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Short communication

U.S. DOE fossil energy fuel cells program☆

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Abstract

The U.S. Department of Energy's (DOE) Office of Fossil Energy's (FE) National Energy Technology Laboratory (NETL), in partnership with private industry, educational institutions and national laboratories, is leading the development and demonstration of high efficiency, high temperature solid oxide fuel cells (SOFCs) and fuel cell turbine (FCT) hybrid power generation systems for stationary markets including auxiliary power units (APUs), distributed generation (DG) and large, coal-based central power plants. The DOE FE fuel cells program has three aspects: the Solid State Energy Conversion Alliance (SECA), Fuel Cell Coal Based Systems for central power, and the High Temperature Electrochemistry Center (HiTEC). The SECA goal is to decrease SOFC system cost to US$ 400 per kilowatt (kW) by 2010 for stationary markets. DOE FE is ultimately concerned with coal-based central power plants such as FutureGen. The goal is to aggregate SECA-type fuel cells into larger systems and to produce a very high efficiency megawatt-class FCT hybrid for testing at FutureGen. The low-cost, US$ 400 kW^{-1} SECA FCT hybrid is a key component to achieving 60% efficiency by 2020. Advanced aspects of solid oxide technology are part of HiTEC R&D. Technical progress and advances are discussed for all three program aspects.
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Keywords: Fuel cell; SOFC; Energy

1. Introduction

The DOE FE fuel cells program has three aspects: SECA, Fuel Cell Coal Based Systems for central power, and HiTEC. NETL manages these programs for FE and is partnering with Pacific Northwest National Laboratory (PNNL) in developing new directions in research and development (R&D) under SECA for the commercialization of modular, low-cost, and fuel flexible SOFC systems. The DOE FE strategy is to have SECA fuel cell technology demonstrated in stationary applications such as DG before use in large-scale fuel cell coal-based central power generation. The first step is demonstration in large volume DG markets by mass customization. The goal is to have SECA fuel cells capable of being manufactured at US$ 400 kW^{-1} by 2010. Simultaneously, the scale-up, aggregation, and integration of the technology will progress resulting in demonstration of MW-class intermediary fuel flexible products by 2015. An initial US$ 5 million solicitation was issued in 2005 for fuel cell building block and/or FCT hybrid proof of concept systems. With further aggregation and integration, the 2020 goal is the development of large (>100 MW) fuel cell power systems that will produce affordable, efficient and environmentally-friendly electrical power from coal with 60% overall efficiency from coal (higher heating value-HHV) to ac power, including integrated coal gasification and CO_2 separation processes and at least 90% of the CO_2 emissions from the system must be captured. System cost, exclusive of the coal gasification unit and CO_2 separation subsystems, must be US$ 400 kWe^{-1} or less.

DOE FE is ultimately concerned with coal-based central power plants such as FutureGen, a presidential initiative to produce hydrogen from coal with zero emissions, and all aspects of the DOE FE R&D programs now support it. The goal is to aggregate SECA-type fuel cells into larger systems and to produce a very high efficiency megawatt-class FCT hybrid for testing at FutureGen. The low-cost, US$ 400 kW^{-1} SECA FCT hybrid is a key component to achieving 60% efficiency by 2020.

This paper begins with detailed discussion of the U.S. DOE role in SOFC R&D under SECA, the hurdles it seeks to overcome, and recent advances. Fuel Cell Coal Based Systems,

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including fuel cell building blocks and FCT hybrids for central power system applications such as FutureGen, are the ultimate goal. Other technologies that impact solid oxide R&D are discussed under HiTEC. Finally, SOFC attributes are discussed.

2. Solid State Energy Conversion Alliance (SECA) Program

The SECA Program is the main thrust of the DOE FE fuel cells program. It is dedicated to developing innovative, effective and low-cost ways to commercialize SOFC power generation systems. The program is designed to move fuel cells out of limited niche markets and into widespread market applications by making them available at a cost of US$ 400 kW^{-1} or less by the year 2010. The enabling concept behind this objective is the mass customization of common modules. SECA fuel cells will operate on today's conventional fuels such as natural gas, diesel and coal synthesis gas, as well as hydrogen, the fuel of tomorrow. The program will provide a bridge to the hydrogen economy beginning with the introduction of SECA fuel cells for stationary (both central generation and DG) and APU applications [1–4].

