WHITE PAPER

Fuel cells: a new source for beverage-grade CO_2

Using fuel cells to capture and recycle CO_2 into ISBT Beverage-grade standards.

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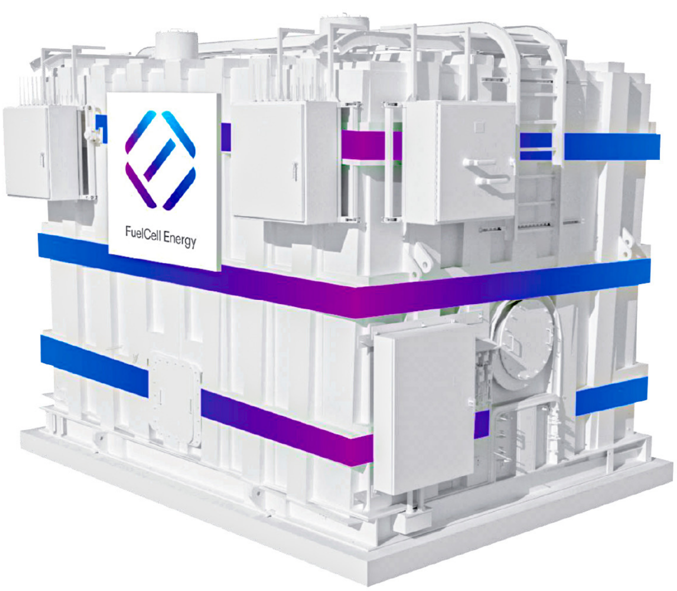


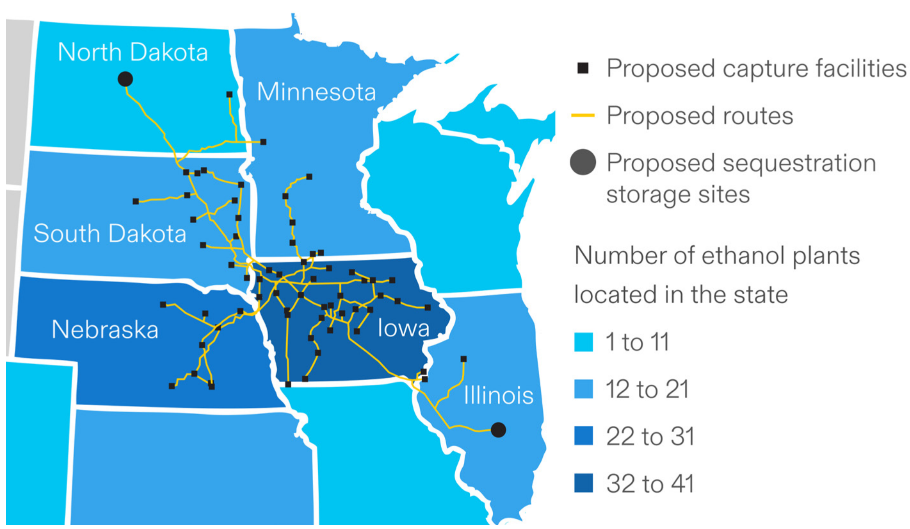
The CO_2 Supply Chain

Fuel cells can help businesses produce beverage-grade CO_2 to secure consistent price, availability, and quality

Industrial and commercial demand for CO_2 is estimated at 230 megatonnes (Mt) per year globally[1]. CO_2 is commonly used for beverage bottling, food processing, dry ice production, fertilizer, cooling, welding, metal fabrication, enhanced oil recovery, water treatment, and fire suppression. By its nature, CO_2 is a byproduct of chemical processes or combustion. The gas can be released naturally from activities like volcanic eruptions or from industrial activities like ethanol production. The three main sources of CO_2 used for beverage-grade purposes are ethanol plants, ammonia plants, and natural wells.

The commercial CO_2 supply may shrink whenever ethanol and ammonia plants lower production capacity or if natural reservoirs become contaminated. Supply shocks can impact the contractual agreements of CO_2 providers, resulting in unfulfilled deliveries or price increases under force majeure clauses. Early in the COVID-19 pandemic, a CO_2 shortage was experienced throughout the food and beverage supply chain, compelling food processors to write to the federal government for relief and forcing some breweries to shut down entirely. Supply was also impacted by the Jackson Dome reservoir contamination and by European ammonia plants curtailing operations due to high natural gas prices.

