FuelCell Energy

WHITE PAPER

Reducing the cost of hydrogen production

Fundamentals of high-temperature, high-efficiency solid oxide electrolysis

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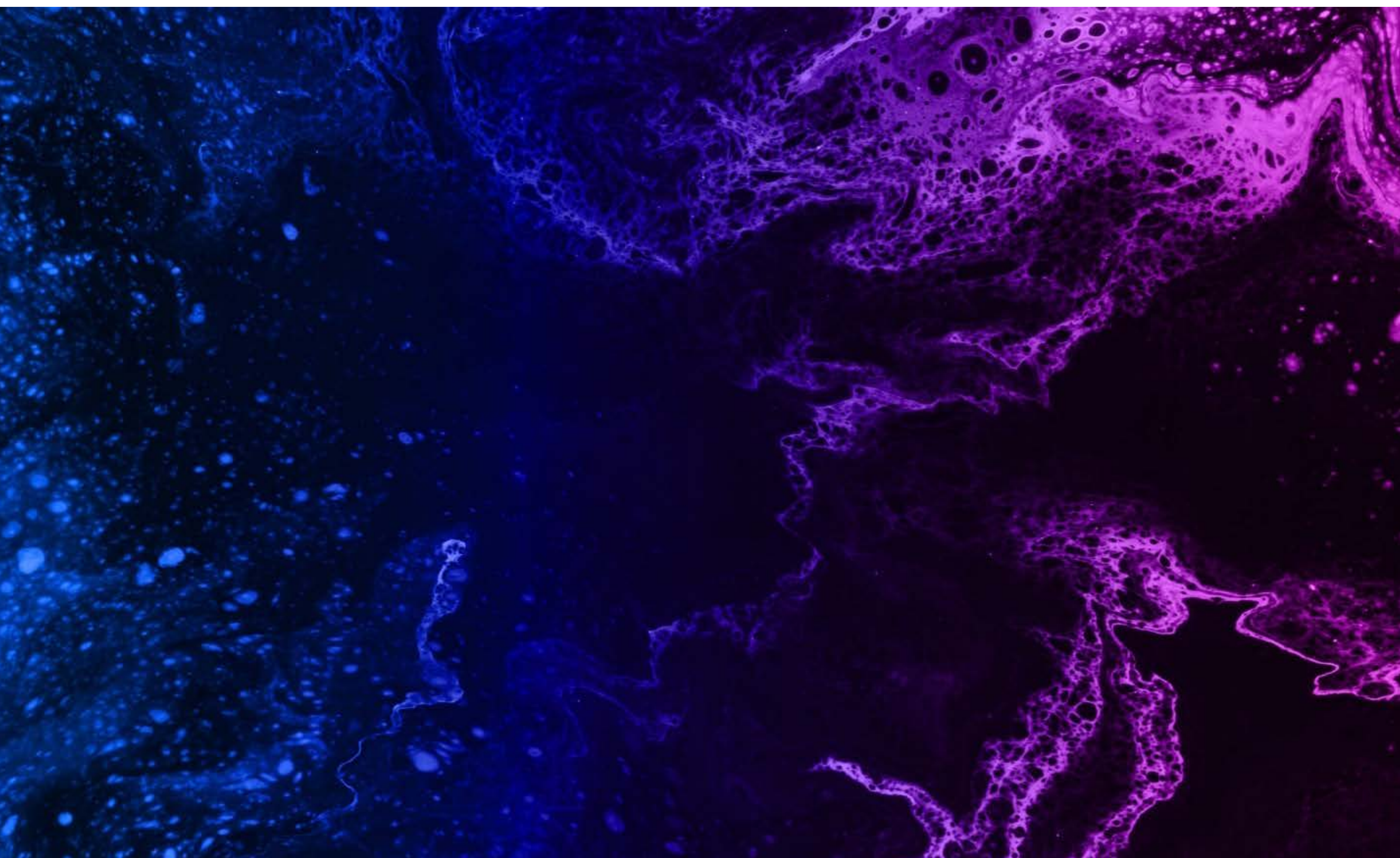

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Electrolysis Market and Survey of Technologies

Addressing the growing demand for megawatt-sized hydrogen production from solid oxide electrolysis

Deep decarbonization efforts will be necessary to achieve global climate change mitigation targets. Hydrogen and the hydrogen-based fuel cell industry will likely play a critical role, given their ability to partner with intermittent resources that are quickly coming online to serve the grid. Hydrogen platforms will also be central to enabling the energy transition – including renewable adoption, electrification, and the decarbonization of power in sectors like heavy industry and transportation. Sixty percent of Fortune 500 companies have set targets to reduce Scope 1 to Scope 3 greenhouse gas emissions[1]. Increased demand for clean energy technology and infrastructure is driving investment toward an energy landscape where hydrogen increasingly displaces traditional carbon-based fuels and serves as an affordable energy storage medium.

