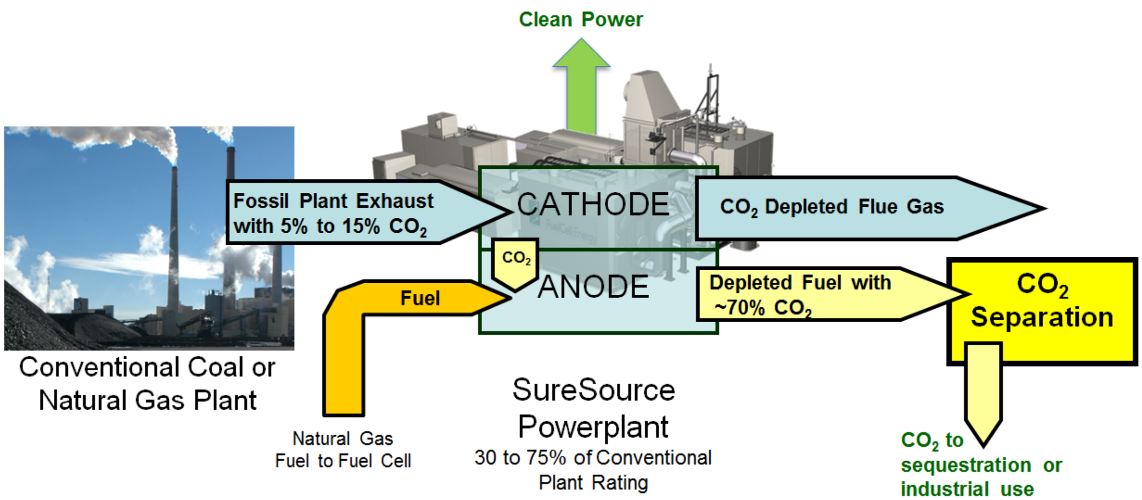
An Affordable Solution for Carbon Capture from Coal and Gas Fired Systems

Using SureSource fuel cell technology to capture CO_2 while producing additional power



June, 2017

Executive Summary

A better option is now available for the capture of carbon dioxide from the exhaust of fossil fueled power and thermal systems. FuelCell Energy has developed an application of its SureSource powerplant technology 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, the SureSource 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. And processing flue gas in a SureSource Capture system will destroy 70% of the NOX in the flue gas, reducing or eliminating capital and operating costs for NOX destruction equipment.

The potential benefits of this technology include:

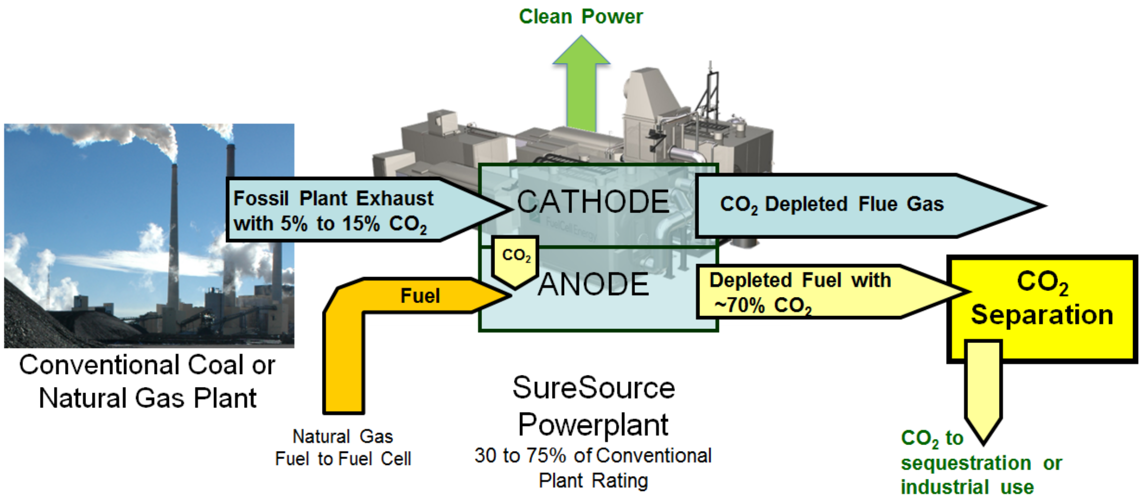
- **Modular, affordable approach to carbon capture**. SureSource systems can be configured to capture up to 90% of the CO_2 in the exhaust of a powerplant or thermal system, or smaller systems can be added in as little as 5% capture increments with no appreciable change in the cost of power and with minimum capital outlay.
- **Additional value stream** from power generation results in carbon capture cost below alternatives. A project with this technology generates a return on capital rather than an increase in operating expense.
- **Applicable to coal and natural gas** power generation and thermal systems. Enables low carbon utilization of domestic coal and gas resources.
- **Based on proven technology**, currently in operation in more than 100 SureSource powerplants around the world.