The ethanol industry is a significant source of CO_2 used for food and beverage production, with a heavy concentration of plants located in Iowa and the surrounding states[2]. Multiple CO_2 pipelines are planned in the Midwest, with federal tax credits poised to incentivize ethanol producers to sequester CO_2 underground in Illinois and North Dakota. Sequestration infrastructure could increasingly reduce the commercial CO_2 supply available in the coming decade.



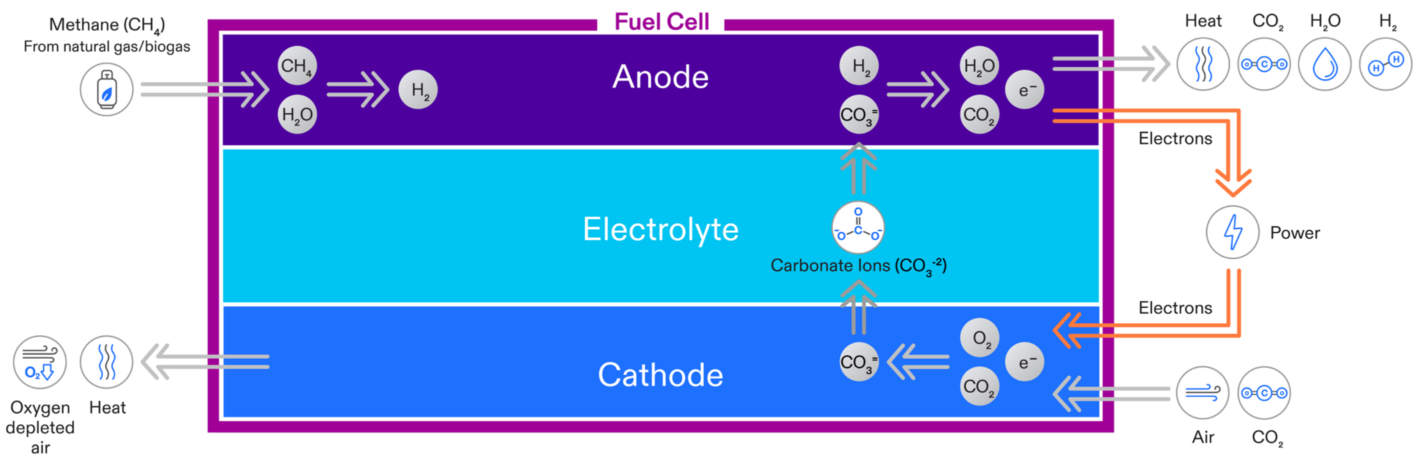
How Carbon Recovery Works

How fuel cells produce power

Fuel cells electrochemically react fuel and air to create power, without combustion. Reacting fuel and air electrochemically involves delivering fuel to a set of negative electrodes (called anodes) and delivering air to a set of positive electrodes (called cathodes). The electrochemical reaction of fuel produces electrons. The electrochemical reaction of oxygen in air consumes electrons. Connecting the two produces the current of usable electrical power.

How our fuel cells recover CO_2

Inside the fuel cell modules, methane (CH_4) is steam-reformed into hydrogen (H_2) and carbon dioxide (CO_2). The isolated carbonate ions filter through the electrolytes in each cell, resulting in a concentrated stream of CO_2 available for recovery.



The purification process

An output stream containing high concentrations of CO_2 is cooled and pre-filtered before entering a shift reactor, where any residual traces of chemicals are converted into pure value streams of water, hydrogen, and CO_2. Purification modules can be paired with the system to ensure the final CO_2 product meets beverage-grade CO_2 standards. Rather than being emitted into the atmosphere, the recovered CO_2 can be sold, sequestered, or used on-site. Carbon recovery allows fuel cells to be cleaner sources of power generation, even when they are operating on nonrenewable fuels.

