reliance, key sources and suppliers, and competing uses. The information was extracted from the USGS Mineral Commodity Summaries 2021 unless otherwise noted (USGS 2021). A comprehensive evaluation table with preliminary estimates across the supply chain elements is included in Appendix D.

The PGM catalyst report that is part of this series provides additional information on some of these materials ("Supply Chain Review: Platinum Metal Group Catalysts" 2021).

High-Risk Electrolyzer and Fuel Cell Materials (in alphabetical order)

- **Graphite/Activated Carbon:** The United States is 100% dependent on foreign sources, mainly China, to meet domestic demand of natural graphite. During 2020, China was the world's leading graphite producer, producing an estimated 62% of total world output. Other key producers of natural graphite are Mozambique, Brazil and Madagascar. Competing uses include batteries (including for electric vehicles), brake linings, lubricants, powdered metals, refractory applications, and steelmaking.

- **Iridium:** Iridium is one of the scarcest elements on earth. Iridium mining is highly concentrated in South Africa, and production is coupled with the mining rate of the primary PGMs (i.e., platinum and palladium). The United States is 100% reliant on imports to meet iridium demand. Hence, the presence of an iridium recycling infrastructure, end-of-life recycling rates of at least 90%, and low catalyst loading targets of 0.05 g/kW are crucial to meet future iridium demands for PEMEC. Competing uses for iridium are similar to platinum. (Minke et al. 2021).

- **Platinum:** Platinum mining is mainly concentrated in South Africa (72% of worldwide production), followed by Russia and Zimbabwe. The United States is 79% reliant on imports to meet its platinum demand. The main U.S. import sources of platinum are South Africa, Germany, Italy, and Switzerland. Competing uses include automobile catalytic converters, catalysts for chemical production and petroleum refining, medical devices, electronic applications (e.g., hard disk drives), jewelry, glass manufacturing, and laboratory equipment.

- **Strontium:** The United States imports 100% of the strontium it requires domestically, although significant domestic strontium deposits do exist across the United States. Domestic consumption of strontium is primarily associated with ceramic ferrite magnet manufacturing and pyrotechnics. The main import sources of strontium for the United States in 2020 were Mexico and Germany, which makes the supply somewhat secure.

- **Yttrium:** Currently, the United States does not have a significant domestic demand for yttrium. Primary end uses include catalysts, ceramics, lasers, metallurgy, and phosphors. The United States is currently 100% reliant on imports for yttrium, and 94% of the supply comes from China.

Moderate-Risk Electrolyzer and Fuel Cell Materials (in alphabetical order)

- **Aluminum:** Aluminum is primarily produced from alumina extracted from bauxite; bauxite resources are concentrated in Africa, Oceania, South America and the Caribbean, and Asia. The United States relies on imports to meet ~50% of demand. U.S. import sources include Canada (50%); the United Arab Emirates (10%), Russia (9%), China (5%), and other nations (26%). Domestic resources of bauxite are insufficient to meet long-term U.S. demand, but other subeconomic resources (other than bauxite) are widely available. Competing uses include transportation applications – aerospace and automotive (40%), packaging (21%), building (14%), electrical (8%), consumer durables (7%), machinery (7%), and other uses (3%).

- **Chromium:** Chromium is supplied mainly by South Africa, where 41% of chromium is produced globally. As of 2020, the United States was 75% reliant on imports to meet its chromium demand. The main global suppliers of chromium to the United States in 2020 were South Africa, Kazakhstan, Mexico, and Russia. The main use of chromium is in stainless steel and heat-resisting steel manufacturing.

- **Cobalt:** The United States was 76% reliant on imports to meet its cobalt demand as of 2020. In the United States, cobalt is used mainly to produce superalloys for aircraft gas turbine engines. Globally, cobalt mining is concentrated in the Democratic Republic of Congo, and China is the largest supplier of refined cobalt. The main U.S. suppliers of cobalt intermediates (e.g., cobalt powders) in 2020 were Norway, Canada, Japan, and Finland (Igogo et al. 2019).

- **Copper:** Domestic import reliance of the United States for refined copper is fairly low: around 37% in 2020. The United States mines, smelts, refines, and recycles copper, and it has significant copper reserves. The main U.S. suppliers of refined copper are Chile, Canada, and Mexico.
- **Iron:** The United States was a net exporter of iron in 2020; other major suppliers of iron included Brazil, Canada, Sweden, and Chile.
- **Lanthanum:** There is virtually no domestic production of lanthanum in the United States; it relies for 100% of its domestic lanthanum demand on imports from China. This reliance will lessen once the primary domestic rare earth mine, Mountain Pass in California, starts separating light rare earths at its mining facility in 2022 (MP Materials n.d.).
- **Manganese:** In 2020, the United States was 100% reliant on imports, including imports from Gabon (69%), South Africa (17%), Mexico (8%), and Australia (4%). There is no significant domestic supply of manganese. Steel production—either directly in pig iron manufacturing or indirectly through upgrading the ore to ferroalloys—is the main competing domestic processes that consume manganese.
- **Nickel:** The domestic nickel demand is for stainless and alloy steels (≈85%), nonferrous alloys and superalloys, electroplating, and other uses. It is currently 50% met by imports, mainly from Canada, Finland, Norway, and Russia. In the United States, the leading uses for primary nickel are stainless and alloy steels, nonferrous alloys and superalloys, electroplating, and other uses, including catalysts and chemicals.
- **Titanium:** Production of titanium mineral concentrates is mainly concentrated in China, South Africa, and Australia. In 2020, The United States imported 88% of its titanium mineral concentrates demand and more than 50% of titanium sponge demand. That year, the main U.S. suppliers of titanium mineral concentrates were South Africa, Australia, Madagascar, and Mozambique and those of titanium sponge were Japan, Kazakhstan, and Ukraine. Competing uses include aerospace applications, chemical processing, marine hardware, medical implants, as well as pigments and coatings.
- **Zirconium:** The United States was a net exporter of zirconium before 2020 and now is regarded to be cost competitive among domestic and global suppliers. In years when the United States did import zirconium, the major import sources were Australia and South Africa. The primary uses of zirconium are ceramics, foundry sand, opacifiers, and refractories. Current leading consumers of zirconium metal are chemical processing and the nuclear energy industry.

3.1 Key Vulnerabilities

Key U.S. vulnerabilities with respect to electrolyzer and fuel cell supply chains include the immaturity of electrolytic hydrogen markets, the need for electricity to produce hydrogen and market structures to access that electricity, a lack of sufficient hydrogen infrastructure to support market growth, a lack of electrolyzer and fuel cell manufacturing capacity, energy and environmental justice issues for key materials, a need for workforce development, and a need to consider international competitiveness.

Electrolytic Hydrogen Markets

The electrolytic hydrogen market is miniscule today, but as is shown in Figure 2 (page 7), it needs to grow to over 100 MMT/yr by 2050 to meet climate goals. To do so, technologies will need to improve and become more cost-effective, and all aspects of hydrogen production, utilization, and the transmission-delivery-storage infrastructure will need to grow.

Immature Technologies: PEMEC and SOEC systems are not at cost-parity with conventional hydrogen production technologies (e.g., natural gas reforming) and will require technology development to achieve widespread deployment and commercialization. Likewise, PEMFCs and SOFCs will require significant technology advancement to be cost-competitive with conventional combustion-based technologies currently used in stationary and vehicular applications. Without development, these technologies are unlikely to economically support the hydrogen market size assessment shown in Figure 2. R&D support for electrolyzers and fuel cells, as established in the Infrastructure Investment and Jobs Act (Infrastructure Investment and Jobs Act 2021) would need to be sustained and focused to ensure that clean hydrogen technologies are cost competitive with incumbent technologies.

Lack of Sufficient Emission Reduction Incentives: Currently, electrolytic hydrogen is more expensive than conventional hydrogen (primarily produced via SMR) and current emission reduction incentives are insufficient to enable an electrolytic hydrogen market to grow.

Insufficient Codes and Standards: Regulations, codes, and standards—which provide information needed to safely build, maintain, and operate facilities and systems—are a major institutional barrier to deploying hydrogen technologies and are likely to delay, if not suspend the growth of hydrogen markets. Codes and standards are in place for refining, the chemical industry, and ammonia production (DOE Hydrogen Program n.d.). However, model building codes and technical standards that are recognized by federal, state, and local governments may be insufficient for certain application such as for bulk electricity and nonindustrial applications of hydrogen. NFPA 2, the Hydrogen Technologies Code, undergoes regular revision cycles to address insufficiencies as needed. Efforts within standards development organizations (e.g., International Electrotechnical Commission, International Organization for Standardization, Society of Automotive Engineers) are ongoing to address gaps which may limit the near-term deployment of hydrogen for certain applications. Specific gaps in federal regulations relating to hydrogen technologies have been identified by Sandia National Laboratories (Baird et al. 2021).

Electricity Resources and Markets

Insufficient U.S. Electric Grid Generation Capacity: Electrolytic hydrogen production could increase the needed electricity generation capacity in the United States by 2050 by 2.5 terawatts (TW) or 1.8 TW assuming all additional capacity is solar or wind. For reference, the total installed generation capacity in the United States was 1.12 TW in 2020 (IEA 2020).

Electrolyzers Not Sufficiently Compensated in Electricity Markets: Flexible electrolytic hydrogen production can use electricity during periods of oversupply on the grid and reduce power spikes. By operating flexibly, the electrolyzers' net electricity prices could be lower than market purchase prices (Ruth et al. 2019). Some markets allow electrolyzers to receive value for providing ancillary services. However, current electricity markets are not structured so that electrolyzers realize other values of flexible operations such as real-time electricity prices and avoided dispatchable capacity requirements.

Hydrogen Infrastructure

Insufficient Infrastructure to Support Hydrogen Markets: Hydrogen delivery and storage infrastructure will need to grow to support a large hydrogen market. Pipelines are the most energy-efficient approach to transporting hydrogen. However, their deployment is challenged by their high capital costs. Blending of hydrogen into existing pipelines comingled with natural gas or other products is also possible as the economy builds demand. Some applications can use blends of hydrogen, while other applications may require separation of hydrogen and natural gas at the end use. Also, technology advancement is needed to reduce the cost and ensure the safety of gaseous hydrogen storage, especially in areas not having large-scale geological capabilities (Department of Energy (DOE) 2020).

Electrolyzer and Fuel Cell Material Supply and Manufacturing Capacity

Availability of Key Raw Materials: Many key resources (notably platinum, iridium, graphite, titanium, lanthanum, strontium, manganite, cobalt, yttrium, gadolinium, and samarium) are almost entirely imported and thus introduce supply chain vulnerabilities. Of note, iridium is present in lower concentrations than can support operations and capital investment for platinum mining and refining. Due to this vulnerability, the anticipated iridium supply is likely to be inadequate to meet the demands estimated in the Market Size Estimate section above ("Supply Chain Review: Platinum Metal Group Catalysts" 2021). In addition, many of these materials also have competing uses that are also growing and will require larger quantities to supply multiple applications.

Manufacturing Capacity Growth Requirements: A very large and sustained growth rate is needed to achieve targets; specifically, U.S. PEMEC and SOEC installed capacity needs to grow from the current market sizes of approximately 0.17 GW and 0.023 GW, respectively, to approximately 12.66 GW and 4.85 GW by 2030 and by 396 GW and 144 GW by 2050 as discussed in the Electrolyzer and Fuel Cell Market Size Estimates section above. These installed capacities result in an estimated compound annual growth rate from 2021 to 2050 of 22% and 19% for PEMECs and SOECs, respectively (see Appendix A) (Arjona and Buddhavarapu 2021).

Growth Requirements for Manufacturing Supply Chains: To meet the electrolyzer and fuel cell manufacturing capacity, the ability to supply processed materials and subcomponents will need to grow. In addition, reliance on the few manufacturers that produce some key processed materials (e.g., PFSA) today represents a potential supply chain risk as deployment expands, and it highlights the need to engage multiple suppliers for each supply chain element (James et al 2018).

Energy and Environmental Justice Issues for Key Materials

Energy Justice Issues: Many key materials are extracted and/or refined in nations that use forced labor or have minimal environmental protections.

Environmental Justice Issues: PFSA ionomers and membranes may not meet future environmental regulations due to concerns about possible health hazards associated with the production of PFSAs (Lohmann et al. 2020; Cousins et al. 2019) and perfluorinated compound emissions if the membrane is incinerated (Feng et al. 2015). Some governments are moving to ban per- and polyfluoroalkyl substances (PFAS) which may include PFSAs due to these and other environmental concerns – impacts on human health and their high global warming potential.

Workforce development

Mismatch in demand and supply of domestic workforce: A large workforce will be needed that is capable of manufacturing and operating electrolyzers and fuel cells.

International Competitiveness

Consistent and Equal Emission Standards for Hydrogen: International markets for hydrogen are emerging with production in countries rich in low-carbon energy resources planning to export to countries with strong demands for clean hydrogen. Without consistent and equal standards, which would also suppress hydrogen production with carbon-intensive means, energy and environmental justice issues may arise around traded hydrogen.

4. U.S. Opportunities and Challenges

The overarching opportunity for electrolytic hydrogen within the United States is a potential market of over 100 MMT/yr for applications across the industrial, transportation, and power sectors. By taking advantage of the sub-opportunities below, the United States could capture high value-added links of the electrolytic hydrogen supply chain.

An electrolytic hydrogen market of that size powered with clean electricity would provide decarbonization opportunities for difficult to abate sectors including synthetic fuels for air and marine transport, long-distance transport via heavy and medium duty vehicles, energy storage, and high-temperature heat. If the electrolytic hydrogen market does not develop, many of those technologies would need to use fossil fuels and carbon sequestration would be necessary to achieve net zero emissions. Within that overarching opportunity, there are multiple opportunities along the supply chain and challenges that would need to be overcome to reach that level of production.

Electrolytic Hydrogen Markets

Commercialization of Electrolytic Hydrogen Production: Electrolytic hydrogen offers an opportunity to the United States to decarbonize heavy industry and meet climate goals, but electrolytic hydrogen is currently more expensive than SMR-produced hydrogen which is currently widely used by industry. Thus, to commercialize and scale this technology, the cost will need to be addressed. This can be achieved through R&D that reduces electrolyzer capital costs both directly and through at-scale manufacturing technologies. R&D could also increase electrolyzer durability and efficiency. The recently passed Infrastructure Investment and Jobs Act, through sections 40313 and 40314, provides a starting point by initiating the Clean Hydrogen Research and Development Program, as well as support for the development of hydrogen demonstration hubs (Infrastructure Investment and Jobs Act 2021). Beyond R&D on electrolytic hydrogen production, there are opportunities to support manufacturing development, scale, and ensure market pull for electrolytic hydrogen.

