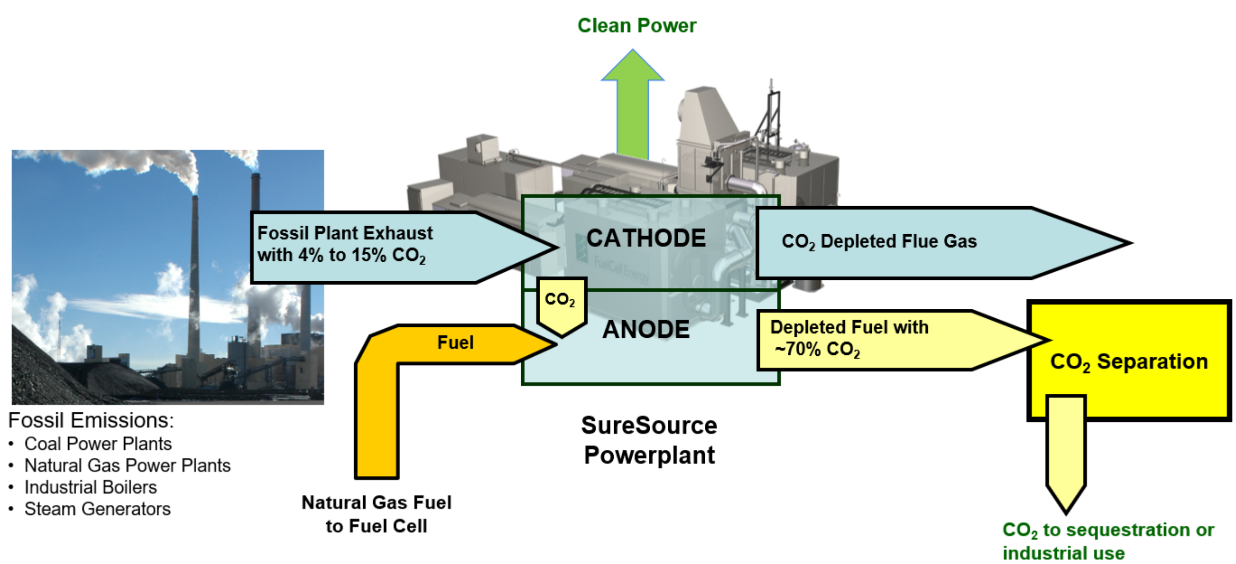
Carbon Capture with fuel cell power plants

Using FuelCell Energy's fuel cell technology to capture CO_2 while producing additional power



Executive summary

A better option is now available for the capture of carbon dioxide (CO_2) from the exhaust of fossil fueled power and thermal systems. FuelCell Energy has developed an application where the electrochemical stacks used for power generation are used to separate CO_2 from the exhaust of natural gas or coal-fired systems, while producing ultra-clean electric power. This technology produces power during CO_2 capture, rather than consuming it like other technologies. The extra power generation is a value stream which makes this approach to CO_2 capture uniquely affordable.

Besides the generation of valuable clean power, FuelCell Energy's capture system provides additional benefits. It produces clean water as a byproduct of power generation, which can be used to offset water requirements of the coal or gas system. Processing flue gas in a FuelCell Energy system will remove 70% of the NOX in the flue gas, reducing or eliminating costs for NOX destruction equipment.

The potential benefits of this technology include:

- **A modular and affordable approach to carbon capture.** FuelCell Energy systems can be configured to capture up to 90% of the CO_2 in the exhaust of a power plant or thermal system. Smaller systems can be added in increments to manage capital outlay and changes in the cost of power.

- **An additional value stream from power generation.** Power generation improves the net cost of capture economics, making the fuel cell a practical solution on the path to net-zero. A project with this technology generates a return on capital rather than an increase in operating expense.

- **An applicable solution for coal and natural gas** systems. The platform enables low carbon utilization of domestic coal and gas resources.