The SECA Program is currently structured to include six competing Industry Teams supported by a crosscutting core technology program (CTP): Cummins, Delphi, General Electric (GE), Siemens Power Generation (SPG), Acumentrics, and FuelCell Energy (FCE). These Industry Teams are working on designs and manufacturing methods amenable to mass-production at costs that are an order-of-magnitude lower than current costs (see Table 1).

Table 1
SECA Industry Team design and manufacturing

Team	Design	Manufacturing
Cummins	Electrolyte supported-planar 825 °C Thermally matched materials Seal-less stack	Tape casting Screen printing Co-sintering
Delphi	Anode supported-planar 750 °C Ultra compact Rapid transient capability	Tape casting Screen printing Two-stage sintering
General electric	Anode supported-radial 750 °C Hybrid compatible Internal reforming	Tape calendaring Two-stage sintering
Siemens power generation	Cathode supported-flattened oval 800 °C Seal-less stack	Extrusion Plasma spray
Acumentrics	Anode supported-microtubular 750 °C Thermally matched materials Robust & rapid start-up	Extrusion Dip processing Spray deposition Co-sintering
FuelCell Energy	Anode supported-planar <700 °C Low-cost metals Thermal integration	Tape casting Screen printing Co-sintering Electrostatic deposition

DOE reached a significant milestone in the SECA Program in September 2005. GE became the first Industry Team to complete Phase I testing of a prototype fuel cell system. Their prototype met all SECA Phase I targets:

- projected manufacturing cost of US$ 746 kW^{-1} (<US$ 800 kW^{-1});
- efficiency of 38.0% LHV-AC (35–55%);
- degradation: <2% 1000 h^{-1} (<4% 1000 h^{-1}).

This means that a prototype of a fuel cell capable of being manufactured at a cost approaching that of conventional stationary power technology has been successfully tested by GE. While for many years the environmental and efficiency benefits of fuel cells have been well known, we now have a fuel cell prototype with the low-cost potential necessary for the technology to soon become commonplace in energy markets. The vision of an economy driven by pollution-free, low-cost fuel cells has taken a major step toward reality through this successful prototype.

All of the Industry Teams made exceptional progress in 2005, and each achieved fuel utilization values exceeding the interim program goal of 60%. Fuel utilization is the fraction of fuel entering the cell that reacts electrochemically to produce electric power, and it relates directly to the efficiency of a fuel cell and its associated lack of emissions. High fuel utilization is a key early performance milestone for reaching the cost goal of US$ 400 kW^{-1} and the system net-electrical efficiency goal of 40–60% by 2010.

GE researches have demonstrated increased power density and reliability with the development of full-size single-cell SOFC modules that consistently achieve a power density of 404 mW cm^{-2} at 88% fuel utilization, substantially surpassing their SECA Phase I goal of 300 mW cm^{-2}. This represents a 47% increase over GE's 2004 baseline performance. The cells have also demonstrated stable operation at 95% fuel utilization—a record for full-size planar SOFCs.

Delphi reached a power density of 575 mW cm^{-2} while maintaining a voltage of 0.7 V. This exceeds the Phase III goal of 500 mW cm^{-2} while meeting the necessary voltage target. Delphi also successfully completed the initial test sequence for their first stand alone Stationary Power Unit in May 2005. Operating independently of the grid, the unit produced a record peak net power output of 1.5 kW and surpassed previous milestones for system run-time and efficiency. Prototype testing began at the end of September.

FuelCell Energy, under a teaming relationship with Versa Power Systems (VPS), designed a new fuel cell stack design that boosts the overall power output of the stack by 50%. Testing was initiated in May 2005 for this 3 kW SECA SOFC "3-1" system, and they have reported successful operation for more than 1000 h under actual system conditions. They also measured a voltage

Fig. 1. Siemens HPD5 and Delta9 cell stacks.

degradation rate of 1.3% per 1000 h after 26,000 h of single cell operation using stainless steel cross flow interconnects.