Applications for Electrolytic Hydrogen: Many of the hydrogen applications in the transportation, electricity, industrial, commercial building, and residential building sectors are more expensive than alternatives, but they provide benefits such as emissions-minimal long-duration storage and chemical reduction that alternatives do not. For example, PEMFCs and SOFCs are more expensive than conventional combustion-based technologies currently used in transportation and stationary applications. Customers and industry are reluctant to invest in hydrogen technologies that are more expensive than incumbent technologies. There is the opportunity for R&D to reduce the cost of fuel cells and other hydrogen applications so that they are competitive if low-cost electrolytic hydrogen is available. Under sections 40313 and 40314 of the Infrastructure Investment and Jobs Act, funding is provided to address this need through the Clean Hydrogen R&D Program and the development of hydrogen demonstration hubs (Infrastructure Investment and Jobs Act 2021).

Leadership in Developing Codes and Standards: For some applications, standards prevent hydrogen from being used to its potential (e.g., the natural gas system does not allow for more than very low hydrogen concentrations). Improved, science-based standards could safely increase hydrogen's potential. Leadership by the United States in setting global hydrogen codes and standards could enable the United States to capitalize on the green hydrogen economy in tandem with other countries as the world transitions to a carbon-free future, including manufacturing of equipment that meets those standards. Efforts have begun to develop updated standards in one area – hydrogen blended with natural gas (Infrastructure Investment and Jobs Act 2021).

Electricity Resources and Markets

Expanding the U.S. Electric Grid Capacity: Achieving the overall opportunity of 100 MMT/yr hydrogen would require around 5000 TWh electricity annually—approximately doubling the grid's annual generation. That additional need could drive economic and job growth where clean electricity generation resources are the most abundant—especially in rural areas. Electrolysis can also benefit the grid by acting as a dispatchable load that absorbs excess generation when it is available and shutting off when the electrical load is high or generation is low. However, adding 5000 TWh/yr electricity will require much more generation capacity. Recently established efforts for the development of regional hydrogen hubs in section 40314 of the Infrastructure Investment and Jobs Act could serve as an opportunity to investigate regional needs and conduct an economic assessment where electricity prices are prohibitive or balancing markets create opportunities for services; this could help identify opportunities where the grid and electrolysis can grow symbiotically (Infrastructure Investment and Jobs Act 2021).

Hydrogen Infrastructure

Development and Management of Bulk Hydrogen Storage: Large-scale hydrogen storage systems provide supply chain value (e.g., steady supply, increased resilience, and predictable prices) to multiple end-use industries. The geology necessary for large-scale hydrogen storage (e.g., salt caverns, saline aquifers, depleted natural gas or oil reservoirs, and engineered hard rock reservoirs) are available and can provide the physical conditions for this type of storage. However, financial performance of storage built early in the evolution of an electrolytic hydrogen market will be poor because most of the expenses are in construction and initial income will be low due to low initial utilization, although they are likely to grow over time.

Utilization of the Natural Gas Infrastructure for Hydrogen Transport and Storage: The natural gas infrastructure could be converted to transport and store hydrogen instead, reducing the cost of hydrogen transmission and storage as larger volumes of clean hydrogen are produced and used. However, the technical requirements and methods to convert it (and the subsequent costs) are unknown. In addition, the supply and demand locations are likely to be different so the network will likely need to be modified. Current efforts have begun to address technical barriers to hydrogen blending into natural gas pipelines (DOE Hydrogen and Fuel Cell Technologies Office 2021) and quantify the benefit of using the existing natural gas infrastructure (Infrastructure Investment and Jobs Act 2021).

Electrolyzer and Fuel Cell Material Supply and Manufacturing Capacity

Domestic Material Supplies: There is an opportunity for domestic supplies to meet at least a portion of the demand for platinum, iridium, graphite, lanthanum, and yttrium, including exploration, extraction, and processing and refining infrastructure. Additionally, recovery and recycling of valuable materials from end-of-life products, including the technology and processes to do so economically, represent a potential area of leadership and domestic sourcing. Challenges exist in the long lead times for permitting and mitigating of environmental impact. In addition, there are opportunities to further reduce PGM-content and even develop alternatives to PGM catalysts in electrolyzers and fuel cells. Additional R&D will be necessary to develop those advanced low-PGM and PGM-free catalyst options.

Electrolyzer and Fuel Cell Manufacturing Capacity: Manufacturing of electrolyzers and other hydrogen production technologies as well as fuel cells has significant growth potential and the opportunity for economic leadership by countries that are early adopters. Stakeholder (developers, suppliers and end-user) coordination at the regional level, as envisioned in the support of hydrogen hubs established in section 40314 of the Infrastructure Investment and Jobs Act (Infrastructure Investment and Jobs Act 2021), can strengthen the business structures around hydrogen technology manufacturing.

Energy and Environmental Justice Issues for Key Materials in a New Industry

Leadership on Equity and Environmental Justice Issues: A developing supply chain for electrolyzers and fuel cells is an opportunity to lead equity and environment in a growing industry, instead of addressing them after commercialization. Global challenges regarding the environmental, community, and labor impacts of the manufacturing of energy technologies present an opportunity for collaboration and demonstration of positive environmental, social, and governance performance as the manufacturing and supply chains for electrolytic hydrogen are built.

International Competitiveness

Potential Electrolytic Hydrogen Exports: Some countries recognize the need for electrolytic hydrogen to decarbonize, but they lack the electricity generation resources to address the need. The United States is resource-rich and may be able to export low-carbon, electrolytic hydrogen, and related chemicals, as well as the electrolyzers, fuel cells, and related equipment. An international standard could limit global deployment of carbon-intensive produced hydrogen and enhance U.S. competitiveness.

5. Conclusions

This report summarizes potential supply chain and materials issues for electrolyzers and fuel cells in a decarbonized future. The overarching opportunity for electrolytic hydrogen within the United States is a potential market of over 100 MMT/yr for applications across the industrial, transportation, and power sectors. An electrolytic hydrogen market of that size powered with clean electricity would provide decarbonization opportunities for difficult-to-abate sectors, including synthetic fuels for air and marine transport, long-distance transport via heavy- and medium-duty vehicles, energy storage, and high-temperature heat. For the domestic electrolytic hydrogen market to grow to 100 MMT/yr, the electrolyzer capacity required ranges up to 1,000 GW to meet new capacity deployments and replace existing capacity at the end of its lifetime. This is a large increase over the approximately 0.17 GW of capacity currently installed or planned in the United States, resulting in an approximately 20% compound annual growth rate from 2021 to 2050. In addition, over 50 GW of domestic fuel cell capacity is required in the decarbonization scenario with an annual manufacturing requirement of over 3 GW/yr. This level of growth represents a significant opportunity for the United States as electrolytic hydrogen markets and supply chains rapidly grow and develop globally.

Large increases in extraction and refining of many materials would be needed, with many key materials currently being addressed primarily (and exclusively, for some) by imports. Especially of concern are several materials that have both (1) larger projected electrolyzer and fuel cell demands than their current totals and (2) a currently high percentage of total market being met via imports with no specific plans for domestic production. Those include iridium, yttrium, platinum, strontium, and graphite. The United States appears to have sufficient resources and supply chains for many of the other key materials, including stainless steel, titanium, zirconium, and nickel.

It is difficult to exactly predict manufacturing challenges because of the extraordinary growth required in the electrolytic hydrogen market and thus the electrolyzer and fuel cell markets. Key processed materials for polymer electrolyte technologies include perfluorosulfonic acid ionomers, catalysts, graphite composites, and titanium meshes. Key processed materials for solid oxide technologies include air electrode materials, fuel electrode materials, and the electrolyte. The United States currently has manufacturing capabilities in most of the necessary key processed materials and subcomponent manufacturing for both polymer electrolyte and solid oxide technologies. Likewise, the United States has relatively well-positioned end product manufacturing capabilities for both technologies. However, how and where manufacturing capacity along the supply chain may grow are unknown. Thus, government support may be needed to support those industries and meet cost reduction, growth, decarbonization, and supply chain security objectives.

Key vulnerabilities in regard to developing an electrolytic hydrogen market and the supply chains needed for that market include:

- Immature technologies that are not currently cost-competitive for both electrolytic hydrogen production and utilization
- Lack of sufficient emission reduction incentives
- Insufficient codes and standards
- Insufficient electricity generation capacity
- Electrolyzers not being compensated sufficiently in the electricity market
- Insufficient infrastructure to support hydrogen markets at their potential

- Availability of raw materials
- Growth requirements for manufacturing supply chains
- Energy justice issues
- Environmental justice issues
- Mismatch in demand and supply of domestic workforce
- Consistent and equal standards for hydrogen production around the world.

While the United States has technology development targets and an RD&D plan (Department of Energy (DOE) 2020), it does not currently have hydrogen deployment targets or a national plan, unlike at least 15 other countries. However, the United States is developing one as required by section 40314 of the Infrastructure Investment and Jobs Act (Infrastructure Investment and Jobs Act 2021).

Key opportunities to enable the growth of electrolytic hydrogen and fuel cell markets to meet the overarching opportunity of 100 MMT/yr and associated supply chains include:

- Reducing cost and increasing commercialization of electrolytic hydrogen production
- Developing economically competitive applications
- Leading development of codes and standards
- Expanding the U.S. electric grid capacity
- Development and management of bulk hydrogen storage
- Utilization of the natural gas infrastructure for hydrogen transport and storage
- Development of domestic material supplies, including recycling and PGM-free catalysts
- Development of electrolyzer and fuel cell manufacturing capacity
- Leadership on energy and environmental justice issues
- Potential hydrogen exports.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

References

Arjona, Vanessa, and Priya Buddhavarapu. 2021. "Electrolyzer Capacity Installations in the United States." DOE Hydrogen Program Record 20009. https://www.hydrogen.energy.gov/pdfs/20009-electrolyzers-installed-in-united-states.pdf.

Badgett, Alex, Mark Ruth, and Bryan Pivovar. 2022. "Chapter 10 - Economic Considerations for Hydrogen Production with a Focus on Polymer Electrolyte Membrane Electrolysis." In *Electrochemical Power Sources: Fundamentals, Systems, and Applications*, edited by Tom Smolinka and Jurgen Garche, 327–64. Elsevier. https://doi.org/10.1016/B978-0-12-819424-9.00005-7.

Baird, Austin, Brian Ehrhart, Austin Glover, and Chris LaFleur. 2021. *Federal Oversight of Hydrogen Systems*. SAND2021-2955, 1773235, 695026. https://doi.org/10.2172/1773235.

Blagoeva, D., F. Pasimeni, D. Wittmer, J. Huisman, C. Pavel, and C. Pavel. 2020. *Materials Dependencies for Dual-Use Technologies Relevant to Europe's Defence Sector: Background Report*. LU: Joint Research Centre, European Commission. https://data.europa.eu/doi/10.2760/977597.

Bloom Energy. 2019. "A Primer to Understanding Fuel Cell Power Module Life, 2019." https://www.bloomenergy.com/wp-content/uploads/bloom-energy-a-primer-to-understanding-fuel-cell-power-module-life.pdf.

BNEF. 2021. "Organisations Database."

Cochran, Jaquelin, Paul Denholm, Meghan Mooney, Daniel Steinberg, Elaine Hale, Garvin Heath, Bryan Palmintier, et al. 2021. "LA100: The Los Angeles 100% Renewable Energy Study Executive Summary." National Renewable Energy Lab. (NREL), Golden, CO (United States). https://www.nrel.gov/docs/fy21osti/79444-ES.pdf.

Connelly, Elizabeth, Amgad Elgowainy, and Mark Ruth. 2019. "Current Hydrogen Market Size: Domestic and Global (DOE Hydrogen and Fuel Cells Program Record 19002)." Washington, D.C.: DOE. https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf.

Cousins, Ian T., Gretta Goldenman, Dorte Herzke, Rainer Lohmann, Mark Miller, Carla A. Ng, Sharyle Patton, et al. 2019. "The Concept of Essential Use for Determining When Uses of PFASs Can Be Phased Out." *Environmental Science: Processes & Impacts* 21 (11): 1803–15. https://doi.org/10.1039/C9EM00163H.

Cummins. 2019. "Cummins Closes on Its Acquisition of Hydrogenics." Cummins Inc. September 9, 2019. https://www.cummins.com/news/releases/2019/09/09/cummins-closes-its-acquisition-hydrogenics.

Curtin, Dennis E., Robert D. Lousenberg, Timothy J. Henry, Paul C. Tangeman, and Monica E. Tisack. 2004. "Advanced Materials for Improved PEMFC Performance and Life." *Journal of Power Sources*, Selected papers presented at the Eighth Grove Fuel Cell Symposium, 131 (1): 41–48. https://doi.org/10.1016/j.jpowsour.2004.01.023.

Denholm, Paul, Douglas J. Arent, Samuel F. Baldwin, Daniel E. Bilello, Gregory L. Brinkman, Jaquelin M. Cochran, Wesley J. Cole, et al. 2021. "The Challenges of Achieving a 100% Renewable Electricity System in the United States." *Joule* 5 (6): 1331–52. https://doi.org/10.1016/j.joule.2021.03.028.

Department of Energy (DOE). 2021. "Hydrogen Shot." https://www.energy.gov/eere/fuelcells/hydrogen-shot.

DOE. 2020. "Department of Energy Hydrogen Program Plan." United States Department of Energy. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.

DOE. "Parts of a Fuel Cell." Accessed November 8, 2021. https://www.energy.gov/eere/fuelcells/parts-fuel-cell.

DOE Hydrogen and Fuel Cell Technologies Office. 2021. "HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines." Energy.Gov. June 2021. https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines.

DOE Hydrogen Program. "Codes and Standards." Accessed November 8, 2021. https://www.hydrogen.energy.gov/codes_standards.html.

E4Tech. 2019. "Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies." FCH 2 JU in partnership with Ecorys and Strategic Analysis Inc. https://www.fch.europa.eu/sites/default/files/Evidence%20Report%20v4.pdf.

Elogen. "Our Facilities." Accessed November 8, 2021. https://elogenh2.com/en/discover-elogen/our-locations/.

European Commission. 2020. *Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study*. Luxembourg: Publications Office of the European Union. https://data.europa.eu/doi/10.2873/58081.

Exec. Order No. 14017, 2021. 2021. "Executive Order (EO) 14017, 86 FR 11849 (Febrauray 24, 2021)." EERE Office of Policy.

Feng, Mingbao, Ruijuan Qu, Zhongbo Wei, Liansheng Wang, Ping Sun, and Zunyao Wang. 2015. "Characterization of the Thermolysis Products of Nafion Membrane: A Potential Source of Perfluorinated Compounds in the Environment." *Scientific Reports* 5 (1): 9859. https://doi.org/10.1038/srep09859.

Fuel Cell and Hydrogen Energy Association. 2021. *Road Map to a US Hydrogen Economy.* https://www.fchea.org/us-hydrogen-study.