FCE has demonstrated the CO_2 capture application on commercial scale hardware and is in the process of engineering the first MW-scale system, based on FCE's 2.8MW SureSource 3000 product. This system will be installed at an operating coal fired power plant to capture 60 tons of CO_2 per day from the plant in a US Department of Energy supported program. A development program focused on capture from natural gas sources is also underway as a joint effort with ExxonMobil.

Introduction

FCE's SureSource fuel cell power generation technology has the potential to solve a problem that utilities and policy makers around the world have been struggling with for years: is there a way to concentrate and capture the CO_2 in the exhaust of large coal or natural gas powerplants to avoid the harmful greenhouse effects that these exhaust gasses cause? The SureSource fuel cell is based on the 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 SureSource 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 not developmental items – they are industrial scale components configured into large cell-stacks in MW-scale fuel cell powerplant systems that are commercially deployed around the world today.

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, FCE's SureSource-based 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 SureSource-based carbon capture system has ancillary benefits beyond the CO_2 capture. One benefit is that since the fuel cell product water is condensed and removed while separating CO_2 from the anode exhaust, the SureSource powerplant is a net clean water producer. This can reduce cost 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 powerplant will be destroyed as it flows through the SureSource stacks. Most of the NOX will be reduced to nitrogen through chemical and electrochemical mechanisms as it flows over the cathodes.