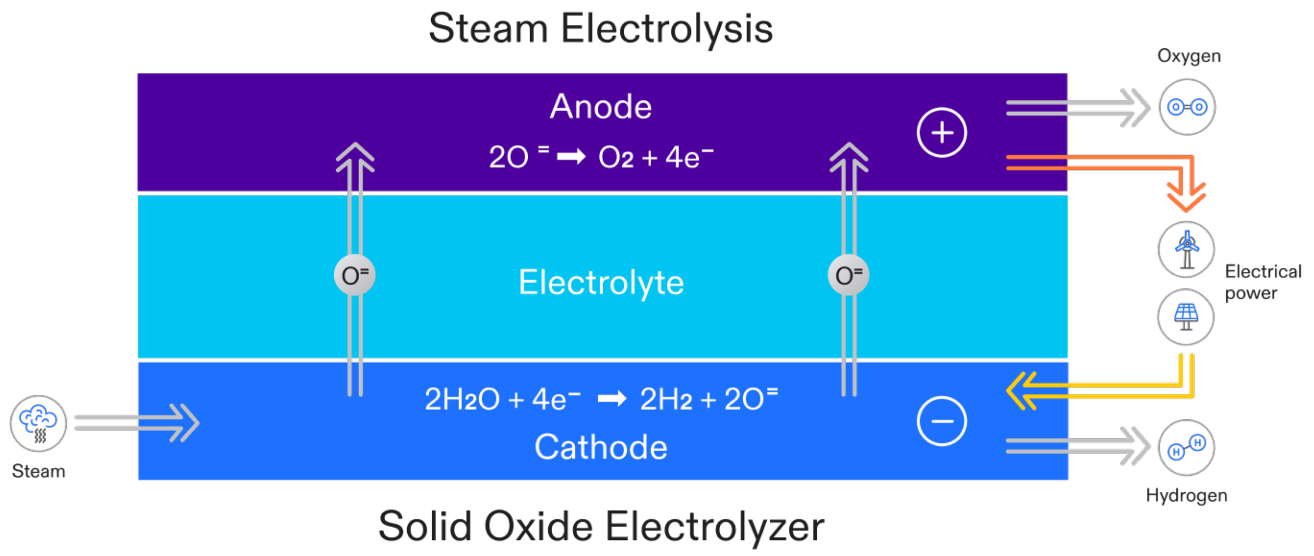
Today's common uses of hydrogen include power plant generator cooling, semiconductor fabrication, heat treating metals, fertilizer production, petroleum refining, and food production. Although hydrogen today is predominantly produced via steam methane reformation (SMR) using natural gas as a feedstock, there is growing demand for clean hydrogen produced with little to zero greenhouse gas emissions. Technologies exist today to support this need. Demand for hydrogen is expected to grow from ~90 million tonnes (Mt) per annum at the start of this decade to ~140 Mt by 2030 and ~385 Mt by 2040, according to Hydrogen Council estimates[2]. The portion of this production that is clean and carbon free is expected to rise from less than 1 percent today to ~50 percent and ~90 percent for those periods respectively. Electrolysis-based hydrogen production is capable of operating as clean as the energy used to power the process and is poised to meet this demand for clean hydrogen.

Electrolysis technologies today include alkaline water electrolysis (AWE), proton exchange membrane electrolysis (PEM), and solid oxide electrolyzer cell electrolysis (SOEC), among others in development. Solid oxide systems present one of the best opportunities to minimize the overall cost of hydrogen by offering the greatest known efficiency. Electric power is currently the highest variable cost in the production of hydrogen through electrolysis. By offering up to 100 percent electrical efficiency, solid oxide systems are expected to have one of the best chances of achieving the $1 USD per kg levelized cost of hydrogen targeted by the U.S. Department of Energy (DOE) by 2050.