Fullenkamp, Patrick, Diane Holody, Brian James, Cassidy Houchins, Douglas Wheeler, David Hart, and Franz Lehner. 2017. "U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competitiveness Analysis." DE-EE0006935. Westside Industrial Retention & Expansion Network, Cleveland, OH (United States). https://doi.org/10.2172/1410998.

GTT Group. n.d. "Elogen, a GTT Company." Elogen. Accessed November 8, 2021. https://elogenh2.com/en/discover-elogen/gtt-group/.

Hauch, A., R. Küngas, P. Blennow, A. B. Hansen, J. B. Hansen, B. V. Mathiesen, and M. B. Mogensen. 2020. "Recent Advances in Solid Oxide Cell Technology for Electrolysis." *Science*. 370 (6513). https://doi.org/10.1126/science.aba6118.

Hunter, Chad A., Michael M. Penev, Evan P. Reznicek, Joshua Eichman, Neha Rustagi, and Samuel F. Baldwin. 2021. "Techno-Economic Analysis of Long-Duration Energy Storage and Flexible Power Generation Technologies to Support High-Variable Renewable Energy Grids." *Joule* 5 (8). https://doi.org/10.1016/j.joule.2021.06.018.

HyTechCycling. 2017. "D2.5 Study on Needs and Challenges in the Phase of Recycling and Dismantling." http://hytechcycling.eu/wp-content/uploads/D2.5-Study-on-needs-and-challenges-in-the-phase-of-recycling.pdf.

———. 2018a. "D3.1 New End-of-Life Technologies Applicable to FCH Products." http://hytechcycling.eu/wp-content/uploads/D3.1-New-end-of-life-technologies-applicable-to-FCH-products.pdf.

———. 2018b. "D2.2 Existing End-of-Life Technologies Applicable to FCH Products." http://hytechcycling.eu/wp-content/uploads/d2-2-report-on-existing-recycling-technologies-applicable-to-fch-products.pdf.

———. 2019. "D2.1: Assessment of Critical Materials and Components in FCH Technologies by Laboratory for Heat and Power." 4113562. https://issuu.com/flumaback/docs/d2.1_-_identification_of_critical_m.

IEA. 2019. *The Future of Hydrogen: Seizing Today's Opportunities.* IEA. June 2019. https://www.iea.org/reports/the-future-of-hydrogen.

———. 2020. *Analysis (World Energy Outlook 2020).* https://www.iea.org/analysis.

———. 2021a. *Global Hydrogen Review 2021 – Analysis*. https://www.iea.org/reports/global-hydrogen-review-2021.

———. 2021b. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. https://doi.org/10.1787/c8328405-en.

Igogo, Tsisilile A., Debra L. Sandor, Ahmad T. Mayyas, and Jill Engel-Cox. 2019. "Supply Chain of Raw Materials Used in the Manufacturing of Light-Duty Vehicle Lithium-Ion Batteries." NREL/TP-6A20-73374. National Renewable Energy Lab. (NREL), Golden, CO (United States). https://doi.org/10.2172/1560124.

Infrastructure Investment and Jobs Act. 2021. *Infrastructure Investment and Jobs Act. Public Law 117–58.* https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

James, Brian, Jennie M. Huya-Kouadio, Cassidy Houchins, and Daniel Desantis. 2018. *Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update.* Strategic Analysis. https://www.sainc.com/assets/site_18/files/publications/final%20sa%202018%20transportation%20fuel%20cell%20cost%20analysis%20-2020-01-23.pdf.

Kroposki, Benjamin, Brian Johnson, Yingchen Zhang, Vahan Gevorgian, Paul Denholm, Bri-Mathias Hodge, and Bryan Hannegan. 2017. "Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy." *IEEE Power and Energy Magazine* 15 (2): 61–73. https://doi.org/10.1109/MPE.2016.2637122.

Larson, Eric, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, and R. Socolow. 2021. *Princeton Net-Zero America Study.* https://www.dropbox.com/s/ptp92f65lgds5n2/Princeton%20NZA%20FINAL%20REPORT%20%2829Oct2021%29.pdf?dl=0.

Lohmann, Rainer, Ian T. Cousins, Jamie C. DeWitt, Juliane Glüge, Gretta Goldenman, Dorte Herzke, Andrew B. Lindstrom, et al. 2020. "Are Fluoropolymers Really of Low Concern for Human and Environmental Health and Separate from Other PFAS?" *Environmental Science & Technology* 54 (20): 12820–28. https://doi.org/10.1021/acs.est.0c03244.

Løkke, Jon André. 2021. "Q2 2021." https://nelhydrogen.com/wp-content/uploads/2021/08/Nel-ASA-Q2-2021-Results-presentation.pdf.

Mayyas, Ahmad, and Margaret Mann. 2019. "Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations and Electrolyzers." *International Journal of Hydrogen Energy* 44 (8): 9121–42. https://doi.org/10.1016/j.ijhydene.2019.02.135.

Miller, Hamish Andrew, Karel Bouzek, Jaromir Hnat, Stefan Loos, Christian Immanuel Bernäcker, Thomas Weißgärber, Lars Röntzsch, and Jochen Meier-Haack. 2020. "Green Hydrogen from Anion Exchange Membrane Water Electrolysis: A Review of Recent Developments in Critical Materials and Operating Conditions." *Sustainable Energy & Fuels* 4 (5): 2114–33. https://doi.org/10.1039/C9SE01240K.

Minke, Christine, Michel Suermann, Boris Bensmann, and Richard Hanke-Rauschenbach. 2021. "Is Iridium Demand a Potential Bottleneck in the Realization of Large-Scale PEM Water Electrolysis?" *International Journal of Hydrogen Energy* 46 (46): 23581–90. https://doi.org/10.1016/j.ijhydene.2021.04.174.

MP Materials. "What Are Rare Earth Elements?" Accessed November 9, 2021. https://mpmaterials.com/what-we-do/.

Pearre, Nathaniel, and Lukas Swan. 2020. "Reimagining Renewable Electricity Grid Management with Dispatchable Generation to Stabilize Energy Storage." *Energy* 203 (July): 117917. https://doi.org/10.1016/j.energy.2020.117917.

Pivovar, Bryan, and Richard Boardman. 2021. "H2NEW: Hydrogen (H2) from Next-Generation Electrolyzers of Water Overview." Presented at the DOE Hydrogen Program 2021 Annual Merit Review and Peer Evaluation Meeting. https://www.hydrogen.energy.gov/pdfs/review21/p196_pivovar_boardman_2021_o.pdf.

Plug Power. "Plug Power | Green Hydrogen & Fuel Cell Solutions." Accessed November 8, 2021. https://www.plugpower.com/.

Ruth, Mark F, Jadun Paige, Daniel Levie, and Bethany Frew. 2019. "Electrolysis' Potential Value for Supporting the Electrical Grid." Presented at the Presented at the 2019 Fuel Cell Seminar & Energy Exposition, Long Beach, California. https://www.nrel.gov/docs/fy20osti/75373.pdf.

"Semiconductors for Energy: Global Supply Chain Analysis for Evaluation of U.S. Manufacturing Resilience." 2021. Response to Executive Order (EO) 14017, "America's Supply Chains."

Siemens Energy. 2020. "Siemens Energy: Company Presentation." November 16. https://assets.siemens-energy.com/siemens/assets/api/uuid:fc59adb3-bc23-4642-a227-d5d30f7e4c4e/company-presentation-siemens-energy-en.pdf.

"Supply Chain Review: Platinum Metal Group Catalysts." 2021. Response to Executive Order (EO) 14017, "America's Supply Chains." Argonne National Lab. (ANL), Argonne, IL (United States).

United States Department of State and United States Executive Office of the President. 2021. "The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050." https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

USGS. 2021. "Mineral Commodity Summaries 2021." Reston, VA: USGS. https://doi.org/10.3133/mcs2021.

Xun, Dengye, Xin Sun, Jingxuan Geng, Zongwei Liu, Fuquan Zhao, and Han Hao. 2021. "Mapping Global Fuel Cell Vehicle Industry Chain and Assessing Potential Supply Risks." *International Journal of Hydrogen Energy* 46 (29): 15097–109. https://doi.org/10.1016/j.ijhydene.2021.02.041.

Appendix A: Performance and Material Use Assumptions

A-1. Technology Assumptions

Tables A-1 through A-3 outline electrolysis and fuel cell specific design criteria and performance values that are used to estimate material requirements.

Table A-1. Water Electrolyzer and Fuel Cell Design and Performance Assumptions

Type	Capacity Factor (%)	Cell Voltage (V)	Current Density (A/cm^2)	Efficiency (kWh/kg)	Anode Catalyst	Anode Catalyst Loading (mg/cm^2)	Cathode Catalyst	Cathode Catalyst Loading (mg/cm^2)	Lifetime (thousand h)
PEMEC	90% (a)	1.9 (b)	2 (b)	55 (b)	Iridium oxide (b)	2 (b)	Platinum (b)	1 (b)	40 (b)
Alkaline electrolyzer	90% (a)	2.1 (c)	0.3 (c)	64 (d)	Nickel (d)		Nickel (d)		80 (c)
SOEC	90% (a)	1.28	1.0	36.8	LSCF		Ni-YSZ		35
AEMEC	90% (a)	2 (c)	0.4 (c)	63 (e)	Ni-Fe-Ox (f)	2.5 (f)	Ni-Fe-Co (f)	2.5 (f)	5 (e)
PEMFC	90% (a)	0.55 (g)	1.5 (g)	23.64 (d)	Platinum (g)	0.05 (g)	Platinum (g) and Pt alloys (PtNi, PtCo)	0.1 (g)	80
SOFC	90% (a)	0.8	0.4	52% higher heating value (natural gas)	Ni-YSZ		LSCF, LSM-YSZ		40

[a] High capacity factor operation assumed

[b] H2NEW baseline model

[c] Miller, Hamish Andrew, Karel Bouzek, Jaromir Hnat, Stefan Loos, Christian Immanuel Bernäcker, Thomas Weißgärber, Lars Röntzsch, and Jochen Meier-Haack. 2020. "Green Hydrogen from Anion Exchange Membrane Water Electrolysis: A Review of Recent Developments in Critical Materials and Operating Conditions." *Sustainable Energy and Fuels* 4 (5): 2114–33. https://doi.org/10.1039/c9se01240k.

[d] Vincent, Immanuel, and Dmitri Bessarabov. 2018. "Low Cost Hydrogen Production by Anion Exchange Membrane Electrolysis: A Review." *Renewable and Sustainable Energy Reviews* 81 : 1690–1704. https://doi.org/10.1016/j.rser.2017.05.258.

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

[f] Vincent, Immanuel, Eun Chong Lee, and Hyung Man Kim. 2021. "Comprehensive Impedance Investigation of Low-Cost Anion Exchange Membrane Electrolysis for Large-Scale Hydrogen Production." *Scientific Reports* 11 (1): 1–12. https://doi.org/10.1038/s41598-020-80683-6.

[g] Memorial Institute. 2016. "Manufacturing Cost Analysis of PEM Fuel Cell Systems for 5- and 10-KW Backup Power Applications."

Table A-2. Low-Temperature Water Electrolyzer and Fuel Cell Bipolar Plate and Gas Diffusion Layer Material Assumptions

Type	Bipolar Plate Material	Bipolar Plate Thickness (cm)	Cathode GDL Material	Cathode GDL Thickness (cm)	Cathode GDL Porosity (%)	Anode GDL Material	Anode GDL Thickness (cm)	Anode GDL Porosity (%)
PEMEC	Titanium (a)	0.15 (a)	Carbon paper (a)	n/a	n/a	Titanium mesh (a)	0.025 (a)	0.3 (a)

Type	Bipolar Plate Material	Bipolar Plate Thickness (cm)	Cathode GDL Material	Cathode GDL Thickness (cm)	Cathode GDL Porosity (%)	Anode GDL Material	Anode GDL Thickness (cm)	Anode GDL Porosity (%)
Alkaline electrolyzer	Stainless steel (b)	0.15	n/a	n/a	n/a	n/a	n/a	n/a
AEMEC	Stainless steel (b)	0.15	n/a	n/a	n/a	n/a	n/a	n/a
PEMFC	Graphite	0.15	n/a	n/a	n/a	n/a	n/a	n/a

[a] H2NEW baseline model

[b] IRENA. 2020. *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal. /Publications/2020/Dec/Green-Hydrogen-Cost-Reduction*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf.

Table A-3. SOC Electrolyzer and Fuel Cell Material Use Assumptions

Type	LSM (kg LSM/MW)	LSCF (kg LSCF/MW)	LSM-YSZ (kg LSM-YSZ/MW)	Gd/Sm (kg GdSm/kMW)	8YSZ (kg 8YSZ/MW)	Ni-YSZ (kg Ni-YSZ/MW)	441-SS (kg 441 SS/MW)	Borosilicate Glass (kg borosilicate glass/MW)
SOEC	5.14	12.33	9.54	3.06	3.98	228	2579	79.05
SOFC	19.35	46.45	35.94	11.53	14.99	861	9709	297.47

LSM: Lanthanum strontium magnatite
LSCF: Lanthanum strontium cobalt ferrite
LSM-YSZ: Lanthanum strontium magnetite-yttria stabilized zirconia
441-SS: Stainless steel type 441

A-2. Market Scenario Assumptions

Tables A-4 and A-5 summarize hydrogen demand projections for global and domestic hydrogen by sector from current to 2050.

International Energy Agency (IEA) Net Zero by 2050 Scenario

The following tables outline market sizes and electrolysis supply mixes for various sectors outlined in a recent report by the International Energy Association (IEA 2021b).

Table A-4. Ambitious Scenario Hydrogen Market Demand Assumptions by Sector (MMT/yr)

Year	Units	2020	2040	2050
Total	MMT/yr	87.4	390.1	528.1
Blended in gas grid	MMT/yr	0	37.9	59.9
Energy storage	MMT/yr	0	110	100
Buildings	MMT/yr	0	11.4	16.2

Year	Units	2020	2040	2050
Road transportation	MMT/yr	0	46	93.2
Aviation	MMT/yr	0	22.1	51.9
Shipping	MMT/yr	0	35.1	57.3
Industry	MMT/yr	1	20.5	28.3
Refineries	MMT/yr	13.8	5	4.6
Chemicals: onsite	MMT/yr	45.9	58.4	60.3
Iron and steel: onsite	MMT/yr	4.7	28.9	40.4
Refineries: onsite	MMT/yr	22	8.1	3.8
Other	MMT/yr	0	6.7	12.2

Princeton Net-Zero America: E+RE+ scenario

The following tables outline market sizes and electrolysis supply mixes for various sectors outlined in the Princeton University Net-Zero America E+RE+ scenario (Larson et al. 2021). Hydrogen market sizes for subsectors are provided in annual energy consumed, and were converted from these units to MMT/yr as shown in Table A-5. An efficiency of 50.51 kWh/kg hydrogen was assumed. Estimates for installed electrolyzer capacity provided in this report vary slightly from those in the Princeton NZA scenarios due to differences in assumptions regarding the types of electrolyzers (e.g., PEMEC, SOEC, etc.) used to meet hydrogen demand and the rate at which these electrolyzers replace conventional sources of hydrogen over time (Table A-8).