SPG began electrical testing of a Delta9 cell in 2005. The power per cell at the same length cell is significantly improved over HPD5 and HPD10 cells due to higher surface area of the Delta9 corrugated cell (see Fig. 1). The cell has accumulated 2100 h with no voltage degradation at 1000 °C. At approximately 1200 h, the current density was increased to 500 mA cm^{-2}.

Acumentrics improved the power of their cells by increasing the number of power takeoffs and improving conductivity along the cell length. This led to improvements of 80–100%, which are being implemented into acumentrics' generator designs. They have also developed a path to eventually triple the power of the state of the art SOFC tube.

Cummins exhibited significant progress in area specific resistance (ASR) and degradation with its ScSZ cells. The non-cell ASR contribution was reduced significantly, and the short stack power degradation reduced to <3% 500 h^{-1}. Along with this, Cummins demonstrated control of its live fuel cell system using its controls and power electronics. All of this has Cummins projecting successful demonstration of SECA Phase I performance targets.

Under the SECA CTP, collaborative technology transfer is helping to solve seal, interconnect, electrode, and fuel processing issues. Moreover, Virginia Tech has developed a highly efficient converter that boosts low direct current (dc) voltage to the higher voltage required for conversion to alternating current (ac) for household and commercial applications. The converter facilitates downsizing of the fuel cell stack and boosts net power output, while concurrently reducing the size and cost of the electronic systems behind it. SECA studies indicate that each 1% improvement in inverter efficiency can reduce fuel cell stack sots by US$ 5–10 kW^{-1}.

2.1. Manufacturing

SECA SOFCs are anticipated to be superior to existing fuel cells in cost and efficiency at comparable sizes. SECA fuel cell technology is currently capable of being manufactured for US$ 800 kW^{-1} if manufacturing facilities were built. However, no adequate fuel cell manufacturing facilities currently exist. Limited prototype testing of SECA fuel cells is planned to avoid the cost of too many high cost demonstrations. Efforts are underway to build a prototype SECA fuel cell manufacturing facility. Manufacturing facility scale-up will occur as the SECA technology meets cost and performance reliability goals and will improve U.S. international competitiveness in this new manufacturing industry. Moving from today's laboratory-scale fabrication technologies to low-cost, high volume commercial manufacturing is necessary for the development of low-cost SOFCs.

Today, we have some initial small manufacturing facilities. No more than 500 MW $year^{-1}$, maybe less, manufacturing volume is necessary to achieve the SECA US$ 400 kW^{-1} cost goal. Approximately US$ 0.2–0.5 million capital investment per megawatt per year manufacturing capacity is required. This means that only approximately a US$ 100–200 million investment is required for a 500 MW $year^{-1}$ manufacturing facility, a significant but not unreasonable amount to create an SOFC industry.

Now, the SECA Industry Teams and the SECA Program are entering the phase where active cultivation of manufacturing infrastructure will be desirable. Manufacturing and manufacturing jobs exists within the borders of the various states. The number of jobs at stake is enormous. Some estimate one job created for every MW of sales.

Fuel cells have benefited from the momentum created by the renewable energy technologies to create incentives at the state level for DG and "clean energy" technologies. State legislatures and governors are realizing that fuel cells represent an emerging industry base that will create high tech, high paying employment as well as potential sources of economic development. Originally the incentives were targeted for installation which only brought low levels of installation and operation and maintenance (O&M) type employment. The states in the past 18 months have shifted their "fuel cell specific incentives" to having fuel cell manufacturing companies locate their new facilities and R&D organizations in their state.

When one considers the sum total of all of the available state level incentives, they far exceed the federal R&D budget for stationary fuel cells. This is an affirmation of the technology push by the federal government and the "market pull" by the state regulators and legislators for fuel cells. The dollar amount of state incentives authorized or appropriated for fuel cells exceeds US$ 150 million per year. Much of this goes under-utilized, for no one is aware of any state fuel cell incentive program that has met or maxed out its cap.