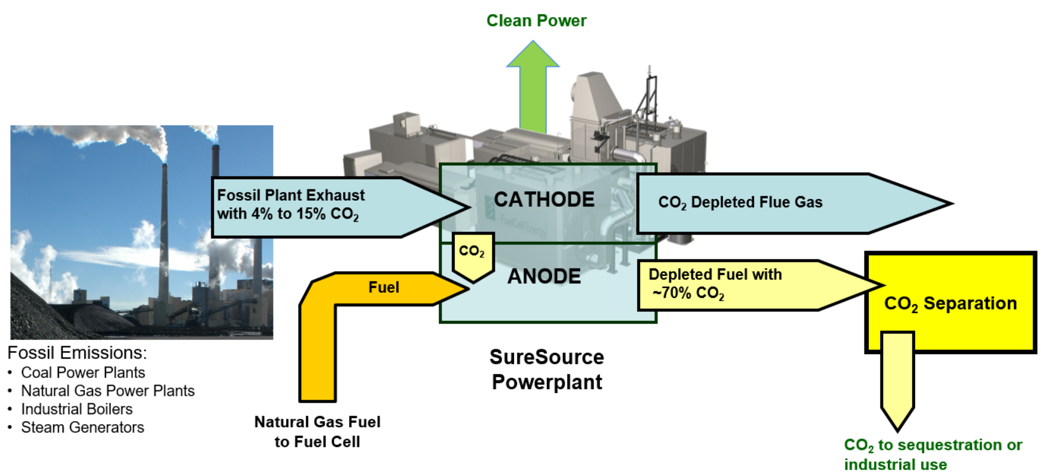
- **A proven technology platform.** There are currently more than 100 FuelCell Energy power plants in operation around the world.

FuelCell Energy has demonstrated the CO_2 capture application on commercial scale hardware and has done preliminary engineering for demonstration projects using hardware optimized for power generation. A program focused on developing a new generation of fuel cell hardware optimized for carbon capture is underway as a joint effort with ExxonMobil.

Introduction

FuelCell Energy's power generation technology has the potential to concentrate and capture CO_2 from the exhaust of large coal or natural gas power plants, avoiding the harmful greenhouse effects. The FuelCell Energy fuel cell is based on carbonate fuel cell technology, where electrochemical reactions are supported by an electrolyte layer in which carbonate ions serve as the ion bridge that completes the electrical circuit. A side effect of this basic characteristic of the technology is that carbon dioxide introduced at the air electrode is transferred through the electrolyte layer to the fuel electrode, where it is more highly concentrated and easy to remove. This means that a FuelCell Energy electrochemical cell can be used as a carbon purification membrane--transferring CO_2 from a dilute oxidant stream to a more concentrated fuel exhaust stream. These cells are configured into large stacks in MW-scale fuel cell power plant systems that are commercially deployed around the world today. Continued efforts are underway to optimize the cell configuration for carbon capture.

Conventional technologies that are being considered for carbon capture are expensive and have high power and heat needs, consuming a significant fraction of the power output of the fossil plant they are trying to clean up. In contrast, instead of consuming power, FuelCell Energy's carbon capture system produces additional clean power—an added value stream which is the key to reducing the cost of the carbon capture process. Using a FuelCell Energy carbon capture system has benefits beyond the CO_2 capture. Since the fuel cell product water is condensed and removed while separating CO_2 from the anode exhaust, the power plant is a net clean water producer. This can reduce costs and environmental impact since many of the CO_2 source systems are significant water consumers. Another benefit is that a large percentage of any NOX in the source power plant will be removed as it flows through the FuelCell Energy stacks. Most of the NOX will be reduced to nitrogen through chemical and electrochemical mechanisms as it flows over the cathodes.