Table A-5. E+RE+ Scenario Hydrogen Market Demand Assumptions by Sector (MMT/yr)

Year	Units	2020	2025	2030	2035	2040	2045	2050
Total	MMT/yr	4.9	5.2	8.6	14.7	28.1	54.9	106.0
Bulk chemicals manufacturing	MMT/yr	4.9	5.1	5.1	5.2	5.6	5.8	5.9
Direct reduced iron production	MMT/yr	0.0	0.0	0.1	0.8	1.5	1.9	2.4
Gas turbine fuel	MMT/yr	0.0	0.0	0.0	0.0	0.0	0.2	1.4
Gaseous fuel synthesis	MMT/yr	0.0	0.0	0.0	0.0	0.0	0.0	5.6
Hythane	MMT/yr	0.0	0.0	0.0	0.0	0.2	0.6	1.2

Year	Units	2020	2025	2030	2035	2040	2045	2050
Industrial boilers	MMT/yr	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Liquid fuels synthesis	MMT/yr	0.0	0.0	2.5	6.1	14.6	37.0	78.0
MD/HD FCEVs	MMT/yr	0.0	0.1	0.7	2.4	4.6	6.4	7.5
Other industry	MMT/yr	0.0	0.0	0.0	0.2	0.8	1.4	1.5
Other transportation	MMT/yr	0.0	0.0	0.1	0.1	0.9	1.6	2.4

A-3. Sectoral Aggregation and Market Shares for Electrolyzers and Fuel Cells

The following tables summarize sector aggregation between global and domestic hydrogen demand projections. Both projections are aggregated into like sectors for comparison between the two reports. Tables A-6 and A-7 summarize the market shares between hydrogen production technologies and fuel cells over time, respectively.

Table A-6. Sector Aggregation Between Global and U.S. Hydrogen Market Projections

Aggregated Sectors in this report	IEA: Global	Princeton: Net-Zero America
Natural gas blending	Blended in gas grid	Hythane
Energy storage	Energy storage	Gas turbine fuel
Buildings	Buildings	
FCEVs	Road transportation	MD/HD FCVs
		Other transportation
Synfuels	Aviation	Gaseous fuel synthesis
	Shipping	Liquid fuels synthesis
Industry	Industry	Industrial boilers
Chemicals and existing feedstock	Refineries	Bulk chemicals manufacturing
	Refineries: onsite	
	Chemicals: onsite	
New feedstock	Iron and steel: onsite	Other industry
	Other	Direct-reduced iron production

Table A-7. Estimated U.S. and Global Hydrogen Market Share for Electrolyzers for New Installed Capacity Used in this Analysis

Year	2020	2025	2027	2050
Natural gas blending	100% SMR	Growth in hydrogen demand	SMR phase-out begins, completed by 2050	100% PEM
Energy storage	100% SMR			60% PEM 40% SOEC

Year	2020	2025	2027	2050
Buildings	100% SMR	met with electrolysis		100% PEM
FCEVs	100% SMR			50% PEM 20% alkaline 30% SOEC
Synfuels	100% SMR			50% PEM 20% alkaline 30% SOEC
Industry	100% SMR			30% PEM 70% SOEC
Chemicals and existing feedstock	100% SMR			35% PEM 30% alkaline 35% SOEC
New feedstock	100% SMR			100% PEM

Table A-8. Estimated U.S. and Global Hydrogen Market Share for Fuel Cells Used in this Analysis

Year	2020	2030	2040	2050
Natural gas blending	n/a	n/a	n/a	n/a
Energy storage	40% PEM 60% SOFC	40% PEM 60% SOFC	40% PEM 60% SOFC	40% PEM 60% SOFC
Buildings	n/a	n/a	n/a	n/a
FCEVs	100% PEM	100% PEM	100% PEM	100% PEM
Synfuels	n/a	n/a	n/a	n/a
Industry	n/a	n/a	n/a	n/a

Year	2020	2030	2040	2050
Chemicals and existing feedstock	n/a	n/a	n/a	n/a
New feedstock	n/a	n/a	n/a	n/a

This analysis uses projections for the size of hydrogen markets as a basis for estimating the installed capacity of electrolyzers E_{PEMEC}, which is estimated using Equation A-1. Equation A-1 shows values for PEMEC systems, but this methodology extends to all electrolyzer types. In this equation, D_{H2} is the annual hydrogen demand in MMT/yr, S_{PEMEC} is the market share for PEMEC systems, η_{PEMEC} is the efficiency of the PEMEC system in kWh/kg H2, and CF is the capacity factor for the electrolyzer.

$$E_{PEMEC} = \frac{D_{H2} S_{PEMEC} \eta_{PEMEC}}{CF(8{,}760)} \qquad \text{(A-1)}$$

Two types of components are included in the model for material use in electrolyzers and fuel cells: components that directly scale with the catalytic active area of the system as a function of loading rate (e.g., catalyst coatings) and components that scale based on the total area of each cell in a stack and thickness of the component (e.g., bipolar plates).

Equation A-2 calculates the material required for material j per MW of PEMEC capacity, where LR_j is the loading rate of material j in mg/cm^2, AA_{PEMEC} is the catalytic active area per cell within the stack in cm^2/cell, K_{PEMEC} is the number of cells per PEMEC stack (cells/stack), and P_{PEMEC} is the power rating of the stack (MW/stack).

$$m_j = \frac{LR_j AA_{PEMEC} K_{PEMEC}}{P_{PEMEC}} \qquad \text{(A-2)}$$

For components such as bipolar plates whose size is quantified using a thickness rather than loading rate, the material demand per MW estimate is slightly modified (Equation A-3). Bipolar plates extend beyond the catalytic active area, covering buffer areas outside the cell, therefore the dimension of this component is based on the total area in the PEMEC cell TA_{PEMEC}. The thickness of material j is included in variable T_j, and the density of the material used in the component converts the volume to mass ρ_j.

$$m_j = \frac{T_j TA_{PEMEC} K_{PEMEC} \rho_j}{P_{PEMEC}} \qquad \text{(A-3)}$$

The compound annual growth rate for installed electrolyzer capacity is estimated with Equation A-4, where C_2 and C_1 signify installed electrolyzer capacity in 2050 and 2021, respectively. In this equation t is the number of years between the installed capacity values (29 in this case).

$$CAGR = (C_2 - C_1)^{\frac{1}{t}} - 1 \qquad \text{(A-4)}$$

A-4. Low Material Use Scenario Assumptions

This section describes assumptions used to generate low scenario material estimates that are shown in Figure 9 (page 29). The upper bound of these ranges is given by the baseline scenario material estimates documented in this appendix and throughout the remainder of the report.

The low material use scenario assumes lower market penetration of electrolyzer and a large portion of hydrogen comes from bioenergy with carbon capture and sequestration (BECCS) rather than electrolysis (Table A-9). These assumptions are based on the Princeton Net Zero America E+ scenario, while the baseline estimates use the E+RE+ scenario (Larson et al. 2021). While the total hydrogen market sizes between these two scenarios are similar, the market shares of hydrogen production technologies varies. In the E+RE+ scenario nearly all hydrogen is produced from electrolysis by 2050, while nearly 60% of hydrogen is produced with BECCS in the E+ scenario.

Table A-9. Estimated U.S. Hydrogen Market Share for Electrolyzers for Low Material Use Scenario Used in this Analysis

Year	2020	2025	2027	2050
Natural gas blending	100% SMR	Growth in hydrogen demand met with electrolysis and BECCS	SMR phase-out begins, completed by 2050	40% PEM 60% BECCS
Energy storage	100% SMR			20% PEM 20% SOEC 60% BECCS
Buildings	100% SMR			40% PEM 60% BECCS
FCEVs	100% SMR			15% PEM 10% alkaline 15% SOEC 60% BECCS
Synfuels	100% SMR			15% PEM 10% alkaline 15% SOEC 60% BECCS
Industry	100% SMR			20% PEM 20% SOEC

Year	2020	2025	2027	2050
				60% BECCS
Chemicals and existing feedstock	100% SMR			15% PEM 10% alkaline 15% SOEC 60% BECCS
New feedstock	100% SMR			40% PEM 60% BECCS

Additionally, usage rates for key materials in electrolyzers and fuel cells are assumed to decrease 80% by 2035 in the low material use scenario (Table A-10) (Pivovar and Boardman 2021). Decreasing the use rates of these materials lowers the rates that they are used in newly manufactured systems. Any systems manufactured prior to 2035 use materials at the same rates outlined in Tables A-1 through A-3.

Table A-10. Estimated Adjusted Material Usage Rates for Key Materials in Low Material Use Scenario Used in this Analysis

Values are expressed in percentage of baseline material demand

Year	2020	2035	2050
PEMEC platinum usage	100%	20%	20%
PEMEC iridium usage	100%	20%	20%
SOEC LSCF usage	100%	20%	20%
SOEC LSM-YSZ usage	100%	20%	20%
SOEC Ni-YSZ usage	100%	20%	20%
PEMFC platinum usage	100%	20%	20%
SOFC LSCF usage	100%	20%	20%
SOFC LSM-YSZ usage	100%	20%	20%
SOFC LSCF usage	100%	20%	20%

Appendix B: Electrolyzer and Fuel Cell Manufacturers

B-1. PEMEC and PEMFC Technology

We surveyed market report pages, company websites and reports, press releases, and Bloomberg New Energy Finance (BNEF) databases to compile information on PEMEC and PEMFC manufacturers, locations, and capacities, shown in Tables B-1 through B-3. Manufacturers of electrolyzers using alkaline technology are included because most market reports were not specific to PEMEC technology. Additionally, alkaline technology is used significantly today and is worth considering in the short term (see source 43 in list below). Some listed companies are vertically integrated, at least to a certain extent, and produce many of the components but sell only the end product. Intermediate components are not listed for those companies except where noted.

Not all companies are listed and the data represents only one snapshot in time. Given the rapid pace of growth and the number of acquisitions, emerging companies, and joint ventures in numerous countries, the data in these tables will change frequently.

Table B-1. Examples of PEMEC and Other Electrolyzer Manufacturers

Company[1]	Headquarters	Manufacturing Location(s)[2]	Technology	Additional source(s)[1]
Angstrom Advanced[4]	Stoughton, MA, US	MA, US	PEMEC, Alkaline	88,122,123
Asahi Kasei Corporation[3]	Japan	Japan	Alkaline	124,125
Cockerill Jingli Hydrogen	Suzhou, China	China	Alkaline	22, 37
Electric Hydrogen[4]	Boston MA, San Francisco, CA, US	Boston MA, San Francisco, CA, US	components of PEMEC	93
Elogen (subsidiary of GTT, recently rebranded from Areva H2Gen)	Les Ulis, France	Les Ulis, France	PEMEC	13, 14
Erredue[3]	Livorno, Italy	Italy	PEMEC, Alkaline	16, 115
Green Hydrogen	Kolding, Denmark	Kolding Denmark	Alkaline, maybe PEMEC	33, 35, 36
GTA, Inc.[4]	Atlanta, GA, US	Atlanta, GA, US	PEMEC	91
Heraeus	Hanau, Germany	Hanau, Germany; Nanjing, China	Catalyst	81, 82, 136
Hydrogenics (subsidiary of Cummins)	Mississauga, Ontario, Canada	Ontario, Canada; IN, US; CA, US	PEMEC, Alkaline	5, 15
Idroenergy[3]	Livorno, Italy	Italy	Alkaline	17, 126
Ion Power	New Castle, DE, US	DE, US; PA, US	Membrane	83, 84

Company[1]	Headquarters	Manufacturing Location(s)[2]	Technology	Additional source(s)[1]
ITM	Sheffield, UK	UK	PEMEC	126
Kobelco Eco-solutions	Kobe, Japan	Harima, Japan	PEMEC, Alkaline	105
Longi[3,4]	Xi'an, China	Jiangsu, China	Alkaline	38, 39, 43, 116
McPhy	La Motte-Fanjas, France	San Miniato, Italy; Wildau, Germany	Alkaline	18
Millennium Reign Energy[4]	Dayton OH, US	Unavailable	Alkaline	95
Nel ASA	Oslo, Norway	Wallingford, CT, US; Notodden/Herøya, Norway; Denmark	PEMEC, Alkaline	19, 80
Next Hydrogen[3]	Mississauga, Ontario, Canada	Mississauga, Ontario, Canada	Alkaline	20, 121
Ohmium[4]	Incline Village, NV, US	Bengaluru, India	PEMEC	89,90
Plug Power	Latham, NY, US	Rochester, NY, US	PEMEC	9
Pochari Technologies[4]	Bodega Bay, CA, US	China	Alkaline	92
Siemens Energy[3]	Munich, Germany	Germany	PEMEC	21
Teledyne Energy Systems	Hunt Valley, MD, US	MD, US	Alkaline	117, 135
Tianjin Mainland Hydrogen Equipment[3]	China (specific city/region unavailable)	Unavailable	Unavailable	
Toshiba Energy Systems	Kanagawa, Japan	Kawasaki, Japan	Alkaline	118

[1] *Included companies were mentioned by at least two market reports and BNEF except where noted (sources 45–70). Additional sources were used when location and technology information was unavailable from market reports and BNEF.*

[2] *Manufacturing locations may not be a complete list for a given company.*

[3] *Company was not mentioned in BNEF regarding electrolyzers.*

[4] *Company was not mentioned by market reports but is believed to be a significant manufacturer of electrolyzers. Longi specifically is a major manufacturer of solar cell technology that recently expanded into electrolyzer manufacturing (see source 38).*