In response, the Department of Commerce, National Institute of Standards and Technology (NIST), initiated an early stage partnership with DOE and the National Science Foundation to hold a national workshop on SOFC manufacturing in 2006. The proposed workshop will identify potential partnerships among manufacturers, government, material suppliers, and the manufacturing extension partnerships within all 50 states for establishing pilot manufacturing facilities. This workshop will be used to (1) provide general information, (2) guide R&D on critical manufacturing technologies and technical standards required for high volume production, (3) involve state public benefit funds and (4) direct future public–private partnerships that will facilitate transfer of technology to industry through cost-shared projects.

3. Fuel Cell Coal Based Systems

FCT hybrids will form the essential power block component of the FutureGen plant, enabling high overall efficiency and superior environmental performance to be achieved at low-cost. These benefits have been clearly established through conceptual studies and limited small-scale demonstrations fueled with natural gas. Making large-scale (>100 MW) FCT hybrid systems a reality requires advances in fuel cell cost and scalability to larger sizes. Cost issues are being addressed with considerable success within the SECA Program, as 3–10 kW SOFC system costs of less than US$ 800 kW^{-1} have been demonstrated in 2005.

In order to address the issue of scalability, DOE FE initiated the new Fuel cell coal-based systems program in 2005. The goal of this program is to develop and demonstrate the fuel cell technology required for central power station applications to produce affordable, efficient, environmentally-friendly electricity from coal. The new program leverages the advances made in SOFC technology under the SECA Program, extending coal-based SOFC technology to large central power generation station applications.

The R&D will help meet the Nation's future energy needs while achieving near-zero emissions in coal-fueled central power station applications. Key systems requirements to be achieved include 50% or greater overall efficiency in converting the energy contained in coal to grid electrical power, the capture of 90% or more of the carbon contained in the coal fuel (as CO_2), and a cost of US$ 400 kW^{-1}, exclusive of the coal gasification unit and CO_2 separation subsystems.

The research will be conducted in three phases. During Phase I, the focus will be on the design, cost analysis, fabrication, and testing of large-scale SOFC stacks fueled by simulated coal synthesis gas. Central to the Phase I effort will be the resolution of technical barriers with respect to the manufacture and performance of larger-sized fuel cells. Phases II and III will focus on the fabrication of aggregate SOFC systems and culminate in proof-of-concept systems to be field-tested for a minimum of 25,000 h, beginning in 2012. These systems will be sited at existing or to-be-built coal gasification units, potentially at DOE's FutureGen facility.

The first two projects under this program were selected in August 2005. The projects will be conducted by two research teams—one led by GE Hybrid Power Generations Systems, LLC (GE HPGS) and the other by SPG. The two teams will research, develop, and demonstrate fuel cell technologies that can support power generation systems larger than 100 MW capacity.

GE HPGS, is partnering with GE Energy, GE Global Research, PNNL, and the University of South Carolina to develop an integrated gasification fuel cell (IGFC) system that merges GE's SECA-based planar SOFC, gas turbine, and recently acquired (from ChevronTexaco) coal gasification technologies. The system design incorporates a SOFC/gas turbine hybrid as the main power generation unit.

SPG is partnering with ConocoPhillips and Air Products and Chemicals, Inc., (APCI) to develop large-scale fuel cell systems based upon their in-house gas turbine and SECA modified tubular SOFC technologies. ConocoPhillips will provide coal gasification expertise. In addition, the baseline design incorporates an ITM oxygen air separation unit (ASU) from APCI, offering system efficiency advantages over traditional ASUs.

3.1. Fuel cell turbine hybrids

NETL and FCE are working collaboratively to do large-scale expedient testing of an atmospheric Direct FuelCell/Turbine (DFC/T) hybrid system. To date, the R&D efforts have resulted in significant progress in validating the DFC/T cycle concept. FCE has completed successful proof-of-concept testing of a DFC/T power plant based on a 250 kW DFC integrated initially with a Capstone 30 kW and then a 60 kW modified microturbine as shown in Fig. 2. The results of the sub-MW system tests have accumulated over 6800 h of successful operation with an efficiency of 52%.