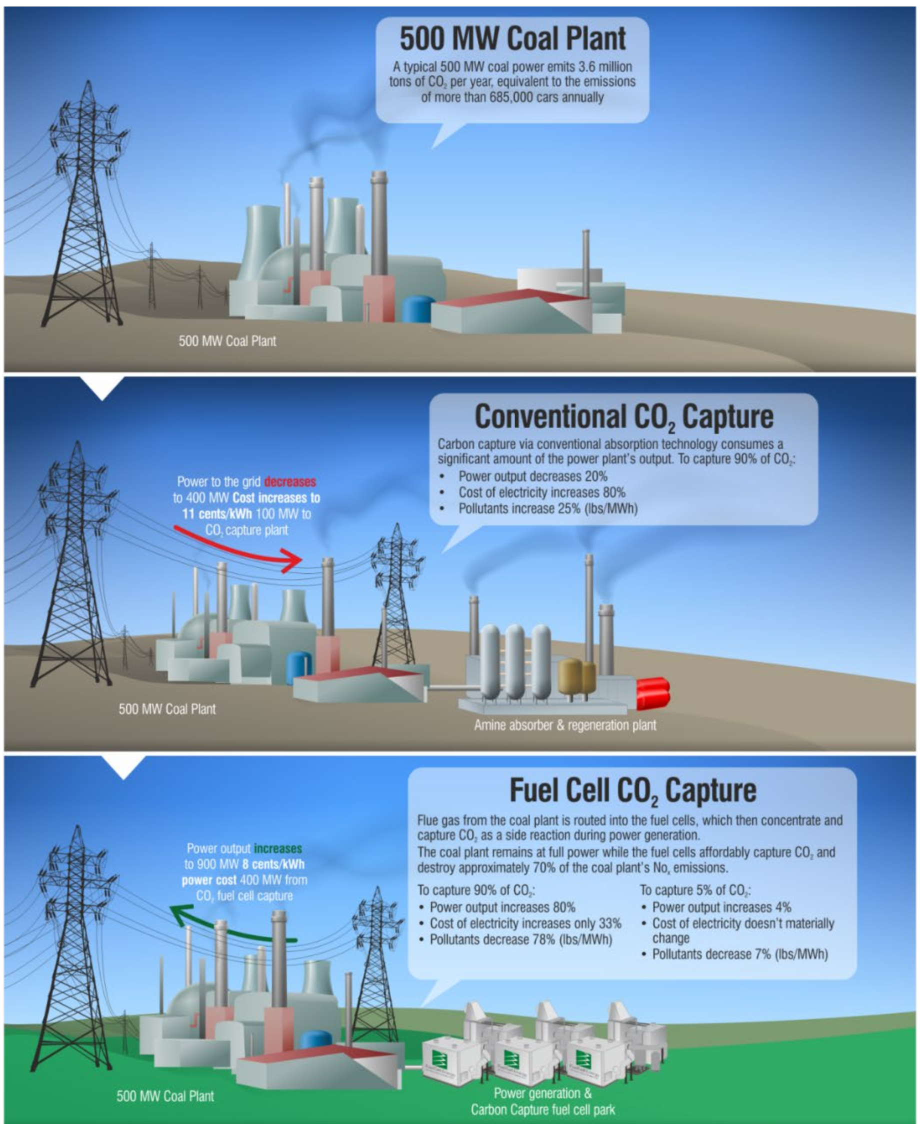


FuelCell Energy carbon capture concept

Exhaust from a fossil power plant or thermal source is sent to the air inlet. The FuelCell Energy power generation process transfers CO_2 from the fossil plant to anode exhaust for easy separation.

The Value Proposition

As illustrated below, FuelCell Energy's carbon capture includes the additional value stream of clean, high-efficiency power, making it significantly more economical than conventional absorption-based carbon capture systems.



	Coal Plant - no CO_2 capture	90% Conventional Amine Capture	90% CO_2 Capture w/ Fuel cells	5% CO_2 Capture w/ Fuel cells
Output (MW)	500	400	900	522
Cost of electricity (cents/kWh)	$ 0.06	$ 0.11	$ 0.08 ($0.075 w/ ITC)	$ 0.06
NO_x emissions (lbs/MWh)	0.6	0.8	0.1	0.6

The illustration is based on a design and cost study funded by the U.S. Department of Energy (DOE) using a third-party engineering company. The company specified the design and evaluated the cost of large-scale FuelCell Energy systems for capture from coal power plants. DOE estimates were used for the non-capture case and the amine capture case. As the chart shows, the addition of a conventional amine absorption system to capture CO_2 from a 500MW coal power plant reduces the output of the plant to 400MW (due to the power and thermal needs of the amine system), and almost doubles the cost of electricity from 6 cents/kWh to 11 cents/kWh. The lower net power output results in an increase in the NOX emission rate from 0.6 to 0.8 lb/MWh.

In contrast, the extra power produced by the FuelCell Energy system increases the power plant output from 500MW to 900MW, and only increases cost of energy to 8 cents/kWh (which can be reduced further if fuel cell incentives, such as the Federal Investment Tax Credit, are available). Another compelling feature of this approach is that it can be applied incrementally, as shown in the 5% capture case in the illustration. This would require a 22MW FuelCell Energy fuel cell system—a size which has been deployed multiple times for power generation applications already. These kinds of incremental CO_2 reductions can be effective in economically rolling out a carbon reduction strategy.