Table B-2. Examples of PEMFC and Component Manufacturers

Company[1]	Headquarters	Manufacturing Location(s)[2]	Product(s)	Additional source(s)[1]
3M	St. Paul, MN, US	MN, US; Menomonie, WI, US	Membrane, Ionomer	32, 106, 107, 108
Advent	Athens, Greece; Boston, MA, US	Patras, Greece; MA, US	Membrane (high-temperature), MEA	85
Altergy[4]	Folsom, CA, US	Folsom, CA, US	PEMFC	100, 101
AvCarb	Lowell, MA, US	Lowell, MA, US	GDL	134
Ballard Power Systems	Burnaby, British Columbia, Canada	Burnaby, British Columbia, Canada; Hobro, Denmark	PEMFC, MEA[5], BPP[5]	1
BASF	Ludwigshafen, Germany	Germany	MEA, Catalyst	127,128
Bosch and PowerCell Sweden (strategic partnership)[4]	Gerlingen, Germany (Bosch) & Gothenburg, Sweden (PowerCell)	Bamberg, Germany	PEMFC (automotive applications)	96, 97, 98, 99
Cell Impact	Karlskoga, Sweden	Karlskoga, Sweden	BPP	2
Chemours (2015 spin-off from DuPont)	Wilmington, DE, US	Fayetteville, SC, US	Membrane, Ionomer	71, 72, 109
Dana	Maumee, OH, US	Neu-Ulm, Germany	BPP	119
ElringKlinger	Dettingen, Germany	Dettingen, Germany	PEMFC, BPP	3, 129
Freudenberg	Weinheim, Germany	Weinheim, Germany	GDL	120
Greenerity[3] (subsidiary of Toray)	Alzenau, Germany	Alzenau, Germany	MEA	4
Heraeus	Hanau, Germany	Hanau, Germany; Nanjing, China	Catalyst	80, 81, 82
Horizon Fuel Cell	Singapore	Singapore, China	PEMFC	130, 86
Hydrogenics (subsidiary of Cummins)	Mississauga, Ontario, Canada	Ontario, Canada	PEMFC	5, 74
HyPlat[3]	Cape Town, South Africa	Cape Town, South Africa; Johannesburg, South Africa	MEA, Catalyst	6

Company[1]	Headquarters	Manufacturing Location(s)[2]	Product(s)	Additional source(s)[1]
Hypoint[5]	Menlo Park, CA, US; Sandwich, UK	None (still in product development)	High-temperature PEMFC (aviation applications)	103
Hyzon Motors[4]	Rochester, NY, US	Rochester, NY, US (PEMFC); Chicago, IL, US (MEA)	PEMFC (automotive applications), MEA[5]	102
Intelligent Energy	Loughborough, UK	Loughborough, UK	PEMFC	110
Ion Power	New Castle, DE, US	DE, US; PA, US	MEA	83, 84
IRD Fuel Cells Technology	Denmark	Denmark; Albuquerque, NM, US	MEA, BPP	7, 111
Johnson Matthey	London, UK	Swindon, UK; Sonning Common, UK	MEA, Catalyst	31, 112
Mitsubishi Chemical Corporation	Tokyo, Japan	Unavailable	GDL	
Nedstack Fuel Cell Technology B.V.	Arnhem, The Netherlands	Arnhem, The Netherlands	PEMFC	131
Nisshinbo	Tokyo, Japan	Japan	BPP, Catalyst	41
Nuvera Fuel Cells, LLC	Billerica, MA, US	Billerica, MA, US; Fuyang, China	PEMFC	8
Plug Power	Latham, NY, US	Rochester, NY, US	PEMFC, MEA[5]	9
POCO Materials (subsidiary of Entegris)	Billerica, MA, US	Decatur, TX, US; Russellville, AR, US	BPP	10
Proton Motor Fuel Cell[3,4]	Puchheim, Germany	Nuremburg, Germany	PEMFC	29, 42
Renewable Innovations[5]	Salt Lake City, UT, US	Salt Lake City, UT, US	PEMFC	104
SGL	Wiesbaden, Germany	Germany	BPP, GDL	132
Shanghai Hongfeng Industrial[3]	Shanghai, China	China	BPP	12, 94
Solvay[4]	Brussels, Belgium	West Deptford NJ, US; Italy	Membrane, Ionomer	75, 76

Company[1]	Headquarters	Manufacturing Location(s)[2]	Product(s)	Additional source(s)[1]
Symbio[4]	Lyon, France	France	PEMFC	28
TANAKA[4]	Tokyo, Japan	Kanagawa, Japan	Catalyst	77, 78, 79
Toray	Tokyo, Japan	Japan, France, US, Korea	GDL	113, 114
Toshiba Energy Systems	Kanagawa, Japan	Kawasaki, Japan	PEMFC	11, 118
Umicore	Brussels, Belgium	China, US, Germany, Denmark and Korea	Catalyst	87
W. L. Gore	Newark, DE, US	Newark, DE, US; Germany, UK, Japan and China	Membrane	73, 133

[1] *Included companies were mentioned by at least three market reports and BNEF except where noted (sources 45–70). Additional sources were used when location and technology information was unavailable from market reports and BNEF.*

[2] *Manufacturing locations are specifically for fuel cell components and may not be a complete list for a given company.*

[3] *Company was not mentioned in BNEF regarding fuel cells.*

[4] *Company was not mentioned by market reports but is believed to be a significant manufacturer of fuel cells.*

[5] *Component is produced for use in company end-products but is not sold directly.*

Table B-3. Selected Manufacturing Capacities and Upcoming Developments for PEMEC, Alkaline Electrolyzer, and PEMFC Manufacturers

	Company	Manufacturing		Upcoming developments	Source(s)
		Location	*Capacity*		
Electrolyzers	Plug Power	Rochester, NY, US	500 MW/yr		9
	Nel ASA	Herøya/Notodden, Norway	500 MW/yr	Room to expand Herøya to capacity of 2 GW/yr	19
		Wallingford, CT	50+ MW/yr		
	Cummins	Ontario	Unavailable	Planning to build a PEM electrolyzer manufacturing facility in Guadalajara, Spain, in 2023 with capacity of 0.5–1.0 GW/yr	30
		San Miniato, Italy	300 MW/yr		13

	Company	Manufacturing		Upcoming developments	Source(s)
		Location	*Capacity*		
	McPhy (alkaline)	Wildau, Germany	Unavailable		
	Elogen	Les Ulis, France	160 stacks/yr (40 electrolyzers/ yr)		14
	Next Hydrogen	Mississauga, Ontario, Canada	20 MW/yr		20
	Green Hydrogen	Kolding, Denmark	75 MW/yr	Planning to scale to 400 MW/yr in 2023, with ability for eventual expansion to 1 GW/yr	34
	Cockerill Jingli Hydrogen (alkaline)	Suzhou, China	350 MW/yr	Planning to scale up to 500 MW/yr	37
	ITM	UK	GW scale		40
Fuel Cells	Plug Power	Rochester, NY, US	60,000 stacks/yr 7 million MEAs/yr		9
	Doosan[1] (phosphoric acid fuel cell)	Iskan, South Korea	63 MW/yr (144 units/yr)	Increase Iksan plant capacity to 275 MW/yr by 2022; Commercialize PEMEC/PEMFC technology 2023–2025	23, 24
		South Windsor, CT, US	Unavailable		
	Ballard	Burnaby, British Columbia, Canada	10,000 stacks/yr 1 million MEAs/yr	Expand MEA production in Burnaby to 6+ million/yr	1, 25, 26
		Hobro, Denmark	40 MW/yr		

	Company	Manufacturing		Upcoming developments	Source(s)
		Location	*Capacity*		
	Nuvera	Fuyang, China	5,000 stacks/yr		8
	Cummins	Herten, Germany	10 MW/yr		27
	Symbio	Lyon, France	Unavailable	Opening Lyon factory in 2023 with plans to scale to 200,000 stacks/yr by 2030	28
	Proton Motor Fuel Cell	Nuremburg, Germany	10,000 stacks/yr	Nuremberg facility could be scaled up to 30,000–50,000 stacks/yr	29
	Greenerity	Alzenau, Germany	Unavailable	Eventual capacity at Alzenau of 10 million MEAs/yr	44
	Horizon Fuel Cell	Rugao, China	30 MW/yr		86

[1] *Doosan Fuel Cells currently manufacturers phosphoric acid fuel cells (PAFCs) and thus is not included in Table B-2. However, it is included here due to upcoming plans in PEMEC/PEMFC technology.*

Sources Used for Information on PEMEC and PEMFC Manufacturers

The following websites, press releases, company reports, and other sources were used to compile the information above in Tables B-1 through B-3. All web pages were accessed November 5, 2021, unless otherwise noted.

1. "Ballard in Europe." Ballard. n.d. https://www.ballard.com/about-ballard/ballard-in-europe
2. FuelCellsWorks. "Cell Impact Opens New Karlskoga Factory for Production of Flow Plates." FuelCellsWorks. October 13, 2020. https://fuelcellsworks.com/news/cell-impact-opens-new-karlskoga-factory-for-production-of-flow-plates/
3. "Fuel cells. Highly efficient, environmentally compatible, future-proof." ElringKlinger. n.d. https://www.elringklinger.de/en/products-technologies/electromobility/fuel-cells
4. "Global." Greenerity. n.d. https://www.greenerity.com/about/global/
5. "Cummins closes on its acquisition of Hydrogenics." Cummins. September 9, 2019. Columbus, IN. https://www.cummins.com/news/releases/2019/09/09/cummins-closes-its-acquisition-hydrogenics
6. "About Hyplat." HyPlat. n.d. http://www.hyplat.com/about-us/#our-facilities
7. "What we do." IRD Fuel Cells. n.d. https://irdfuelcells.com/products/
8. "Nuvera Breaks Ground on Automated Fuel Cell Production Facility in China." Nuvera. December 18, 2019. Billerica, MA. https://www.nuvera.com/blog/nuvera-breaks-ground-on-automated-fuel-cell-production-facility-in-china

9. "Plug Power announces selection of Rochester to host Plug Power Innovation Center." Plug Power. January 19, 2021. Latham, NY. https://www.ir.plugpower.com/Press-Releases/Press-Release-Details/2021/Plug-Power-Announces-Selection-of-Rochester-to-Host-Plug-Power-Innovation-Center/default.aspx
10. "Locations." Entegris (Poco Materials). n.d. https://poco.entegris.com/en/home/about-us/locations.html
11. "Toshiba 100 kW fuel cell will use hydrogen from plastics recycling [abstract]." 2017. *Fuel Cells Bulletin* 2017 (6): 7. https://doi.org/10.1016/S1464-2859(17)30222-5.
12. "About Hong Feng." Shanghai Hongfeng Industrial Co., Ltd. n.d. http://www.shf.net.cn/en-list-536.html
13. "Elogen, a GTT Company." Elogen. n.d. https://elogenh2.com/en/discover-elogen/gtt-group/
14. "Our Facilities." Elogen. n.d. https://elogenh2.com/en/discover-elogen/our-locations/
15. "Electrolysis." Cummins. n.d. https://www.cummins.com/new-power/applications/about-hydrogen/electrolysis
16. "On Site Gas Generators." ErreDue. n.d. https://www.erreduegas.it/wp-content/uploads/company_profile_ENG_LOW.pdf
17. "Company." Idroenergy. n.d. https://idroenergy.it/azienda/?lang=en
18. "Facilities." McPhy. n.d. https://mcphy.com/en/mcphy/facilities/
19. Jon André Løkke. "Q2 2021." Nel. August 19, 2021. https://nelhydrogen.com/wp-content/uploads/2021/08/Nel-ASA-Q2-2021-Results-presentation.pdf
20. "Next Hydrogen Announces Expansion into New Assembly Facility." Next Hydrogen. September 20, 2021. Mississauga, Ontario. https://nexthydrogen.com/news-release/next-hydrogen-announces-expansion-into-new-assembly-facility/
21. "Siemens Energy: Company presentation." Siemens Energy. November 2020. https://assets.siemens-energy.com/siemens/assets/api/uuid:fc59adb3-bc23-4642-a227-d5d30f7e4c4e/company-presentation-siemens-energy-en.pdf
22. "About Us." Cockerill Jingli Hydrogen. n.d. https://www.jinglihydrogen.com/about-us
23. "Doosan Corporation Completes Construction of Korea's Largest Fuel Cell Production Facility." Doosan. May 23, 2017. https://www.doosan.com/en/media-center/press-release_view/?id=43978&page=8&
24. "Doosan Fuel Cell Q2 2021 Earnings Release." Doosan. July 2021. https://www.doosanfuelcell.com/en/ir/inve-0101/
25. "Competitive Advantage." Ballard. n.d. https://www.ballard.com/fuel-cell-solutions/competitive-advantage
26. "Ballard Power Systems Inc. Management's Discussion and Analysis: Second Quarter and Year to Date 2021." Ballard. n.d. https://www.ballard.com/docs/default-source/financial-reports/2021/2021-mda-q2-final.pdf?sfvrsn=1511df80_4
27. Cummins, Inc., Global Power Leader. "Cummins breaks ground at new fuel cell systems production facility in Germany." Cummins. April 8, 2021. https://www.cummins.com/news/2021/04/08/cummins-breaks-ground-new-fuel-cell-systems-production-facility-germany
28. FuelCellsWorks. "Symbio CEO Confirms Lyon Site for its Hydrogen Fuel Cell Plant." FuelCellsWorks. January 28, 2021. https://fuelcellsworks.com/news/symbio-ceo-confirms-lyon-site-for-its-hydrogen-fuel-cell-plant/
29. Dolan, Connor, Jennifer Gangi, Quailan Homann, Victoria Fink, and John Kopasz. 2020. "2019 Fuel Cell Technologies Market Report." ANL-20/58. Argonne National Laboratory (ANL), Argonne, IL (United States). https://doi.org/10.2172/1814929.
30. "Cummins selects Spain for its gigawatt electrolyzer plant and partners with Iberdrola to lead the green hydrogen value chain." Cummins. May 24, 2021. Columbus, In. https://www.cummins.com/news/releases/2021/05/24/cummins-selects-spain-its-gigawatt-electrolyzer-plant-partners-iberdrola
31. "Johnson Matthey announces manufacturing capacity for key components in Green Hydrogen." Johnson Matthey. January 20, 2021. https://matthey.com/en/news/2021/johnson-matthey-announces-manufacturing-capacity-for-key-components-in-green-hydrogen
32. "Advanced materials for fuel cell electric vehicle (FCEV) applications." 3M. n.d. https://www.3m.com/3M/en_US/oem-tier-us/applications/propulsion/fuel-cell/
33. "About Us." Green Hydrogen Systems. n.d. https://greenhydrogen.dk/about-us/
34. "Launch of the next expansion phase." Green Hydrogen Systems. July 22, 2021. Kolding, Denmark. https://greenhydrogen.dk/launch-of-the-next-expansion-phase/