Researchers in the Energy System Dynamics Division within the Office of Science and Engineering Research at NETL have completed shakedown of an experimental facility capable of physically simulating the dynamic operation of a FCT hybrid system. The objective of the Hybrid Performance (Hyper) project at NETL is to conceptualize, simulate, analyze and demonstrate critical operability issues inherent in hybrid fuel cell systems. The hardware-in-the-loop simulation facility enables researchers to identify dynamic issues related to the interdependencies of fuel cell and turbine technology integration without risk to expensive fuel cell stacks [5,6].

Fig. 2. FuelCell Energy DFC/T hybrid.

3.2. FutureGen

FutureGen [7], the Integrated Hydrogen, Electric Power Production and Carbon Sequestration Research Initiative, is a partnership to design, build and operate a nearly emission-free, coal-fired electric and hydrogen production plant. No coal-to-gas plant in the world today is configured to optimize hydrogen production or to capture carbon. The FutureGen prototype plant would be the world's first. The 275 MW prototype plant will serve as a large-scale engineering laboratory for testing new clean power, carbon capture, and coal-to-hydrogen technologies. It will pioneer advanced hydrogen production from coal, as well as capture and permanently sequester CO_2. The captured CO_2 will be separated from H_2 by novel membranes currently under development. Two primary goals for FutureGen are as follows:

- Design, construct, and operate a nominal 275 MW (net equivalent output) prototype plant that produces electricity and hydrogen with near-zero emissions. The size of the plant is driven by the need for producing commercially-relevant data, including the requirement for producing one million metric tonnes per year of CO_2 to adequately validate the integrated operation of the gasification plant and the receiving geologic formation.
- Validate the engineering, economic, and environmental viability of advanced coal-based, near-zero emission technologies that by 2020 will: (1) produce electricity with less than a 10% increase in cost compared to non-sequestered systems; (2) produce H_2 at US$ 4.00 per million Btus (wholesale), equivalent to US$ 0.48/gallon of gasoline (wholesale).

The future production of hydrogen from fossil fuels requires advances in membranes and fuel cells. The importance and potential of ion conducting ceramics in SOFCs and ceramic membranes to hydrogen production, and their ultimate integration in a coal-based FutureGen plant are discussed below. SOFCs, oxygen and hydrogen separation membranes are based on high temperature ion conducting ceramics. These ceramics are metal oxides with typically a perovskite or fluorite structure [8].

A representative FutureGen plant is conceptualized in Fig. 3. The FCT hybrid is a key part of the FutureGen plant to produce hydrogen from coal. The highly efficient SOFC hybrid plant, with its SECA fuel cells, will produce low-cost electric power and other parts of the plant could produce hydrogen and sequester CO_2. The hydrogen produced can be used in fuel cell cars and for SOFC DG applications [9].

As can be seen, this configuration also integrates all of the ion conducting ceramic components: SOFCs, oxygen and hydrogen separation membranes. It consists of an oxygen (O_2) blown advanced transport reactor (ATR) with hot gas cleanup followed by a shift unit and a high temperature membrane unit. This membrane unit separates the H_2. The tail gas from the membrane unit