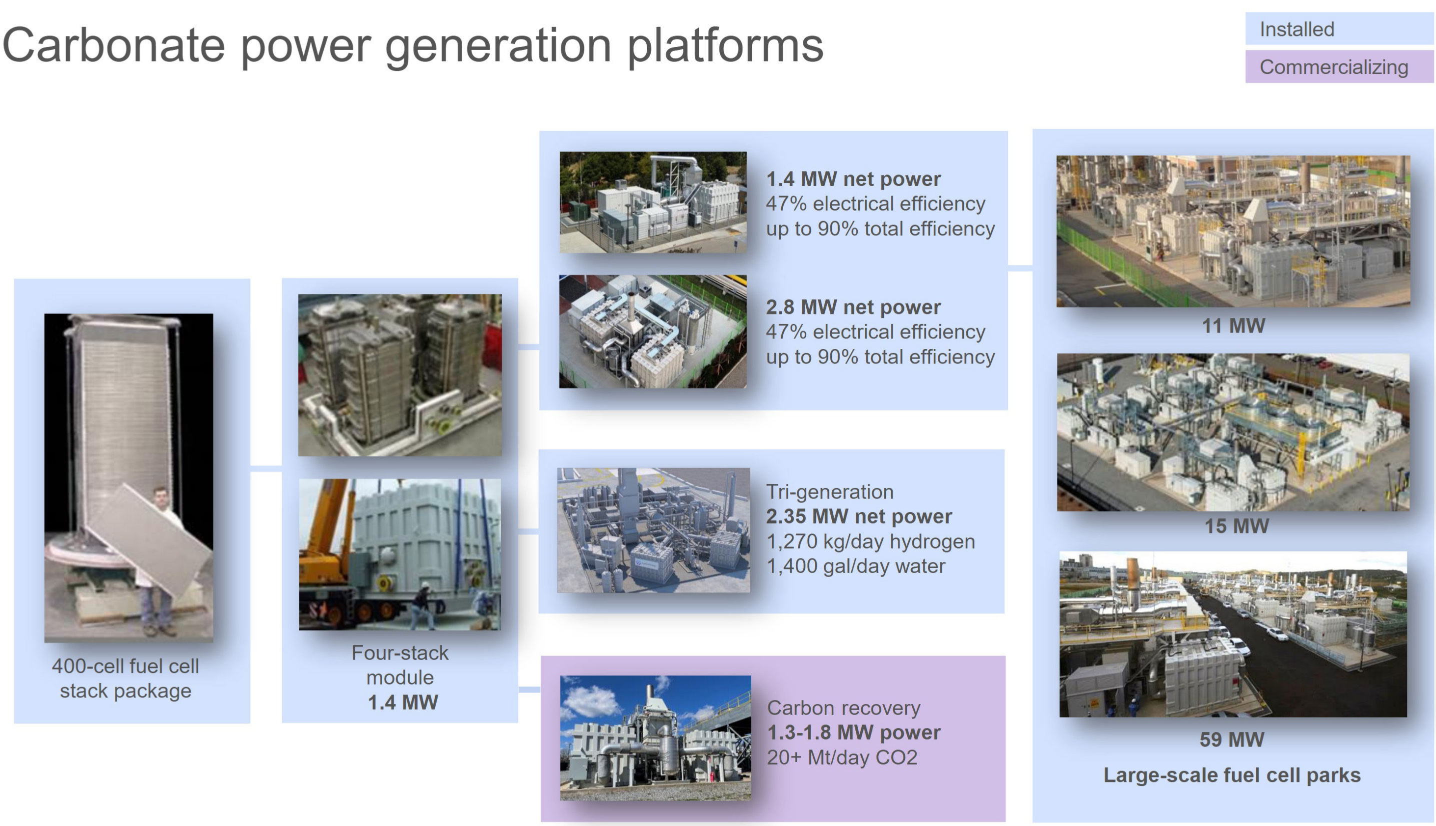
Our Carbonate Fuel Cell Capabilities and Development History

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

Decades of carbonate fuel cell development have established FuelCell Energy as a trusted authority in high-temperature electrochemical technologies. 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 megawatt (MW) of our platforms are operating around the world today, and more than 13 million megawatt-hours (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. FuelCell Energy's diverse customer base ranges from local high schools to global conglomerates.

FuelCell Energy offers the only known platform that can capture carbon from an external source while simultaneously generating power and is jointly developing this technology with ExxonMobil. Power generation improves the net cost of capture economics, making the fuel cell a practical solution on the path to net-zero. Businesses that aren't capturing flue gas from an external source have the option (with fuel cells) to generate CO_2 directly from fuels used in the power generation process.