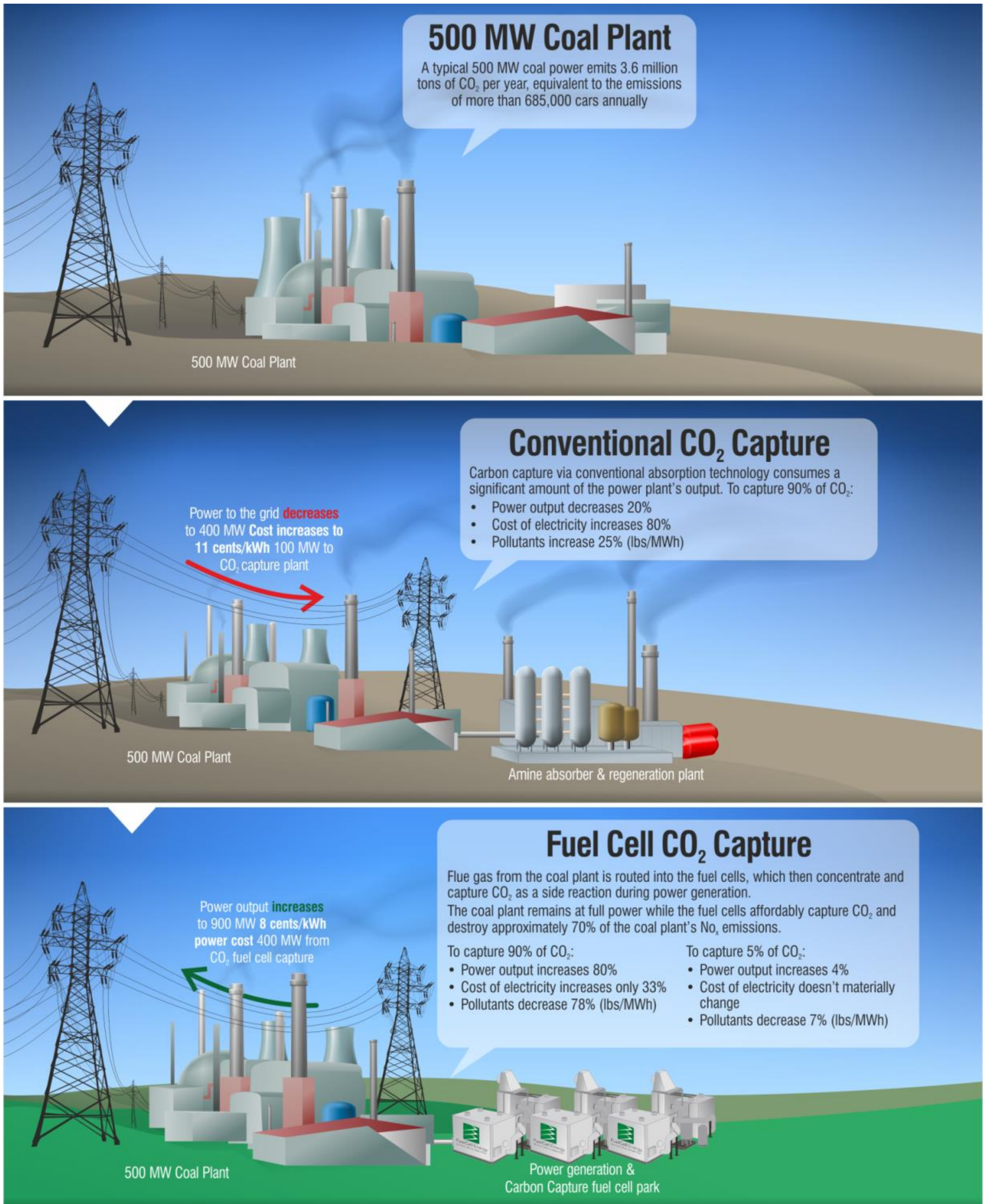


SureSource Carbon Capture Concept

Exhaust from fossil powerplant or thermal source is sent to SureSource air inlet. SureSource fuel cell power generation process transfers CO_2 from fossil plant to anode exhaust for easy separation

The Value Proposition

As illustrated below, SureSource-based carbon capture includes the additional value stream of clean, high efficiency power, thus it is 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 DOE using a third party engineering company to specify the design and evaluate the cost of large scale SureSource-based systems for capture from coal powerplants. 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 powerplant 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.

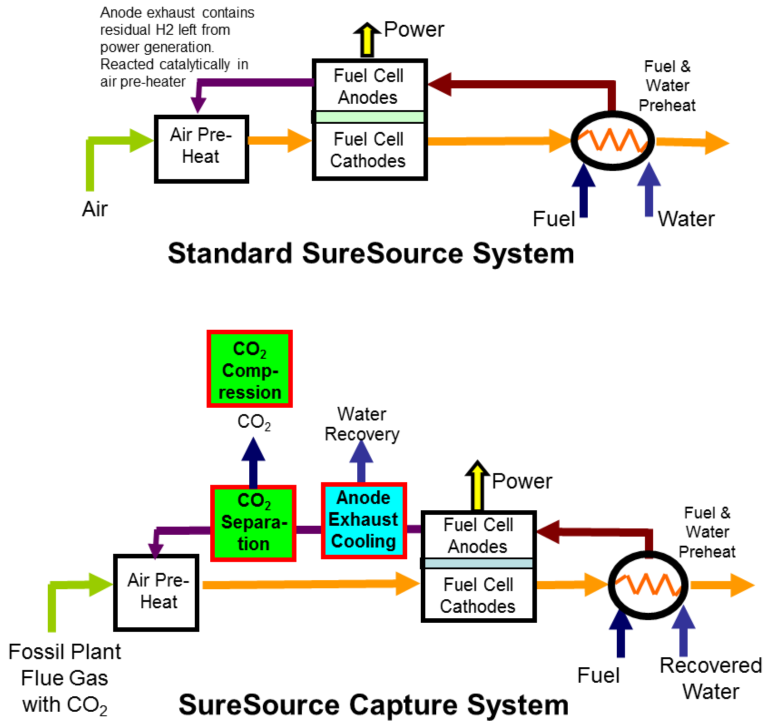
In contrast, the extra power produced by the SureSource Capture system increases the powerplant output from 500MW to 900MW, and only increases cost of energy to 8 cents/kWh (which can be reduced further if fuel cell incentives, such as the Federal Investment Tax Credit, are available). Also, the NOX destruction of the SureSource-based system reduces NOX to one sixth of its original value. 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 SureSource 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 utilizing abundant domestic energy resources cleanly. There are many other near term applications:

- **Smaller scale capture from large coal powerplants**, to achieve incremental CO_2 reductions and allow a staged approach to carbon capture from large systems
- **Capture from natural gas based baseload power generation powerplants**. 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 powerplants, 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 powerplants**. Peaking powerplants 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. SureSource-based 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 as well as activities such as steam generation for oil sands operations can benefit from the CO_2 avoidance as well as the on-site power production of the SureSource-based 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. SureSource-based systems can be used to capture those emissions.

The Technology

The SureSource-based carbon capture system is an extension of the standard SureSource powerplant design, as illustrated below. In a standard SureSource powerplant, 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 powerplant or an industrial source. The dilute CO_2 in the external flue gas will be reacted at the SureSource cathodes and transferred to the anode stream, from which it can be easily separated for sequestration or utilization.



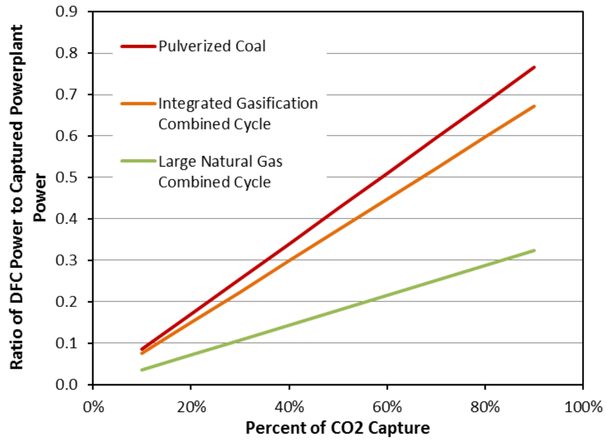
SureSource Modification for Carbon Capture

CO_2 from powerplant 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 percent. 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 powerplant will have as little as 5% 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, which 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 SureSource powerplant 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 SureSource 3000 fuel cell powerplant 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 SureSource powerplant. When used to capture CO_2 from a fossil fueled powerplant, the ratio of SureSource 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 SureSource to captured plant power as a function of CO_2 capture ratio for three types of source plants.



SureSource Carbon Capture Relative Plant Size Requirements

The size of the SureSource Capture system depends on the CO2 emission rate of the source plant and the desired level of capture efficiency

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

These large-scale SureSource-based carbon capture systems will ultimately be specially designed with larger scale balance of plant systems than today's commercial SureSource powerplant products. In the near term, capture systems can be configured as multiple-unit systems based on the 2.8MW SureSource 3000. SureSource-based 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 SureSource fuel cell powerplants have been available since 2003, and large fuel cell parks based on multiple SureSource 3000 powerplants have become common in bulk power generation applications. The largest such system so far is a 59 MW system consisting of twenty one SureSource 3000 powerplants, below.

59 MW Powerplant based on Twenty One SureSource 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 SureSource 3000