35. "Home." Green Hydrogen Systems. n.d. https://greenhydrogen.dk/
36. "HyProvide P-Series." Green Hydrogen. n.d. https://greenhydrogen.dk/wp-content/uploads/2019/11/HyProvideTM-P-Series.pdf
37. "Cockerill Jingli Hydrogen, world leader in hydrogen, inaugurates its new production center at Suzhou (China)." November 22, 2019. https://johncockerill.com/en/press-and-news/news/cockerill-jingli-hydrogen-world-leader-in-hydrogen-inaugurates-its-new-production-center-at-suzhou-china/
38. Yu, Yuki. "China's Electrolysis Market: Would it Repeat Solar' [*sic*] Success Story?" *Energy Iceberg*. September 22, 2021. https://energyiceberg.com/china-electrolysis-market/
39. "Contact Us." Longi. n.d. https://en.longi-solar.com/home/contact/index.html
40. "Green Hydrogen for Humberside Project Deployment Study," ITM Power, April 16, 2020. https://www.itm-power.com/news/green-hydrogen-for-humberside-project-deployment-study. Accessed December 9, 2021.
41. "Map & Access." Nisshinbo Chemical Inc. n.d. https://www.nisshinbo-chem.co.jp/english/profile/map.html#topic05. Accessed December 9, 2021.
42. "Our Contact." Proton Motor Fuel Cells GmbH. n.d. https://www.proton-motor.de/en/contact/
43. Tengler, Martin. "2H 2021 Hydrogen Market Outlook." Bloomberg New Energy Finance, August 5, 2021.
44. "Toray German Subsidiary to Construct Second Plant for key components for Hydrogen Fuel Cells and Water Electrolyzers." Toray. March 3, 2020. Tokyo, Japan. https://cs2.toray.co.jp/news/toray/en/newsrrs02.nsf/0/5C59E13B12C2B4E84925851F002BDF04
45. BloombergNEF. "Organisations." Bloomberg New Energy Finance, October 2021.
46. "Global Hydrogen Fuel Cell Bipolar Plate Market Research Report 2020." Valuates Reports. January 2020. https://reports.valuates.com/market-reports/QYRE-Auto-13M867/global-hydrogen-fuel-cell-bipolar-plate
47. "Global Hydrogen Fuel Cell Catalyst Market Research Report 2020." Valuates Reports. January 2020. https://reports.valuates.com/market-reports/QYRE-Auto-28N638/global-hydrogen-fuel-cell-catalyst
48. "Global Hydrogen Fuel Cell Gas Diffusion Layer Market Size, Manufacturers, Supply Chain, Sales Channel and Clients, 2021-2027." Valuates Reports. August 2021. https://reports.valuates.com/market-reports/QYRE-Othe-1N410/global-hydrogen-fuel-cell-gas-diffusion-layer
49. "Global Hydrogen Fuel Cell Proton Exchange Membrane Market Research Report 2020." Valuates Reports. January 2020. https://reports.valuates.com/market-reports/QYRE-Auto-9M978/global-hydrogen-fuel-cell-proton-exchange-membrane
50. "Hydrogen Fuel Cells Market Size, Share, and Trends Analysis Report By Type, By Application, and Segment Forecasts, 2021-2027." Valuates Reports. September 2021. https://reports.valuates.com/market-reports/QYRE-Auto-26E44/global-hydrogen-fuel-cells
51. "Fuel Cell Market Size & Share, Industry Report, 2021-2028." Grand View Research. May 2021. https://www.grandviewresearch.com/industry-analysis/fuel-cell-market
52. "Fuel Cell Market Size & Share, Industry Report, 2021-2028." Fortune Business Insights. March 2021. https://www.fortunebusinessinsights.com/industry-reports/proton-exchange-membrane-fuel-cell-pemfc-market-101708
53. "Global and Japan Bipolar Plates for PEM Fuel Cells Market Insights, Forecast to 2027." Industry Research. July 8, 2021. https://www.industryresearch.co/global-and-japan-bipolar-plates-for-pem-fuel-cells-market-18718138
54. "Fuel Cell Bipolar Plate Market." Transparency Market Research. February 4, 2021. https://www.transparencymarketresearch.com/fuel-cell-bipolar-plate-market.html
55. "Global Fuel Cell Bipolar Plates Market Development Strategy Pre and Post COVID-19, By Corporate Strategy Analysis, Landscape, Type Application, and Leading 20 Countries." 360 Research Reports. July 1, 2021. https://www.360researchreports.com/global-fuel-cell-bipolar-plates-market-18675998
56. "Global Fuel Cell Catalyst Market Report." Cognitive Market Research. September 2021. https://www.cognitivemarketresearch.com/fuel-cell-catalyst-market-report

57. “Fuel Cell Catalyst Market Size, Share and Global Trend by Type (Platinum, Platinum Ruthenium Alloy, Other) By Application (Methanol Fuel Cell Catalyst, Hydrogen Fuel Cell Catalyst, Reformate Fuel Cell Catalyst, Others) and Geography Forecast till 2021-2028.” Fortune Business Insights. n.d. https://www.fortunebusinessinsights.com/industry-reports/fuel-cell-catalyst-market-101335
58. “Fuel Cells Market by Type (Proton Exchange Membrane Fuel Cell, Phosphoric Acid Fuel Cell, Alkaline Fuel Cell, microbial Fuel Cell), Application (Transport, Stationary, Portable), End-User, Region – Global Forecast to 2025.” Markets and Markets. December 2020. https://www.marketsandmarkets.com/Market-Reports/fuel-cell-market-348.html
59. “Fuel Cell Gas Diffusion Layer Market Size, Share and Global Trend by Product Type (Carbon Paper, Carbon Cloth, Others), by Application (Polymer Electrolyte Fuel Cell, Direct Methanol Fuel Cell, others) and Geography Forecast til 2021-2028.” Fortune Business Insights. n.d. https://www.fortunebusinessinsights.com/industry-reports/fuel-cell-gas-diffusion-layer-market-101333
60. “Fuel Cell Gas Diffusion Layer Market – Global Industry Analysis, Size, Share, Growth, Trends, and Forecast 2019-2027.” Transparency Market Research. n.d. https://www.transparencymarketresearch.com/fuel-cell-gas-diffusion-layer-market.html
61. “Membrane Electrode Assemblies Market by Type (3-Layer Membrane Electrode Assemblies, 5-Layer Electrode Assemblies, and Others) and Application (Electrolyzers, Polymer Electrolyte Fuel Cells, Hydrogen/Oxygen Air Fuel Cells, Direct Methanol Fuel Cells, and Others) – Global Opportunity Analysis and Industry Forecast, 2021-2028.” Allied Market Research. n.d. https://www.alliedmarketresearch.com/membrane-electrode-assemblies-market
62. “Membrane Electrode Assemblies Market – Global Industry Analysis, Size, Share, Growth, Trends, and Forecast 2018-2026.” Transparency Market Research. n.d. https://www.transparencymarketresearch.com/membrane-electrode-assemblies-market.html
63. “Global Membrane Electrode Assemblies Market 2019 by Manufacturers, Regions, Type and Application, Forecast to 2024.” 360 Research Reports. February 6, 2019. https://www.360researchreports.com/global-membrane-electrode-assemblies-market-13836807
64. “Membrane Electrode Assemblies MEA Market Size, Share, and Global Trend by Type (3 Layer Membrane, 5 Layer Membrane, Others), by Application (Hydrogen Fuel Cell, Direct Methanol Fuel Cell, Electrolyser, Polymer Electrolyte Fuel Cell, Others) and Geography Forecast till 2021-2028.” Fortune Business Insights. n.d. https://www.fortunebusinessinsights.com/industry-reports/membrane-electrode-assemblies-mea-market-101346
65. “Polymer Electrolyte Membrane Fuel Cells (PEMFCs) Market – Growth, Trends, COVID-19 Impact, and Forecasts (2021-2026).” Mordor Intelligence. n.d. https://www.mordorintelligence.com/industry-reports/global-polymer-electrolyte-membrane-pem-fuel-cells-market-industry
66. “PEM Fuel Cell Materials Market.” Transparency Market Research. January 22, 2021. https://www.transparencymarketresearch.com/pem-fuel-cells-materials.html
67. “Global and United States PEM Water Electrolyzer Market Insights, Forecast to 2027.” Industry Research. July 13, 2021. https://www.industryresearch.biz/global-and-united-states-pem-water-electrolyzer-market-18732582
68. “Electrolyzer Market Size, by Product (Alkaline Electrolyzer, PEM Electrolyzer, Solid Oxide Electroluzer), by Process (≤500kW, . 500 kw-2MW, Above 2MW), by Application (Power Generation, Transportation, Industry Energy, Industry Feedstock, Building Heating & Power), Industry Analysis Report, Regional Outlook (U.S., Canada, Germany, UK, France, Italy, Netherlands, Denmark, Spain, Norway, China, Japan, Australia), Application Potential, Competitive Market Share & Forecast, 2021-2030 .” Global Market Insights. August 2021. https://www.gminsights.com/industry-analysis/electrolyzer-market
69. “Electrolyzer Market Size, Share & COVID-19 Impact Analysis, by Type (Traditional Alkaline Electrolyzer and PEM Electrolyzer), by Application (Power Plants, Steel Plant, Electronics & Photovoltaics, Industrial Gases, Energy Storage or Fueling for FCEV, Power to Gas, Others) and Regional Forecast, 2020-2027.” Fortune Business Insights. February 2021. https://www.fortunebusinessinsights.com/electrolyzer-market-103919
70. “Electrolyzer Market by Product (Alkaline Electrolyzer, PEM Electrolyzer, and Solid Oxide Electrolyzer), Capacity (Less Than 500 Kw, 500 Kw to 2 MW, and Above 2 MW) and Application (Power Generation, Transportation, Industry Energy, Industry Feedstock, Building Heat & Power, and Others): Global Opportunity Analysis and Industry Forecast 2020=2027.” Allied Market Research. March 2021. https://www.alliedmarketresearch.com/electrolyzer-market-A10609

71. "DuPont, Corteva, and Chemours announce resolution of legacy PFAS claims." DuPont. January 22, 2021. Wilmington, Delaware. https://www.dupont.com/news/dupont-corteva-chemours-announce-resolution-legacy-pfas-claims.html
72. "Contact Chemours." Chemours. n.d. https://www.chemours.com/en/contact
73. "GORE Fuel Cell Technologies." GORE. n.d. https://www.gore.com/fuelcells
74. Personal communication with the Hydrogen and Fuel Cell Technologies Office (U.S. Department of Energy). November 10 and 15, 2021.
75. "Fuel Cell Stack." Solvay. n.d. https://www.solvay.com/en/chemical-categories/specialty-polymers/batteries/fuel-cell-stack
76. "Solvay in Belgium." Solvay. n.d. https://www.solvay.com/en/solvay-around-the-world/belgium
77. "PEFCs Electrode Catalyst." TANAKA. n.d. https://tanaka-preciousmetals.com/en/products/detail/PEFCs/?nav=use
78. "About TANAKA Precious Metals." TANAKA. n.d. https://tanaka-preciousmetals.com/en/corporate/outline/
79. "TANAKA Expands FC Catalyst Production Capacity." TANAKA. July 10, 2018. https://www.tanaka.co.jp/english/topics/fout.html?f=39#:~:text=%E2%96%A0TANAKA's%20Fuel%20Cell%20Electrode,membrane%20fuel%20cells%20(PEFC).
80. "Electrocatalysts for PEM Fuel Cells." Heraeus. n.d. https://www.hannovermesse.de/apollo/hannover_messe_2021/obs/Binary/A1089488/Broschuere_FC_8pages_EN_update%20Feb_26.pdf. Accessed December 9, 2021.
81. "Hydrogen Systems – catalyzing the hydrogen revolution." Haraeus. n.d. https://www.heraeus.com/en/hch/products_and_solutions_chemicals/hydrogen_systems/overview_hydrogen_systems/hydrogen_systems.html. Accessed December 6, 2021.
82. "About Haraeus." Haraeus. n.d. https://www.heraeus.com/en/hpm/about_hpm/about_heraeus_at_a_glance_hpm/about_heraeus_hpm.html. Accessed December 6, 2021.
83. "About Ion Power." Ion Power. n.d. https://ion-power.com/about/. Accessed December 6, 2021.
84. "ISO Certification Announcement." Ion Power. January 25, 2021. https://ion-power.com/iso-certification-announcement/. Accessed December 6, 2021.
85. "HT-PEM MEAs." Advent. n.d. https://www.advent.energy/products-high-temperature-meas/. Accessed December 6, 2021.
86. FuelCellsWorks. "Horizon Fuel Cell Enters US market for Material Handling." FuelCellsWorks. February 26, 2019. https://fuelcellsworks.com/news/horizon-fuel-cell-enters-us-market-for-material-handling/. Accessed December 6, 2021.
87. "Umicore: Fuel Cell & Stationary Catalysts aim to contribute to a better future and to green transition by supplying catalysts for clean mobility in order to improve air quality and reduce CO2 footprint." Umicore. n.d. https://fcs.umicore.com/. Accessed December 6, 2021.
88. "Element Analyzers," Angstrom Advanced. n.d. https://www.angstrom-advanced.com/pro6-HGbyWE.html, Accessed December 7, 2021
89. "Contact Us," Ohmium, n.d. https://ohmium.com/contact. Accessed December 7, 2021
90. "Technology," Ohmium, n.d. https://ohmium.com/technology, Accessed December 7, 2021
91. "Introduction to GTA Technology." GTA, Inc. n.d. https://www.gtah2.com. Accessed December 7, 2021.
92. "Pochari Technologies." Pochari Technologies, n.d. https://pocharitechnologies.com/home/. Accessed January 14, 2022.
93. "Electric Hydrogen Partnership Hopes To Repeat Success With Renewable Hydrogen Technology." NREL, October 8, 2021. https://www.nrel.gov/news/features/2021/electric-hydrogen-partnership-hopes-to-repeat-success-with-renewable-hydrogen-technology.html. Accessed December 7, 2021.
94. "U.S. Customs Records for Shanghai Hongfeng Industrial Co." Import Genius. n.d. https://www.importgenius.com/suppliers/shanghai-hongfeng-industrial-co. Accessed December 9, 2021.
95. "Millennium Reign Energy Impact Profile." Boundless Impact Investing. April 2019. https://residentialhydrogenpower.com/wp-content/uploads/2019/08/MRE-Climate-Impact-Profile-Summary-05.06.19.pdf. Accessed December 9, 2021.