Carbonate power generation platforms



Fuel Cell CO_2 Fingerprint Analysis

FuelCell Energy contracted with B&R Compliance Associates in collaboration with Analytical Sciences & Technologies to conduct a third-party, independently tested fingerprint analysis[3] of the fuel cell's anode exhaust. The anode exhaust gas had negligible traces of aromatics (BTEX: Benzene, Toluene, Ethylbenzene, and Xylene), and had no concern for any hazard from these aromatics compared to other sources of CO_2. The analysis concluded that fuel cell anode exhaust gas can be easily purified to exceed the International Society of Beverage Technologists (ISBT) spec for beverage-grade CO_2.

International Society of Beverage Technologists Carbon Dioxide Guidelines

All values in parts per million (ppm) unless otherwise noted.

Property	ISBT Spec	Raw CO_2 Product Gas	Liquid CO_2 Product Gas
Assay (CO_2)	**99.9%**	~75%	99.99%
Hydrogen	**N/A**	~15%	None
Total Hydrocarbon as Methane	**< 50**	< 3%	< 5
Oxygen	**< 30**	< 1%	< 30
Moisture (H_2O)	**< 20**	< 1%	< 20
Total Non-Methane Hydrocarbon	**< 20**	< 20	< 20
Carbon Monoxide	**< 10**	< 5%	< 10
Methanol	**< 10**	None Detected	None
Non-Volatile Residue	**< 10**	None Detected	None
Non-Volatile Organic Residue	**< 5.0**	None Detected	None
Oxides of Nitrogen	**< 5.0**	None Detected	None
Nitrogen Oxide	**< 2.5**	< 0.20	< 0.20
Nitrogen Dioxide	**< 2.5**	< 0.50	< 0.50
Ammonia	**< 2.5**	None Detected	None
Sulfur Dioxide	**< 1.0**	None Detected	None
Phosphine	**< 0.3**	None Detected	None
Ethylene Oxide	**< 0.2**	None Detected	None
Acetaldehyde	**< 0.2**	None Detected	None
Total Sulfur	**< 0.1**	None Detected	None
Hydrogen Sulfide	**< 0.1**	None Detected	None
Carbonyl Sulfide	**< 0.1**	< 0.03	< 0.03
Aromatic Hydrocarbon (Benzene)	**< 20 ppb**	< 2 ppb	< 2 ppb
Hydrogen Cyanide	**None**	None Detected	None
Vinyl Chloride	**None**	None Detected	None

Anode exhaust fingerprint analysis performed on dehydrated basis

Residual methane, carbon monoxide removed via oxidation

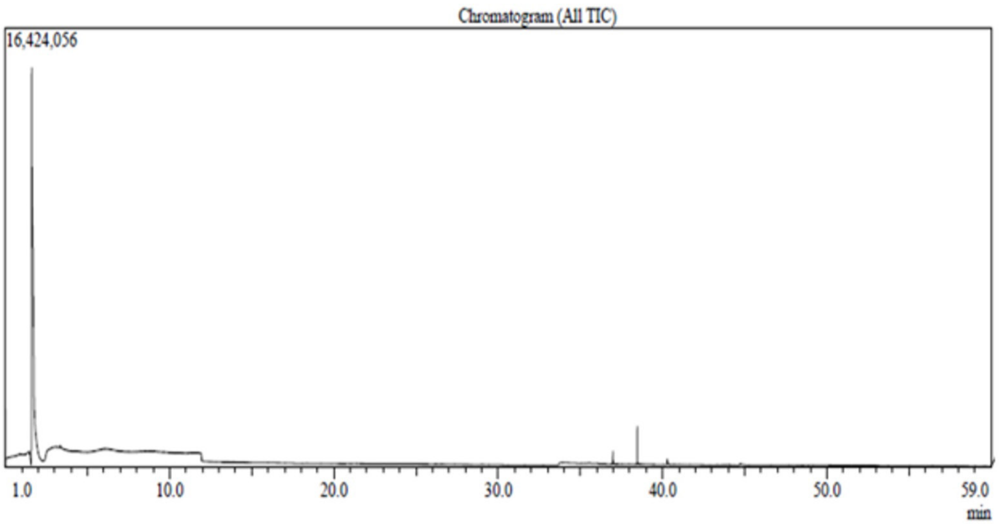
Non-condensable gases are removed during distillation

Purity Comparison vs. Traditional Sources

Fuel cells produce some of the “cleanest” carbon dioxide compared to traditional sources