CO_2 capture from large coal-based systems is a compelling application with the potential to avoid shutdown of existing infrastructure while cleanly using abundant domestic energy resources. There are many other near-term applications:

- **Smaller scale capture from large coal power plants.** This application achieves incremental CO_2 reductions and allows a staged approach to carbon capture from large systems.
- **Capture from natural gas baseload power generation power plants**. An increasing percentage of power generation in the world is being provided by natural gas systems. Large baseload systems based on combined cycle technology emit much less CO_2 than coal power plants, but they still emit hundreds of pounds per MWh. Capturing CO_2 from this growing fleet would avoid significant emissions of greenhouse gases.
- **Capture from natural gas based peaking power plants**. Peaking power plants are increasingly being added to the grid mix to compensate for intermittent renewables. The emissions associated with this compensation are often cited as a reason that the renewables are not entirely clean. FuelCell Energy's CO_2 capture systems could make these peaking plants almost as carbon free as the renewables they support.
- **Capture from thermal sources**. Gas and oil-fired thermal boilers are significant contributors to CO_2 emissions. Industrial sources and activities such as steam generation for oil sands operations can benefit from the CO_2 avoidance, along with the on-site power production of the FuelCell Energy carbon capture system.

- **Capture from industrial sources.** Some industrial operations (for example, cement production) produce CO_2 as a byproduct in addition to emissions from thermal sources. FuelCell Energy's systems can be used to capture those emissions.

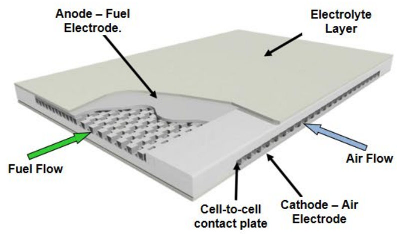
The Technology

A key advantage of fuel cell power generation over combustion heat engine systems is that fuel is converted to power more directly through an electrochemical non-combustion reaction. This direct conversion is more efficient and avoids the production of pollutants such as NOX and particulates associated with combustion-based power generation. Fuel cells are electrochemical devices comprised of negative and positive electrodes that can be connected in a series or parallel electrical configuration to get the desired system voltage. The negative electrodes produce electrons and the positive electrodes consume electrons, producing the electrical current. Chemical reactions at the electrodes drive the electron production and consumption. An electrolyte layer between the electrodes supports ion transfer from positive to negative electrodes to maintain charge balance as electrons are produced and consumed. In fuel cells, the chemicals that drive the power reaction are continuously fed into the cells during power production. Typically, a fuel flows through the negative electrodes (anodes) and air flows through the positive electrodes (cathodes). The fuel is often hydrogen, but in the case of FuelCell Energy fuel cells, methane from natural gas or biogas is used, and converted to hydrogen inside the fuel electrodes.

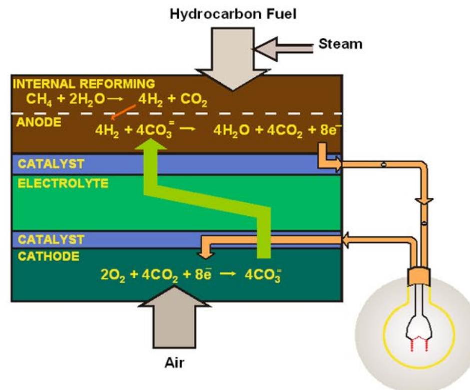
FuelCell Energy's fuel cells are based on carbonate fuel cell technology, where electrochemical reactions are supported by an electrolyte layer in which carbonate ions serve as the ion bridge that completes the electrical circuit. The electrolyte layer separates fuel and air electrodes. During power generation, the carbonate ion transfer results in carbon dioxide being produced in the fuel electrodes and consumed in the air electrodes. The fuel cell system includes a provision for recycling the carbon dioxide, leaving the fuel electrodes back to the stack air electrodes, where it is consumed. This means that a FuelCell Energy stack can be used as a carbon purification membrane--transferring CO_2 from a dilute oxidant stream to a more concentrated fuel exhaust stream. The cell, stack structure, and electrochemical reactions are illustrated below:

1.4MW Four-Stack Module

400-cell stack and individual cell package



Cell Components

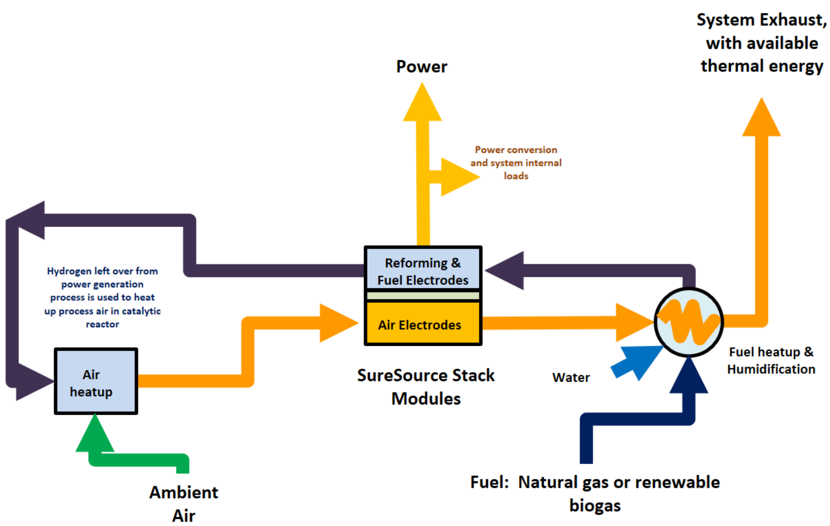


Cell Reactions

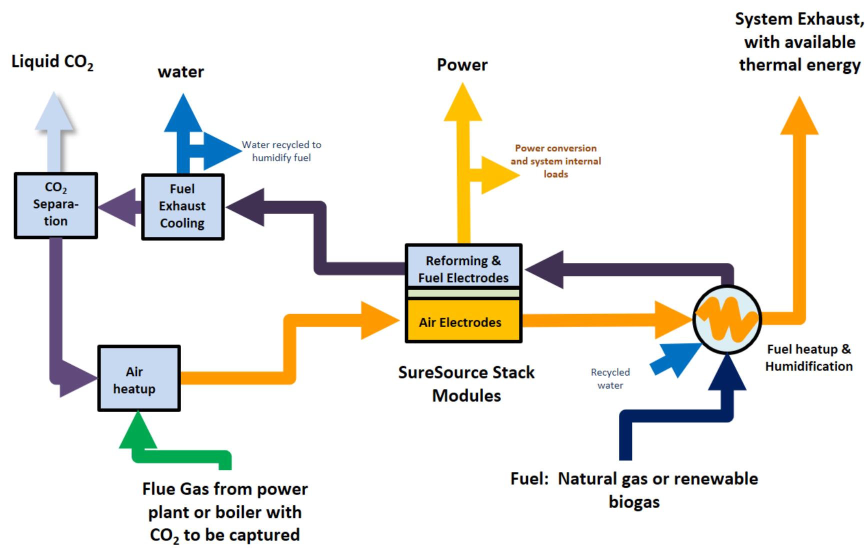
FuelCell Energy's fuel cell electrochemical reactions

Carbonate ion transfer supports electrochemical reaction of hydrogen at anodes and oxygen at cathodes, creating cycle of CO_2 production at anode and CO_2 consumption at cathode.

The FuelCell Energy carbon capture system is an extension of the standard plant design, as illustrated below. In a standard FuelCell Energy power plant, CO_2 produced at the anode is recycled back to the cathode by mechanical systems in the balance of plant. If the concentrated CO_2 in the anode exhaust stream is extracted from the system and not recycled back to the cathode, an external source of CO_2 can support the cathode reaction. This external source can be the exhaust from another power plant or an industrial source. The dilute CO_2 in the external flue gas will be reacted at the cathodes and transferred to the anode stream, from which it can be easily separated for sequestration or use.



Standard System



Carbon Capture Modification

FuelCell Energy modification for carbon capture

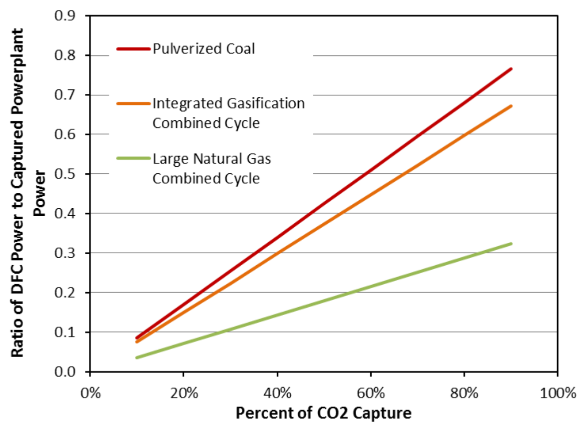
CO_2 from the power plant or industrial source is sent to cathode, transferred and concentrated in anode, and removed from anode exhaust.