Solid Oxide Technology Overview

How the technology works

In solid oxide electrolyzer cells, water in the form of steam is split into oxygen and hydrogen at the surface of a ceramic membrane. Oxygen ions removed from water molecules travel through the membrane and recombine as oxygen molecules on the other side. Hydrogen molecules don't enter the membrane and leave the cell as pure hydrogen.



Benefits of Solid Oxide

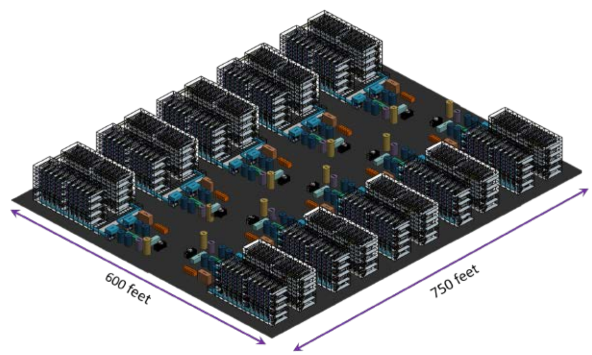
Efficiency

Solid oxide is among the most efficient commercially available electrolysis technologies. FuelCell Energy's SOEC plants have demonstrated about 90 percent efficiency (HHV) when operating solely on electricity, and are capable of 100 percent efficiency (HHV) when paired with available excess heat from industrial or nuclear facilities. This equates to 43.8 kWh/kg when only electricity is used and all the way down to 39.4 kWh/kg when additional heat input is used.

Scalability

Solid oxide's small footprint makes it easy to scale solutions to customer needs. Our 1 MW SOEC modules will fit within the footprint of two standard shipping containers and can be simply replicated for multi-megawatt installations. Future 100 MW or 1 GW installations will feature a centralized balance of plant to take advantage of economies of scale and further increase efficiencies.

1,000 MW Electrolysis
530,000 kg/day of hydrogen



Flexibility

SOEC systems have excellent load ramp design capabilities of 10 percent per minute, which will allow systems to go from hot standby to full load in 10 minutes. This will allow the system to follow rapidly changing supply from renewable energy sources or changing consumer demand throughout the day.