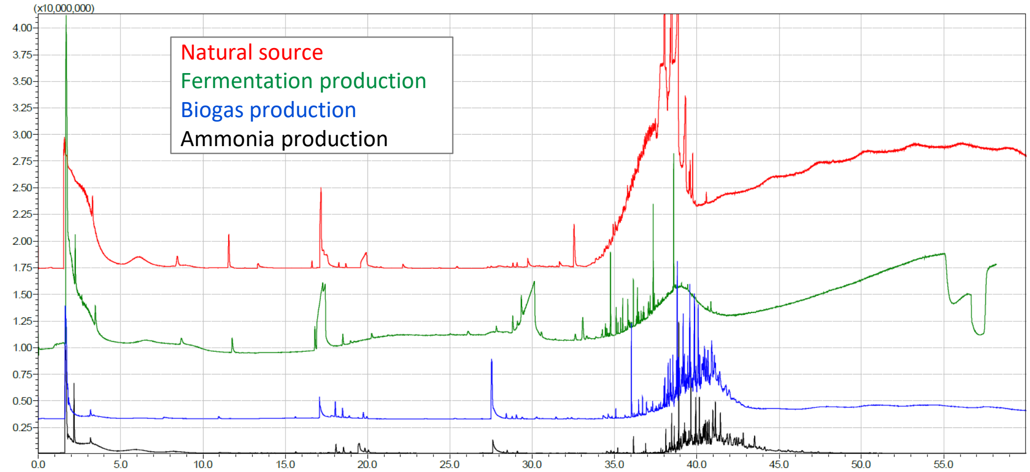
B&R Compliance Associates concluded that the fuel cell anode exhaust is some of the “cleanest” carbon dioxide feedgas they have seen to date. Typical scan results from natural wells, ethanol fermentation, biogas, and ammonia production were included for comparison. The results clearly demonstrate that the number and quantity of impurities detected in fuel cell anode exhaust is far less than those found in traditional feedgas samples.

FuelCell Energy anode exhaust gas results



Typical results from traditional sources of beverage-grade CO_2

Graphs shown below are at the same scale and superimposed over each other.



Fuel Cell Advantages vs. Amine CO_2 Scrubbers

Net production of electricity and heat

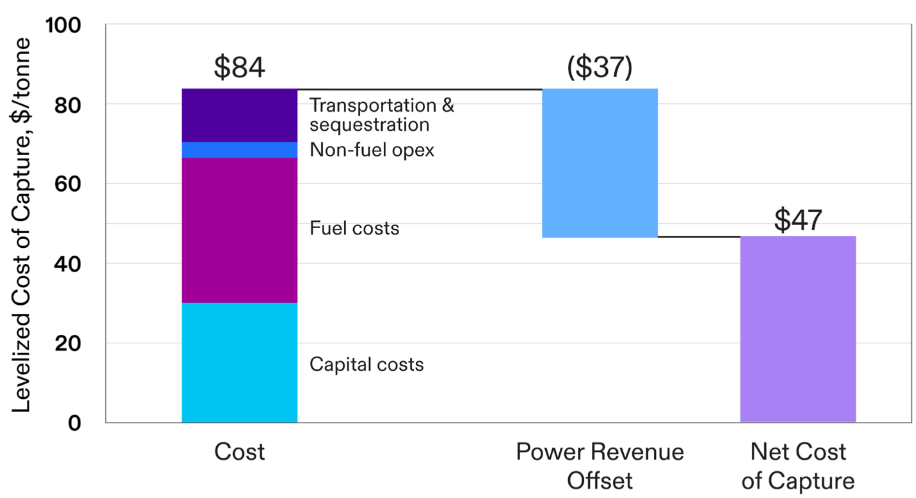
While traditional amine systems consume energy and water, fuel cell systems can be net producers of electricity, heat, and water during the CO_2 capture process. The electricity can be delivered to the grid or used by the hosting facility. Fuel cells also produce useful thermal energy and can be configured to preheat water to reduce on-site boiler operation, saving money and further reducing emissions. Heat can be used for facilities, hot water, bottle cleaning, bakery operations, or even the anaerobic digestion process.

Water circularity

Fuel cells can also reuse water to reduce consumption. Water circularity is increasingly important for areas impacted by drought. In some applications, like tri-generation, fuel cells can generate more water than they consume.

Enhanced economics from co-production of power

The co-production of power while capturing carbon is a key differentiator of the carbonate fuel cell approach compared to other types of carbon capture, which consume power or other forms of energy. This drives a significant economic benefit because of the value of the power as a revenue stream, which reduces the effective cost of CO_2 capture. This is illustrated by the following figure, which summarizes a cost study done during a DOE project evaluating carbonate based carbon capture from coal based power generation systems.