In the standard system, a hydrocarbon fuel (e.g. natural gas or biogas) is sent to the anodes and reformed to hydrogen. Most of the hydrogen is consumed in the anode power production reaction. The anode exhaust contains residual hydrogen, any CO_2 from the input fuel, and the CO_2 produced as a result of the carbonate ion transfer. The anode exhaust is mixed with fresh air and sent to a catalytic oxidizer, where the residual hydrogen is used to heat the oxidant stream up to the stack temperature. The cathode consumes oxygen from the air and the CO_2 from the carbonate ion transfer. Water vapor, residual oxygen, nitrogen, and the CO_2 from the input fuel pass through the cathode to the system exhaust.

The modification for carbon capture involves cooling the anode exhaust and separating most of the CO_2 from the exhaust stream. Since most of the CO_2 is removed from the anode exhaust, the CO_2 needed for the cathode reaction is provided by the exhaust of the external source. If this source is a conventional coal fired plant, the CO_2 concentration will be in the range of 12% to 15%. An advanced Integrated Gasification Combined Cycle coal plant will have 7% to 8% CO_2 in its exhaust. A large-scale combined cycle natural gas power plant will have as little as 4% CO_2 in its exhaust. Separating CO_2 from these dilute streams is difficult, but once the CO_2 is sent to the fuel cell cathodes it is transferred to the anode exhaust stream. The anode exhaust stream has a CO_2 dry-basis concentration of about 70%, so it is very easy to remove CO_2 from this stream.

The size of the FuelCell Energy power plant required to capture CO_2 from a specific source depends on the size of the source and the CO_2 emission rate. A 2.8MW FuelCell Energy

3000 fuel cell power plant during normal power operation is transferring about 3200 kg of CO_2 per hour from the cathode to anode streams in the stack modules. In carbon capture mode, this system could capture and purify up to 2300 kg per hour of external CO_2 in addition to the CO_2 exhaust of the power plant. When used to capture CO_2 from a fossil fueled power plant, the ratio of power to captured plant power depends on the CO_2 emission rate of the source power plant. A conventional pulverized coal power plant with a typical CO_2 emission rate of 820 kg/MWh would require a larger capture system than a large-scale natural gas combined cycle plant with a CO_2 emission rate of 360 kg/MWh. The size of the capture plant would also depend on the desired capture percentage. An illustration of these relationships is given in the following chart, which shows the ratio of fuel cell to captured plant power as a function of CO_2 capture ratio for three types of source plants.



FuelCell Energy carbon capture relative plant size requirements
The size of the FuelCell Energy Capture system depends on the CO_2 emission rate of the source plant and the desired level of capture efficiency.

A 500MW pulverized coal plant requires an approximately 400MW FuelCell Energy carbon capture plant for a 90% carbon capture rate. A less carbon-intensive 500MW natural gas combined cycle plant would require a carbon capture plant of about 150MW for the same carbon capture ratio.

These large-scale FuelCell Energy carbon capture systems will ultimately be specially designed with larger balance of plant systems than today's commercial FuelCell Energy power plant products. In the near term, demonstration capture systems have been configured based on the current generation of commercially available 1.4MW stack modules. FuelCell Energy carbon capture plants based on multiple units can be installed in modular increments, providing an increasing level of carbon capture over time and reducing initial capital outlay. Commercial FuelCell Energy power plants have been available since 2003, and large fuel cell parks based on multiple FuelCell Energy power plants have become common in bulk power generation applications. The largest such system so far is a 59 MW system using forty-two 1.4MW fuel cell modules, below.

59 MW power plant based on twenty-one FuelCell Energy 3000 systems
Project developed by POSCO, Korea Hydro Nuclear Power Co. (KHNP) and Samchully Gas Co in South Korea is an example of large systems based on 2.8MW FuelCell Energy 3000 plants.

The current generation equipment based on these 1.4MW modules can be used in demonstration projects or early-stage commercial projects with sufficient power value or CO_2 value to drive project economics. One of the projects currently under development involves a carbon capture demonstration at an oil and gas facility in Alberta, Canada. The project participants include Canadian Natural, Suncor Energy, Cenovus Energy Inc., Chevron Canada, and Shell Canada, along with support from Emissions Reduction Alberta. The project involves the construction of a MW-scale carbonate power plant that will capture CO_2 from a process heater at the Scotford Upgrader (jointly owned by Chevron Canada and Shell Canada) near Edmonton, Alberta.

As we execute early projects using currently available fuel cell hardware, FuelCell Energy is working with ExxonMobil in a joint development effort to improve the performance of the fuel cells in carbon capture mode, and to develop advanced stack module and system designs to address large scale carbon capture applications. These improved stack and system designs will enhance the economics of carbon capture by allowing more power co-production during carbon capture, driving down the cost of captured carbon with a higher power revenue offset.