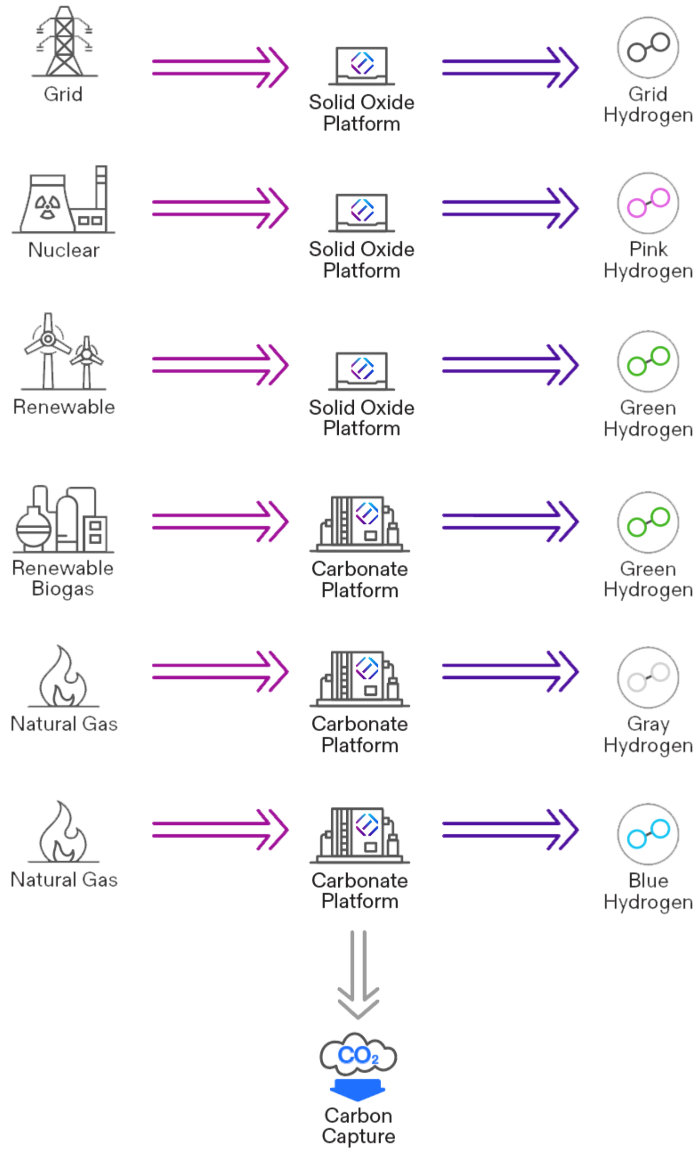
Reversibility

Solid oxide cells can be capable of running as an electrolyzer (SOEC) for hydrogen production or as a fuel cell (SOFC) for electricity production. FuelCell Energy is developing a reversible SOFC that will run in electrolysis mode during periods of energy availability, and switch to fuel cell mode during periods of high demand. With round-trip efficiencies of more than 60 percent, this platform will offer small and large-scale solutions for long-duration energy storage with low energy loss.

Solid Oxide Applications

Distributed hydrogen generation

Distributed hydrogen generation is designed to offer significant cost savings by locating the source of hydrogen production at or near the point of consumption. Solid oxide electrolysis systems are designed in 1.1 MW modular blocks that are each capable of producing up to 600 kg of hydrogen a day. The modular approach makes small scale hydrogen production accessible to operations looking to decarbonize without adding distribution costs. Some examples of small scale (1 MW to 10s of MWs) hydrogen applications are fueling stations, industrial sites, commercial and residential space heating, and direct connections to small solar or wind systems.