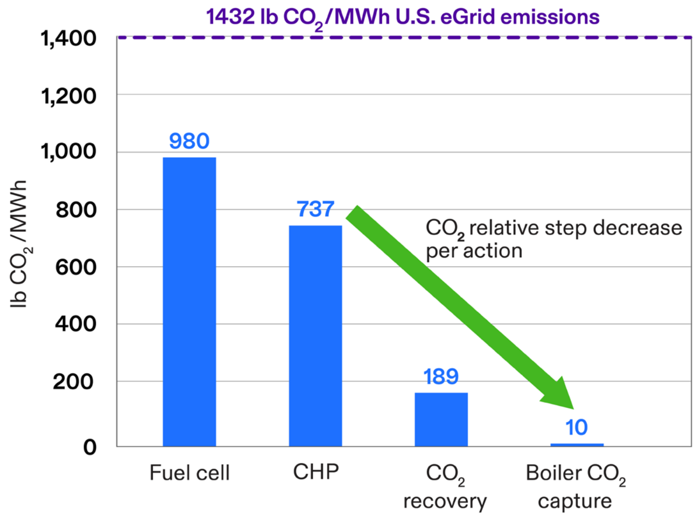


Reduction of Scope 1, 2, and 3 Emissions

Even if a nonrenewable fuel is used to power a fuel cell, there are still significant environmental benefits to its electrochemical method of operation. Fuel cells produce negligible NOx compared to combustion-type generation sources, translating to cost savings on NOx mitigation equipment. By producing cleaner on-site power, fuel cells can reduce Scope 1 and 2 emissions while establishing predictable energy costs. The carbon intensity of operations can be further reduced in applications like combined heat and power (CHP), CO_2 recovery, and boiler CO_2 capture. Today, CO_2 is often transported to the end point of use, often over long distances and at high costs. Businesses producing on-site CO_2 with fuel cells may also reduce Scope 3 emissions by decreasing the logistic and diesel truck trip emissions associated with deliveries.