96. “Company information.” Bosch. n.d. https://www.bosch-mobility-solutions.com/en/about-us/company-information/. Accessed December 7, 2021.
97. “Fuel-cell stacks: the recipe for success in mass manufacturing.” Bosch. n.d. https://www.bosch.com/stories/fuel-cell-stack/. Accessed December 7, 2021.
98. “Why PowerCell Sweden technology?” PowerCell. n.d. https://powercell.se/en/why-powercell-technology. Accessed December 7, 2021.
99. “Contact use [*sic*].” PowerCell. n.d. https://powercell.se/en/contact. Accessed December 7, 2021
100. “History and Vision.” Altergy. n.d. https://www.altergy.com/about-us/history-vision/. Accessed December 7, 2021.
101. “Contact Us.” Altergy. n.d. https://www.altergy.com/contact-us/. Accessed December 7, 2021.
102. “Hyzon Motors to Build United States’ Largest Fuel Cell Material Production Facility.” Hyzon Motors. March 1, 2021. https://hyzonmotors.com/largest-fuel-cme-production-facility/. Accessed December 7, 2021.
103. “Hypoint.” Hypoint. n.d. https://hypoint.com/. Accessed January 14, 2022.
104. “About Renewable Innovations.” Renewable Innovations. n.d. https://www.renewable-innovations.com/aboutrenewableinnovations. Accessed December 7, 2021.
105. “Process Equipment.” Kobelco Eco-Solutions Co., Ltd. n.d. https://www.kobelco-eco.co.jp/english/company/pdf/products&services15-16.pdf. Accessed December 8, 2021.
106. “3M Menomonie Plant.” 3M. n.d. https://www.3m.com/3M/en_US/plant-locations-us/menomonie/. Accessed December 8, 2021.
107. “3M Cottage grove Plant.” 3M. n.d. https://www.3m.com/3M/en_US/plant-locations-us/cottagegrove/. Accessed December 8, 2021.
108. “3M New Ulm Plant.” 3M. n.d. https://www.3m.com/3M/en_US/plant-locations-us/new-ulm/. Accessed December 8, 2021.
109. “Fayetteville Works.” Chemours. n.d. https://www.chemours.com/en/about-chemours/global-reach/fayetteville-works. Accessed December 8, 2021.
110. “New joint fuel cell development will extend flight times for surveillance drones.” Intelligent Energy. September 14, 2021. Loughborough, UK. https://www.intelligent-energy.com/news-and-events/company-news/2021/09/14/new-joint-fuel-cell-development-will-extend-flight-times-for-surveillance-drones/. Accessed December 8, 2021.
111. “About.” IRD Fuel Cells. n.d. https://irdfuelcells.com/about/. Accessed December 8, 2021.
112. “Partners.” Grasshopper. n.d. https://www.grasshopperproject.eu/partners-4/. Accessed December 8, 2021.
113. “Production Capacity.” Toray. n.d. https://www.toray.com/global/ir/management/man_010.html. Accessed December 8, 2021.
114. “Gas Diffusion Layers (GDL).” Toray. n.d. https://www.cf-composites.toray/products/electrode/gdl.html. Accessed December 8, 2021.
115. “MERCURY Hydrogen and Oxygen generators.” ErreDue. n.d. https://www.erreduegas.it/en/prodotti/mercury-hydrogen-and-oxygen-generators/. Accessed December 9, 2021.
116. “Globalization.” Longi. n.d. https://www.longi.com/us/global-distribution/. Accessed December 9, 2021.
117. “Location.” Teledyne Energy Systems. n.d. https://www.teledynees.com/contact-us/location. Accessed January 24, 2022.
118. FuelCellsWorks. “Toshiba to Relocate its Hydrogen Energy Product Site.” FuelCellsWorks. June 22, 2020. https://fuelcellsworks.com/news/toshiba-to-rrelocate-its-hydrogen-energy-product-site/. Accessed December 9, 2021.
119. Hydrogeit. “Bipolar Plates: the Backbone of Fuel Cell Stacks.” H2 International. September 3, 2018. https://www.h2-international.com/2018/09/03/bipolar-plates-the-backbone-of-fuel-cell-stacks/. Accessed December 9, 2021.
120. Freudenberg Group. “2020 Annual Report.” Freudenberg. n.d. https://www.freudenberg.com/fileadmin/downloads/english/FreudenbergGroup_AnnualReport2020.pdf. Accessed December 9, 2021.
121. “NEXT Advantages.” Next Hydrogen. n.d. https://nexthydrogen.com/next-advantages/. Accessed December 9, 2021.
122. “Lab Gas Generators,” Angstrom Advanced. n.d. https://www.angstrom-advanced.com/pro4-HGH10000.html. Accessed December 9, 2021.
123. “Introduction to Hydrogen Generating Plants.” Angstrom Advanced. n.d. https://www.angstrom-advanced.com/Res-HGP-HEP-9.html. Accessed December 9, 2021.
124. “Asahi Kasei Worldwide.” Asahi Kasei Corporation. n.d. https://www.asahi-kasei.com/company/facilities/#anc-03. Accessed December 9, 2021.

125. "Asahi Kasei's electrolysis system starts world's largest-scale hydrogen supply operation at the Fukushima Hydrogen Energy Research Field in Namie." Asahi Kasei Corporation. April 3, 2020. https://www.asahi-kasei.com/news/2020/ze200403.html. Accessed December 9, 2021.
126. Bertuccioli, Luca, Alvin Chan, David Hart, Fanz Lehner, Ben Madden, and Eleanor Standen. "Study on development of water electrolysis in the EU." Fuel Cells and Hydrogen Joint Undertaking. February 7, 2014. https://www.fch.europa.eu/sites/default/files/FCHJUElectrolysisStudy_FullReport%20(ID%20199214).pdf. Accessed January 14, 2022.
127. "Welcome to the Ludwigshafen site." BASF. n.d. https://www.basf.com/global/en/who-we-are/organization/locations/europe/german-sites/ludwigshafen.html. Accessed December 9, 2021.
128. "Proton-Conductive Membrane." BASF. n.d. https://www.basf.com/global/en/who-we-are/organization/group-companies/BASF_New-Business-GmbH/our-solutions/proton-conductive-membrane.html. Accessed December 9, 2021.
129. "Dettingen/Erms Plants." ElringKlinger. n.d. https://www.elringklinger.de/en/company/locations/dettingenerms-plants. Accessed December 9, 2021.
130. "Powering The Hydrogen Age." Horizon Fuel Cell Technologies. n.d. https://www.horizonfuelcell.com. Accessed December 9, 2021.
131. "Maritime and Ports." Nedstack. n.d. https://nedstack.com/en/application-support/maritime-ports. Accessed January 14, 2022.
132. "The Capacity Boosters." SGL Carbon. n.d. https://www.sglcarbon.cn/pdf/SGL-Brochure-SIGRACELL-The-Capacity-Boosters-EN.pdf. Accessed December 9, 2021.
133. "About GORE." GORE. n.d. https://www.gore.com/about. Accessed December 9, 2021.
134. "AvCarb Company Timeline." AvCarb. https://www.avcarb.com/timeline/. Accessed December 17, 2021.
135. Ibrahim, Samir and Michael Stichter. 2008. "Hydrogen Generation from Electrolysis – Revised Final Technical Report." United States. https://doi.org/10.2172/956328.

B-2. SOEC and SOFC Technology

Table B-4. Selected SOEC Companies' Manufacturing Capacity and Future Development Plan

Company	Manufacturing Locations	Capacity	Upcoming Developments	Source(s)
Bloom Energy	San Jose, CA, US	500MW	1GW within 1 year	1,2
FuelCell Energy	Danbury, CT, US	100 MW	200MW when second phase of expansion is done	5
Nexceris	Lewis Center, OH, US	Subsidiary company Fuelcellmaterials offers their own tailored powders SOEC Materials, SO Cell Stacks, catalysts to customer		6

Company	Manufacturing Locations	Capacity	Upcoming Developments	Source(s)
OxEon	Salt Lake Valley, UT, US	Various Testing project with external partners	Under development to commercialize	7
Sunfire	Germany, Norway, and Switzerland	Operated and tested 0.25MW	3MW electrolyzer in the scope of the EU-funded MultiPLHY Project	21
Haldor Topsoe	Denmark		Topsoe will invest in a manufacturing facility producing highly efficient solid oxide electrolyzers (SOEC) with a total capacity of 500 MW/yr with the option to expand to 5 GW/yr. The facility is expected to be operational by 2023.	22
H2E Power	India	Facility in Winterthur, Switzerland and Pune, India to produce 1.5kW, 4kW, 10kW and 50kW SOFC systems.		23

Table B-5. Selected SOFC Companies' Manufacturing Capacity and Future Development Plan

Company	Manufacturing Locations	Capacity	Upcoming Developments	Source(s)
Bloom Energy	San Jose, CA	132.6MW sales in 2020	Contracted additional 500 MW of power between 2022 and 2025 with Korea. Its Korean partner SK E&C are building factory in Gumi to manufacture 50 MW of Bloom's SOFC systems.	2,3,4
FuelCell Energy	Danbury, CT	100 MW	200MW when second phase of expansion is done.	5
Nexceris	Lewis Center, OH	Nexceris claims to have a strong distribution network to ensure global reach		6

Company	Manufacturing Locations	Capacity	Upcoming Developments	Source(s)
WATT Fuel Cell Corporation	Mount Pleasant, PA. Offices in Port Washington and the Hampton Bays, NY	Capacity to support high volume batch or continuous production		8
Cummins	Columbus, IN, US	Cummins signs long-term agreement to ensure highest supply chain performance when purchases externally. And designs and/or manufactures their strategic components in FC technology.		9,10
OxEon	Salt Lake Valley, UT,US	Various testing project with external partners	Under development to commercialize	7
Ceres Power	UK	Bosch and Ceres Power strengthen partnership to prepare for full-scale production. Ceres Power is also working with AVL (Austria) to further strengthen competencies for SOFC technology	Multiple sites in Germany are aiming to produce an initial aggregate 200MW capacity in 2024	11
Convion	Finland	Testing project with Lempäälän Energia's energy community	Under development to commercialize	12
Elcogen	Tallinn, Estonia (SO Cells); Vantaa, Finland (SO Stacks)	In the process of delivering mass produced SOFC and SOEC	Elcogen plans to expand its European cell manufacturing capacity to 50 MW by 2021/22.	13
SolidPower	Italy	In 2020, 16,000 BlueGen power plants came off the production line.	Over the next three years, 18.9 million euros will be invested into the expansion of the factories and modern production machinery.	14
Mitsubishi Power	Japan	Business alliance with NGK Spark Plug Co., Ltd. To mass produce cell stacks		15

Company	Manufacturing Locations	Capacity	Upcoming Developments	Source(s)
Aisin Seiki Co	Japan	In 2020, 47,000 units.		16
Kyocera	Japan	Demonstrated a tubular SOFC 250kW fuel cell also targeting power generation at the MW level	Double productivity by developing production technologies that make full use of AI, robots and IoT, Kyocera will expand these automation technologies and systems to each business in order to improve the productivity of the Group as a whole.	17,18
Posco Energy	South Korea	SOFC under development to commercialize		19
Doosan	South Korea	63MW	Doosan plans to invest 72.4 billion won to build SOFC cell stack manufacturing line and an SOFC system assembly line, Iksan plant will increase capacity to 260MW	20

Sources Used for Information on SOFC and SOEC Manufacturers

1. "Bloom Energy Unveils Electrolyzer to Supercharge the Path to Low-Cost, Net-Zero Hydrogen," Bloom Energy, July 14, 2021, https://www.bloomenergy.com/news/bloom-energy-unveils-electrolyzer/.
2. "SK E&C's New Gumi Fuel Cell Plant Opens," FuelCellsWorks, October 20, 2021, https://fuelcellsworks.com/news/sk-ecs-new-gumi-fuel-cell-plant-opens/
3. "Bloom Energy Announces Initial Strategy for Hydrogen Market Entry," Bloom Energy, July 15, 2020, https://www.bloomenergy.com/news/bloom-energy-announces-initial-strategy-for-hydrogen-market-entry/
4. "Bloom Energy and SK Ecoplant Expand Highly Successful Power Generation Partnership and Invest to Establish Market Leadership in the Hydrogen Economy," Businesswire, October 25, 2021, https://www.businesswire.com/news/home/20211025005311/en/Bloom-Energy-and-SK-ecoplant-Expand-Highly-Successful-Power-Generation-Partnership-and-Invest-to-Establish-Market-Leadership-in-the-Hydrogen-Economy
5. "Our Manufacturing Facilities and Processes," Fuel Cell Energy, n.d. https://www.fuelcellenergy.com/about-us-basic/manufacturing/
6. "Fuel Cell Materials," Nexceris, n.d. https://nexceris.com/solutions/fuel-cell-materials/
7. "Company Overview," OxEon Energy, n.d. https://oxeonenergy.com/overview
8. "About Us," WATT Fuel Cell Corporation, n.d. https://www.wattfuelcell.com/about-us/
9. "Annual Report Pursuant to Section 13 and 15(d)," Cummins, February 29,2021, https://investor.cummins.com/sec-filings/annual-reports
10. "Our Next Step Advancing Fuel Cell Technology," Cummins, July 29, 2021, https://www.cummins.com/news/2021/07/29/our-next-step-advancing-fuel-cell-technology
11. "Ceres Power Holdings plc: Bosch Collaboration with Ceres Progresses To Mass Production of SOFC Systems, with an Initial 200MW Capacity In 2024," PR Newswire, December 7, 2020, https://www.prnewswire.com/news-releases/ceres-power-holdings-plc-bosch-collaboration-with-ceres-progresses-to-mass-production-of-sofc-systems-with-an-initial-200mw-capacity-in-2024-301187095.html
12. "Convion's C60 Fuel Cell System Creates Clean Energy and Excellent Reliability for Smart Micro-grid in Lempäälä," Convion, October, 2021, https://convion.fi/convions-c60-fuel-cell-system-creates-clean-energy-and-excellent-reliability-for-smart-micro-grid-in-lempaala/
13. "Elcogen and Magnex Signed LOI of SOFC Commercialization," Elcogen, April 13, 2020, https://elcogen.com/elcogen-and-magnex-signed-loi-of-sofc-commercialization/
14. "Fuel cells: SolidPower Collects 40 Million Euro to Build a Factory," PV Europe, March 13, 2018, https://www.pveurope.eu/power-heat/fuel-cells-solidpower-collects-40-million-euro-build-factory
15. "NGK SPARK PLUG and Mitsubishi Hitachi Power Systems Conclude an Agreement for the establishment of a Joint Venture to Manufacture and Sell Fuel high-performance Cell Stacks," Mitsubishi Power, July 5, 2019, https://power.mhi.com/news/20190705_02.html
16. "The Fuel Cell Industry Review 2020," E4Tech, March 2021, www.FuelCellIndustryReview.com
17. "Annual Report," Kyocera, June 25, 2021, https://global.kyocera.com/ir/library/pdf/20-f/FY21_4Q_ar.pdf
18. "Global Deployment of Large Capacity Stationary Fuel Cells: Drivers of, and Barriers to, Stationary Fuel Cell Deployment," Publications Office of the European Union, Weidner, E. Ortiz Cebolla, R. Davies, J, 2019, ISBN 978- 92-76-00841-5, doi:10.2760/372263, JRC115923.
19. "Prepared Future," Posco Energy, n.d. https://eng.poscoenergy.com/eng/renew/_ui/down/Fuel_Cell_eng.pdf
20. "Doosan Fuelcell Is Developing a Korean Style Solid Oxide Fuel Cell (SOFC)," FuelCellsWorks, October 19, 2020, https://fuelcellsworks.com/news/doosan-fuelcell-is-developing-a-korean-style-solid-oxide-fuel-cell-sofc/
21. "Sunfire Successfully Tests the World's Largest High Temperature Electrolysis Module," FuelCellsWorks, May 5, 2021, https://fuelcellsworks.com/news/sunfire-successfully-tests-the-worlds-largest-high-temperature-electrolysis-module/
22. "Haldor Topsoe to Build Large Scale SOEC Electrolyzer Manufacturing Facility to Meet Customer Needs for Green Hydrogen Production," Ulrik Frøhlke, March 4, 2021, https://blog.topsoe.com/haldor-topsoe-to-build-large-scale-soec-electrolyzer-manufacturing-facility-to-meet-customer-needs-for-green-hydrogen-production
23. "Solid Oxide Fuel Cell," h2e Power, n.d. https://www.h2epower.net/solid-oxide-fuel-cell/

Appendix C: Applicable Existing U.S. Policies

Existing policies provided here are summaries of information available from the Database of State Incentives for Renewables (DSIRE) and an Alternative Fuels Data Center online database.