Centralized hydrogen generation

Hydrogen production today is predominantly supported through large, centralized, fossil-fueled operations such as steam methane reformation and industrial process byproduct streams. As the hydrogen economy develops further into low- and zero-carbon hydrogen production systems, centralized operations will continue to offer economies of scale for electrolysis equipment, balance of plant, and installation costs. Co-locating electrolysis systems at power-generation hubs, including large central solar, wind, and nuclear sites allows for these efficiencies and will help to create the carbon-neutral products needed to advance climate action targets.

Solid oxide hydrogen-based storage

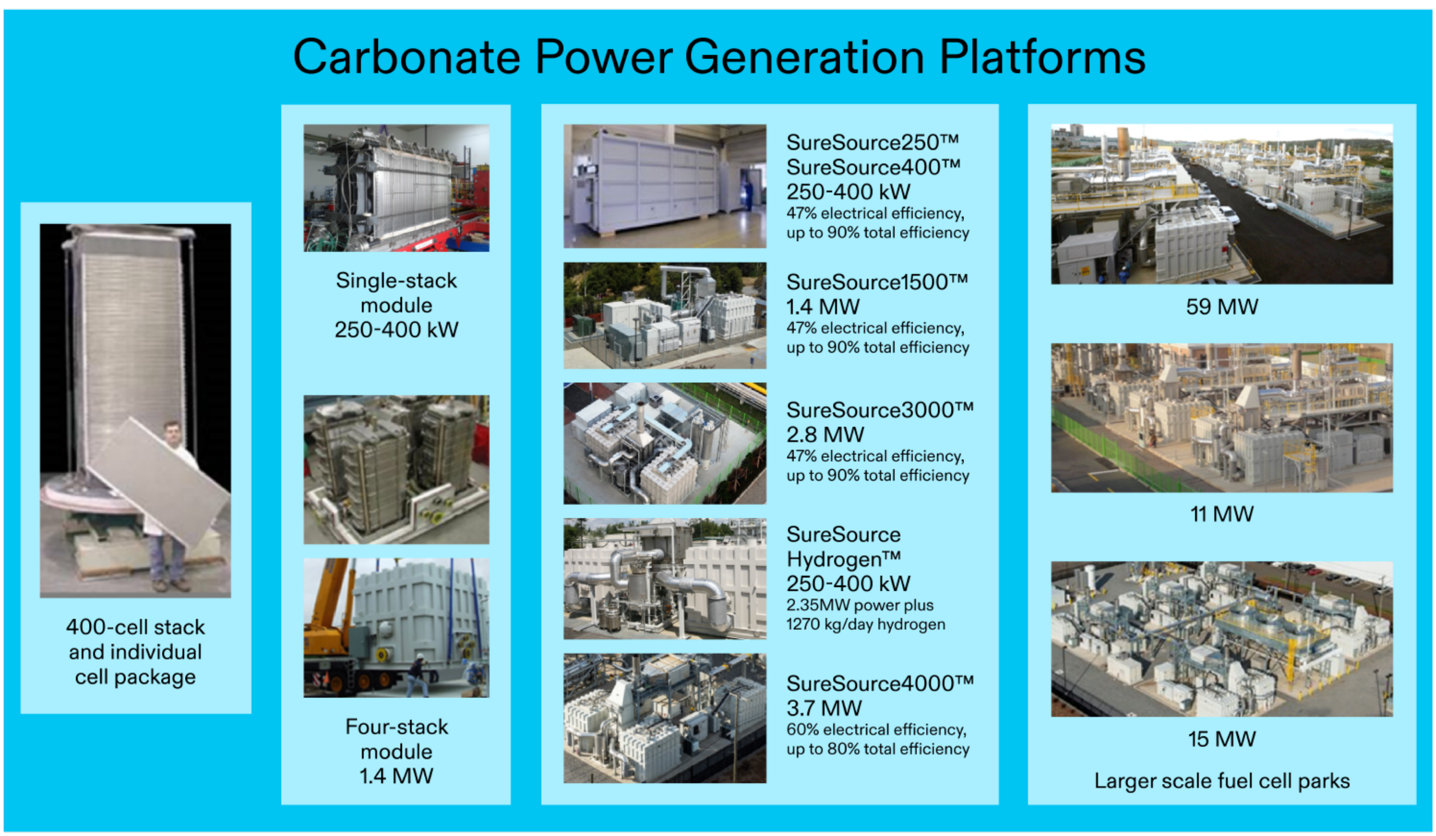
Excess power from wind and solar can be converted into hydrogen and stored for long periods, then converted back to power when needed. Days, months, or even seasonal amounts of hydrogen can be stored long-term or transported. We believe that hydrogen is the most cost-effective solution for storing and transporting large amounts of renewable energy.