Lower carbon intensity across operations

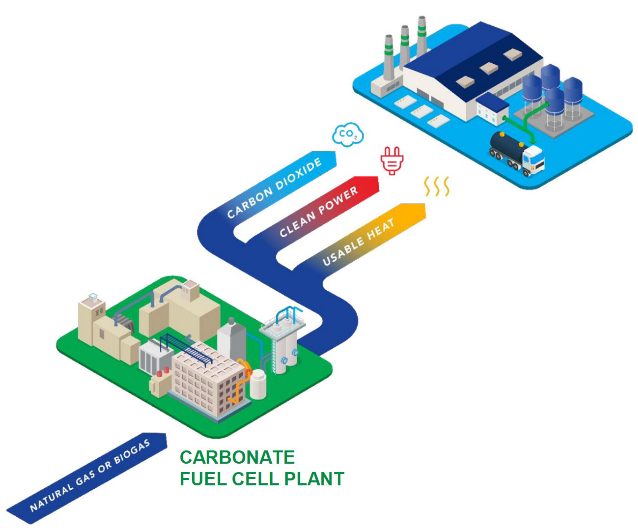
U.S. grid CO_2 reduction with CHP & CC



Carbonate CO_2 recovery and capture applications

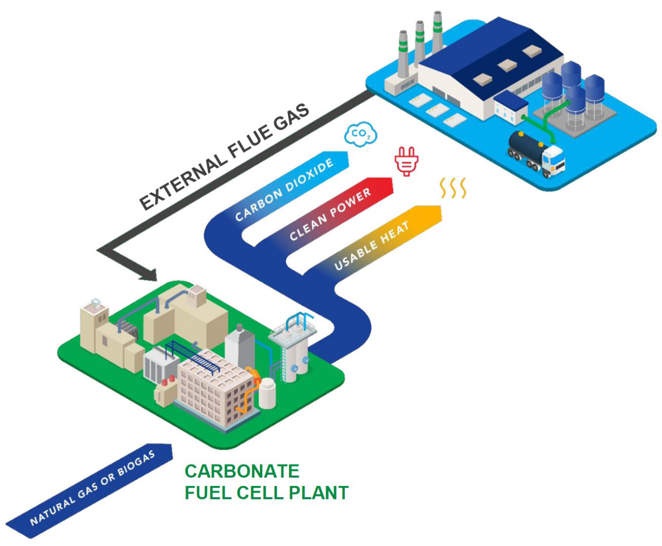
Carbon Recovery

Purification and capture of CO_2 from fuel cell power generation



Carbon Capture

Purification and capture of CO_2 from external flue gas



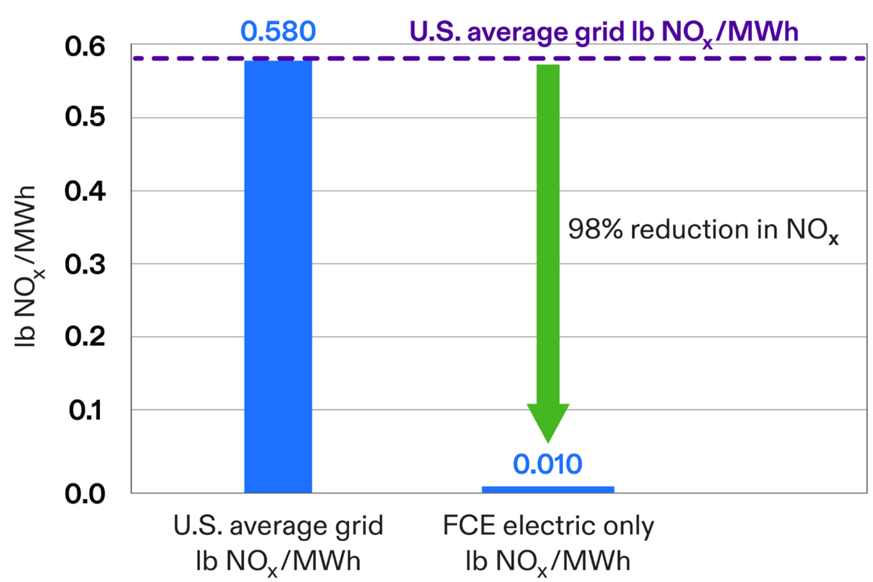
NOx Reduction

Nitrogen oxide (NOx) is destroyed during the process

NOx gases contribute to the formation of smog and acid rain. Since there is no burning of the fuel source during the fuel cell's electrochemical process, air emissions are minimal and much lower than combustion systems. FuelCell Energy's carbon capture method pulls CO_2 from the air stream (where it is difficult to separate) and concentrates it in the anode (where it is easy to separate). If there are nitrogen oxides (NOx) in the flue gas, more than 70 percent is destroyed as the stream passes through the air electrode channels.

Zero combustion = negligible NO_x

U.S. eGrid NO_x emissions



Expedited clean air permitting

Traditional power plants using internal combustion engines have significant permitting issues due to their emissions and noise impacts, which can make permitting both expensive and difficult to obtain. FuelCell Energy's power plants have received key certifications under the California Air Resources Board's (CARB) distributed generation standards, allowing the local air quality management districts in California to exempt the fuel cell installation from the clean air permitting process, which accelerates the approval process.

A New Source for Beverage-Grade CO_2

Fuel cells can turn variables into constants, allowing a business to focus on core issues

FuelCell Energy's platforms present a compelling opportunity for businesses to make progress on their sustainability goals while securing long-term costs they can plan around. Carbonate fuel cell systems can help a business establish predictible costs for power, heat, and CO_2 by generating them on-site. Self-supplying CO_2 eliminates the risk of third-party quality issues, supplier source contamination, availability risks, or force majeure price increases. Fuel cells can also be configured as microgrids, supplying power to the site and grid during normal operation and islanding to provide power in the event of a disturbance. Reliable on-site power can maximize production uptime by avoiding costly outages. The fuel cell's chemical reaction is virtually free of NOx, SOx, and particulate matter emissions.

Operating from a compact footprint, the plants are ideal for sites with limited space and scale modularly to meet higher power demands. FuelCell Energy implements facility improvements by assembling a world-class ecosystem of partners. We have a history of safe and smooth installations through our developed relationships with design firms and licensed contractors.

List of references

1: International Energy Agency (2019). Putting CO_2 to Use: Creating value from emissions

2: U.S. Energy Information Administration, U.S. Fuel Ethanol Plant Production Capacity. https://www.eia.gov/petroleum/ethanolcapacity/

3: B&R Compliance Associates (2023). Carbon Dioxide Feedgas Analysis and Evaluation