C-1. Federal Fuel Cell Investment Tax Credit

The federal fuel cell investment tax credit:

- Applies to new stationary fuel cells or material handling fuel cell equipment rated at 500 W or greater
- Requires the electricity generating efficiency to be greater than 30%
- Can be claimed for $3,000/kW or 30% of project cost, whichever is less
- Began to be phased out starting in 2020
- Is claimed by businesses through Internal Revenue Service Form 3468, Residential installations through Internal Revenue Service Form 5695

For additional information, see "Federal Tax Credits: Fuel Cells (Residential Fuel Cell and Microturbine System)," https://www.energystar.gov/about/federal_tax_credits/fuel_cells.

C-2. Stationary Fuel Cells

(information from Database of State Incentives for Renewables (DSIRE) database: https://www.dsireusa.org/)

At the state level, 46 of 50 states include stationary fuel cells in clean energy financial incentive programs or rules, regulations, and policies:

- 39 states and the District of Columbia include fuel cells in rules, regulations, and policies, such as Renewable Portfolio Standards, Public Benefits Fund, Net Metering, Interconnection, and Green Power Purchasing
- 34 states include fuel cells in financial incentive programs, such as tax incentives, grants, loans, rebates, performance-based incentives, feed-in tariffs, and renewable energy credits (RECs)
- 27 states include fuel cells in both financial incentives programs and rules, regulations, and policies.

Federal programs include tax credits and grants, loan guarantees or grants, and manufacturing assistance programs. Federal programs include:

- Business Energy Investment Tax Credit
- Residential Renewable Energy Tax Credit
- U.S. Department of Agriculture (USDA) Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program
- U.S. Department of Agriculture (USDA) Rural Energy for America Program (REAP) Loan Guarantees or Grants
- U.S. Department of Agriculture (USDA) Rural Energy for America Program (REAP) Energy Audit and Renewable Energy Development Assistance Program
- DOE Loan Guarantee Program.

C-3. Hydrogen Fuel or Fuel Cell Vehicles

(information from the Alternative Fuels Data Center database: https://afdc.energy.gov/)

At the state level, 29 of 50 states include hydrogen fuel or fuel cell vehicles in renewable energy incentive programs or rules, regulations, and policies:

- 21 states and the District of Columbia include hydrogen fuel or fuel cell vehicles in rules, regulations, and policies, such as renewable fuel standards or mandates; air quality or emissions Mandates; Climate Change or renewable energy initiatives
- 19 states and the District of Columbia include fuel cells in financial incentive programs, such as tax incentives or vehicle rebates
- 9 states and the District of Columbia include fuel cells in both incentives programs and rules, regulations, and policies.

Federal programs include tax credits for fuel cell vehicles, fuels, and fueling infrastructure and targeted collaborative grant programs that include alternative fuel vehicles, such as the U.S. Environmental Protection Agency Diesel Emissions Reduction Act and U.S. Department of Transportation Congestion Mitigation and Air Quality programs. Federal programs include:

- Alternative Fuel Excise Tax Credit
- Alternative Fuel Tax Exemption
- Alternative Fuel Infrastructure Tax Credit
- Clean Cities Coalition Network
- Clean Construction and Agriculture
- Clean School Bus
- Congestion Mitigation and Air Quality (CMAQ) Improvement Program
- Diesel Emissions Reduction Act
- Low or Zero Emission Ferry Program
- National Multimodal Cooperative Freight Research Program
- Port Infrastructure Development Program
- Ports Initiative
- Public School Energy Program
- State Carbon Reduction Program
- State Energy Program (SEP) Funding
- Voluntary Airport Low Emission (VALE) Program Alternative Fuel Excise Tax Credit.

Appendix D. Summary of Material Risks

Table D-1. Electrolyzer and Fuel Cell Evaluation Table

(prepared for DOE Office of Policy)

Supply Chain Element	Product/Components	Significant Domestic Suppliers	Significant Domestic Demand	Projected Significant Domestic Demand	Significant Global Market	Projected Significant Global Demand	Cost Competitive among U.S. Suppliers	Cost Competitive between U.S. Suppliers vs. Global Suppliers	Is foreign supply source significant secure?	Is there sufficient effort to address environmental concerns?	Is there sufficient effort to address human rights concerns?	Does it make sense to build a domestic capability for this product/ component?
Raw materials	PGM-containing ore	Yes	Yes	Maybe	Yes	Yes	Maybe	Yes	No	No	No	Maybe
	PGM concentrate	Maybe	Yes	Maybe	Yes	Yes	Maybe	Yes	Maybe	No	No	Maybe
	PGM (Pt) (catalyst)	No	Yes	Yes	Yes	Yes	n/a	n/a	Yes	Yes	Yes	Maybe
	Pt-based catalyst	No	Yes	Yes	Yes	Yes	No	Yes	Maybe	Yes	Maybe	Yes
	PGM (Ir) (catalyst)	No	No	Yes	No	Yes	n/a	n/a	Yes	Yes	Yes	Yes
	Ir	No	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes
	Graphite (BPP)	No	Yes	Yes	Yes	Yes	n/a	n/a	Maybe	Maybe	Unknown	Maybe
	Titanium (ore, metal TiCl)	No	Yes	Yes	Yes	Yes	n/a	n/a	Yes	Unknown	Unknown	
	Aluminum (housing)	Yes	Yes	No	Yes	Unknown	Yes	Yes	No	Unknown	Unknown	
	Chromium (SS)	No	Yes	No	Yes	No	n/a	n/a	Yes	Unknown	Unknown	
	Silicone Elastomer (Seal)	Unknown	Unknown	Unknown	Unknown	No	Unknown	Unknown	Unknown	Unknown	Unknown	
	Viton Elastomer (Seal)	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	

Supply Chain Element	Product/Components	Significant Domestic Suppliers	Significant Domestic Demand	Projected Significant Domestic Demand	Significant Global Market	Projected Significant Global Demand	Cost Competitive among U.S. Suppliers	Cost Competitive between U.S. Suppliers vs. Global Suppliers	Is foreign supply source significant secure?	Is there sufficient effort to address environmental concerns?	Is there sufficient effort to address human rights concerns?	Does it make sense to build a domestic capability for this product/ component?
	Ethylene Propylene Diene Monomer Elastomer (Seal)	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	
	Borosilicate glass (HT)	Unknown	No	Maybe	No	Maybe	Unknown	Unknown	Unknown	Unknown	Unknown	
	Lanthanum (HT)	No	No	Maybe	No	Maybe	n/a	n/a	No	Unknown	Unknown	
	Strontium (HT)	No	No	Maybe	No	Maybe	n/a	n/a	Yes	Unknown	Unknown	Yes
	Cobalt (HT)	No	Yes	Yes	Yes	Yes	n/a	n/a	Yes	Maybe	Maybe	
	Yttrium (HT)	No	No	Yes	No	Yes	n/a	n/a	No	Unknown	Unknown	
	Zirconium (HT)	Yes	No	Maybe	No	Maybe	Yes	Yes	Yes	Unknown	Unknown	
	Manganese (HT)	No	No	Maybe	No	Maybe	n/a	n/a	Maybe	Unknown	Unknown	
	Cerium (HT)	No	Unknown	Unknown	Unknown	Unknown	n/a	n/a	Maybe	Unknown	Unknown	
	Iron (HT)	Yes	Yes	Maybe	Yes	Maybe	Unknown	Unknown	Yes	Unknown	Unknown	
	Nickel (SS)	No	Yes	No	Yes	No	Unknown	Unknown	Yes	Yes	Unknown	
Processed material	Pt-based catalyst	No	Yes	Yes	Yes	Yes	No	Yes	Maybe	Yes	Maybe	Yes
	Ir-based catalyst	No	Yes	Yes	Yes	Yes	No	No	Maybe	Yes	Maybe	Yes
	Other PGM-based catalysts	Maybe	Yes	Yes	Yes	Maybe	Maybe	Maybe	Maybe	Yes	Maybe	Yes
	Perfluorosulfonic acid; PFSA (Nafion) (electrolyte)	Unknown	Yes	Yes	Yes	Yes	Unknown	Unknown	Unknown	Unknown	Unknown	

Supply Chain Element	Product/Components	Significant Domestic Suppliers	Significant Domestic Demand	Projected Significant Domestic Demand	Significant Global Market	Projected Significant Global Demand	Cost Competitive among U.S. Suppliers	Cost Competitive between U.S. Suppliers vs. Global Suppliers	Is foreign supply source significant secure?	Is there sufficient effort to address environmental concerns?	Is there sufficient effort to address human rights concerns?	Does it make sense to build a domestic capability for this product/ component?
	Sulfonated polyether ether ketone (s-PEEK) (alternative electrolyte)	Unknown	No	Maybe	No	Maybe	Unknown	Unknown	Unknown	Unknown	Unknown	
	Polystyrene sulfonic acid (PSSA) (alternative electrolyte)	Unknown	No	Maybe	No	Maybe	Unknown	Unknown	Unknown	Unknown	Unknown	
	Pt alloys (catalyst)	Unknown	No	Yes	Yes	Yes	Unknown	Unknown	Unknown	Unknown	Unknown	
	carbon metal oxide, carbides, etc.) (catalyst support)	Unknown	No	Yes	No	Yes	Unknown	Unknown	Unknown	Unknown	Unknown	
	PAN (polyacrylonitrile)-based carbon fiber (GDL)	Unknown	No	Yes	No	Yes	Unknown	Unknown	Unknown	Unknown	Unknown	
	Polytetraflouroethylene (PTFE) (CF GDL coating, membrane support)	Yes	No	No	Unknown	No	Unknown	Unknown	Unknown	Unknown	Unknown	Yes
	Stainless Steel (end plate)	Unknown	Yes	No	Yes	No	Unknown	Unknown	Unknown	Unknown	Unknown	
	Cathode Contact Layer (LSM)	No	No	Maybe	No	Maybe	n/a	n/a	Unknown	Unknown	Unknown	
	Cathode Current Collector (LSCF)	No	No	Yes	No	Yes	n/a	n/a	Unknown	Unknown	Unknown	

Supply Chain Element	Product/Components	Significant Domestic Suppliers	Significant Domestic Demand	Projected Significant Domestic Demand	Significant Global Market	Projected Significant Global Demand	Cost Competitive among U.S. Suppliers	Cost Competitive between U.S. Suppliers vs. Global Suppliers	Is foreign supply source significant secure?	Is there sufficient effort to address environmental concerns?	Is there sufficient effort to address human rights concerns?	Does it make sense to build a domestic capability for this product/ component?
	Cathode Active Layer (LSM-YSZ)	No	No	Maybe	No	Maybe	n/a	n/a	Unknown	Unknown	Unknown	
	Electrolyte (8YSZ)	No	No	Maybe	No	Maybe	n/a	n/a	Unknown	Unknown	Unknown	
	Anode Active Layer and Support (Ni-YSZ)	No	No	Yes	No	Yes	n/a	n/a	Unknown	Unknown	Unknown	
	Interconnect - Frame, Separator Plate, Anode and Cathode Flow Fields, End Plates (SS-441)	No	No	Yes	No	Yes	n/a	n/a	Unknown	Unknown	Unknown	
	Spacers (Borosilicate glass)	No	No	Maybe	No	Maybe	n/a	n/a	Unknown	Unknown	Unknown	
Subcomponents	Membrane Electrode Assembly	Unknown	No	Yes	No	Yes	Unknown	Unknown	Unknown	Unknown	Unknown	Yes- PEM
	Electrolyte Membrane	Yes (Support) No (Ionomer)	No	Yes	No	Yes	Unknown	Yes	Yes Maybe	Unknown	Unknown	Yes - PEM Support No (PEM ionomer)
	Supported Catalyst	Unknown	No	Yes	No	Yes	Unknown	Yes	Unknown	Unknown	Unknown	
	Gas Diffusion Layer	Unknown	No	Yes	No	Yes	Unknown	Maybe	Yes	Unknown	Unknown	Yes - PEM
	Bipolar Plates	Unknown	No	Yes	No	Yes	Unknown	Yes	Unknown	Unknown	Unknown	Yes - PEM

Supply Chain Element	Product/Components	Significant Domestic Suppliers	Significant Domestic Demand	Projected Significant Domestic Demand	Significant Global Market	Projected Significant Global Demand	Cost Competitive among U.S. Suppliers	Cost Competitive between U.S. Suppliers vs. Global Suppliers	Is foreign supply source significant secure?	Is there sufficient effort to address environmental concerns?	Is there sufficient effort to address human rights concerns?	Does it make sense to build a domestic capability for this product/ component?
	Solid Anode (Active + Support)	No	No	Yes	No	Yes	n/a	n/a	Yes	Unknown	Unknown	No
	Solid Electrolyte	No	No	Yes	No	Yes	n/a	n/a	Yes	Unknown	Unknown	No
	Solid Cathode (Active + Support)	No	No	Yes	No	Yes	n/a	n/a	Yes	Unknown	Unknown	No
	Cell Interconnects	No	No	Yes	No	Yes	n/a	n/a	Yes	Unknown	Unknown	No
End Product	PEM Fuel Cells and Electrolyzers	Yes	No	Yes	No	Yes	Unknown	Yes	Yes	Unknown	Unknown	Yes - PEM
	PEM Electrolyzers	Yes	No	Yes	Yes	Yes	Maybe	Yes	No	Yes	Maybe	Yes
	PEM FCs	Maybe	Maybe	Yes	Yes	Yes	No	Yes	Maybe	Yes	Maybe	Yes
	SOEC Electrolyzers	Yes	No	Yes	Yes	Yes	No	No	Maybe	Yes	Maybe	Maybe
	SOFCs	Maybe	Maybe	Yes	Yes	Yes	Maybe	Maybe	Maybe	Yes	Maybe	Yes
	Solid Oxide Fuel Cell and Electrolyzers	Yes	No	Yes	No	Yes	Unknown	Yes	Yes	Unknown	Unknown	Maybe

Color-coding: Yes = Green; No = Red; Maybe = Yellow; Unknown = Gray; n/a = White
Last column: Yes/Maybe = Blue; No = Dark Gray; All others are white.

U.S. DEPARTMENT OF ENERGY

For more information, visit:
energy.gov/policy/supplychains

DOE/OP-0006 ▪ February 2022