Our Expertise in High-temperature Electrochemical Technologies

We draw from our experience as a global leader in carbonate fuel cell technology

FuelCell Energy was founded in 1969 and completed an initial public offering in 1992. The company began selling stationary fuel cell power plants commercially in 2003. More than 200 MW of our platforms are operating around the world today, and more than 13 million MWh of energy have been generated by the global fleet since we began commercial shipments. This fleet includes customers using behind-the-meter combined heat and power systems and front-of-the-meter utility scale systems. We are currently installing a 1,200 kg/day hydrogen production system for Toyota at the Port of Long Beach based on our carbonate tri-generation platform that produces power, hydrogen, and water.

FuelCell Energy's portfolio of solutions is based on two high-temperature electrochemical technologies: carbonate and solid oxide. Both can be operated in fuel cell mode (producing power from fuel) or electrolysis mode (producing hydrogen from power and steam). Decades of carbonate fuel cell development have established FuelCell Energy as a trusted authority in high-temperature electrochemical technologies. We have the experience, processes, and infrastructure to scale operations in support of solid oxide production.



Our Solid Oxide Development History

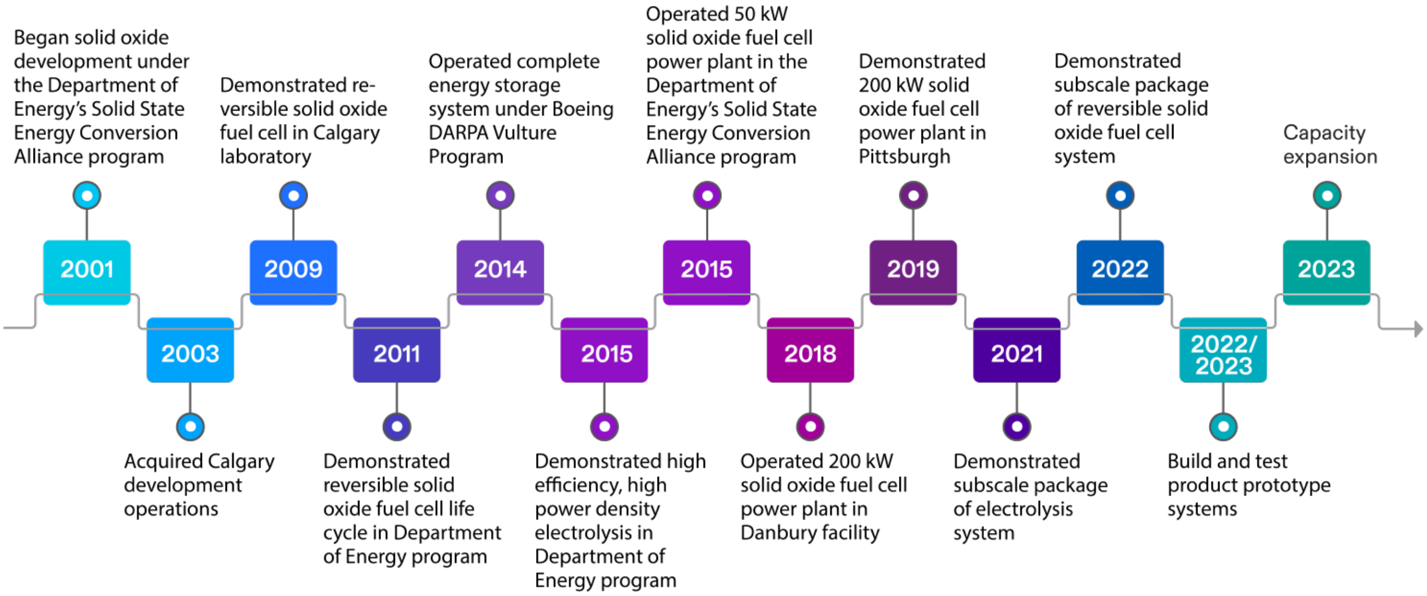
Our solid oxide platform has been in development since the early 2000s with a dual focus on high-efficiency power generation and high-efficiency electrolysis. We have developed a solid oxide stack platform that supports power generation, electrolysis, and energy storage.

We have continued development of reversible solid oxide fuel cells (RSOFC), in which the cells alternate between electrolysis mode (producing hydrogen which is stored) and fuel cell mode (producing power from the stored hydrogen). A complete RSOFC system was built and operated as part of the development of a lightweight, efficient energy storage system for aircrafts in a DARPA-funded project with Boeing in 2014. Our power generation platform was field demonstrated in 2019 at the Clearway Energy Center in Pittsburgh, Pennsylvania where we operated a packaged 200kW natural gas-fueled power generation system. We are in the process of introducing a 250kW power-generation product based on that field trial and subsequent advances to the stack technology. Our electrolysis development has advanced using the same cell platform as the power-generation application. In 2021, we successfully demonstrated a subscale packaged SOEC system at our testing facility in Danbury, Connecticut and stack tests at Idaho National Laboratory demonstrated the high efficiency performance of our technology.

The FuelCell Energy team in Calgary, Alberta is focused on developing cell and stack technology while our Danbury, Connecticut team is engineering the stack module and balance of plant systems, while manufacturing integrated electrolysis systems. Our solid oxide manufacturing facilities include an advanced automated cell and stack-manufacturing line. The line has been developed with the goal of ensuring that the labor and overhead required to produce these technologies are optimized for efficiency and complement the low direct-material cost of the stack. We plan to add solid oxide stack production capacity in the United States as we expand operations.

How we got here

An overview of key milestones in FuelCell Energy's solid oxide development.



Reducing the Cost of Hydrogen Production

Solid oxide has the potential to significantly outperform alkaline and PEM electrolyzers

We believe an SOEC electrolyzer will produce 30 percent more hydrogen than alkaline and PEM systems with the same input electricity. Conventional electrolysis systems based on polymer membrane or alkaline electrolyte cells operate near ambient temperature and convert water to hydrogen with electrical efficiency ranging from about 60 percent to 70 percent. FuelCell Energy's SOEC platform operates at much higher efficiency, producing more hydrogen with the same level of power input.

Under some conditions, the cells can be operated at or above 100 percent electrical efficiency (39.4 kWh/kg), as long as thermal energy is supplied to the stack to maintain thermal balance, as shown in the figure below. Even without the use of excess heat from industrial or nuclear facilities, FuelCell Energy's SOEC system has been shown to operate at nearly 90 percent efficiency (43.8 kWh/kg).

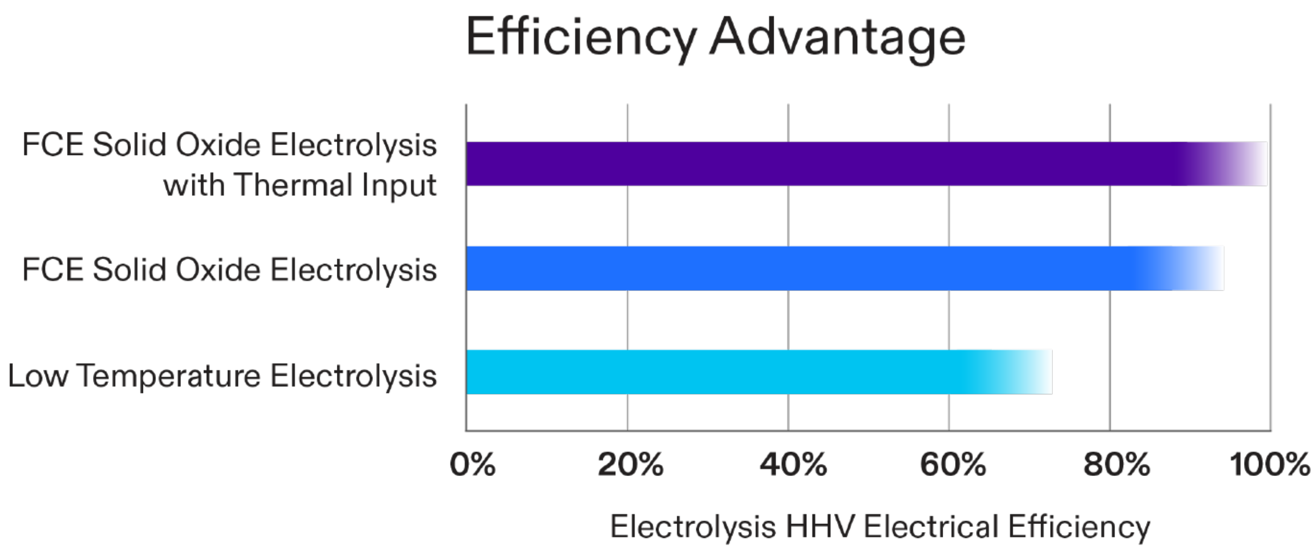
These efficiency levels have been demonstrated in full-system tests. Electrolysis efficiency is often calculated in ways that can confuse understanding of the true performance level, such as when a stack-only efficiency is reported without the losses associated with parasitic loads or power conversion. The efficiencies described are full-system efficiencies—from AC power into the system to pure hydrogen out of the system at ambient pressure. Efficiency is the main cost of hydrogen produced through electrolysis. At scale and at volume, different types of electrolysis systems will have similar capital and operating costs, since they have many common or similar systems. Electricity is typically the largest portion of hydrogen production costs in electrolysis systems. We believe that SOEC will be capable of reducing hydrogen production costs by 30 percent.

Alkaline / PEM (55 kWh/kg)	SOEC (43.8 kWh/kg)
4,320 kg/day	5,580 kg/day

Estimated hydrogen produced from a fixed input of 10 MW.

Alkaline / PEM (55 kWh/kg)	SOEC (43.8 kWh/kg)
10 MW	8 MW

Estimated energy required to produce the same amount of hydrogen.



The Electrolyzer of Choice for the Future

We believe SOEC's efficiency will make it the clear choice for the future when manufactured at scale

Electrolyzers show a promising learning rate potential, with the International Renewable Energy Agency (IRENA) estimating that a ~40 percent reduction in the cost of electrolyzers can be achievable by 2030. Our existing North American production facility has 100 MW of integrated capacity for our carbonate platform. Based on our experience commercializing carbonate fuel cells, we expect that our capital cost will achieve parity with legacy electrolysis technology as we achieve commercial volumes of large-scale systems, making SOEC's efficiency advantage the clear choice. When installed, we believe SOEC plants will produce more hydrogen, or consume less energy, than conventional electrolysis. By minimizing hardware costs and increasing efficiency, we believe our SOEC platform will reduce the levelized cost of hydrogen and help enable a world empowered by clean energy.

List of references

1: World Wide Fund for Nature, Inc. (2021). Power Forward 4.0 A Progress Report of the Fortune 500's Transition to a Net-Zero Economy

2: Hydrogen Council (2021), Hydrogen for Net-Zero: A Critical Cost-competitive Energy Vector

3: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal, Abu Dhabi