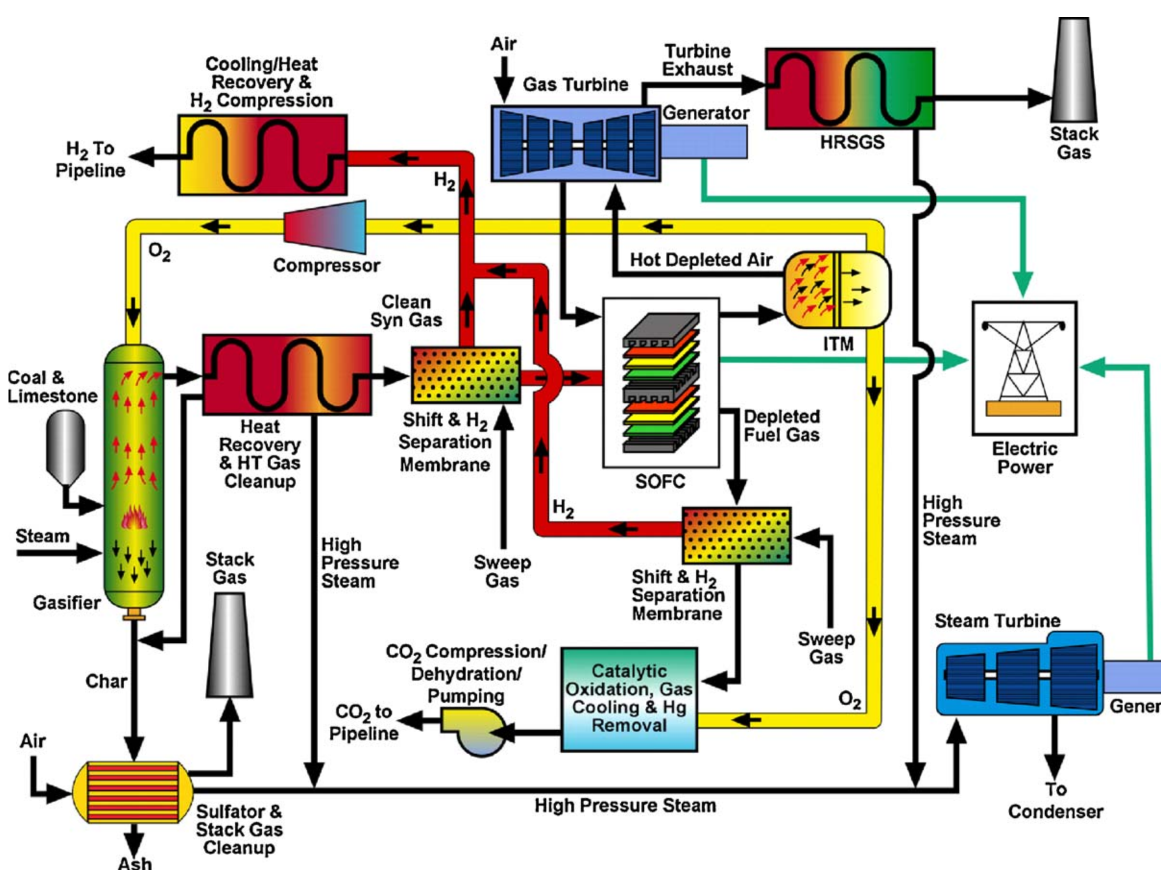

Fig. 3. FutureGen simplified process flow diagram.

consisting primarily of CO, CO_2, portion of the H_2 that is not separated, H_2O and inerts such as N_2 are fed to the anode side of a SOFC. Air to the cathode side of the SOFC is supplied by the compressor of a gas turbine. The anode exhaust gas after heat recovery is fed to a second shift unit where additional H_2 is formed by shifting the remaining CO. The shifted gas, now mainly CO_2 with some small CO and H_2 content goes to a H_2 membrane separator to capture the 80% of the H_2 for recycle to the SOFC. Alternately, a membrane shift unit can be utilized. The non-permeate is fed to a catalytic combustor using O_2 from the ion transport membrane (ITM) oxygen plant to fully remove the small amounts of any remaining CO and H_2, leaving only CO_2, H_2O, and a very small amount of O_2 in the stream. This stream is cooled, the Hg is removed in the sulfided activated carbon bed, and the cooled CO_2 stream is pressurized to 2000 psi, for shipping to sequestration area.

On the cathode side, the compressed air, at approximately 20 bar, is heated in a regenerator (not shown in the diagram) prior to entering the SOFC. The hot depleted air exiting the cathode enters the hot side of the regenerator and is cooled to 900 °C, the temperature required by the ITM (or oxygen transport membrane OTM) unit for air separation. In this membrane unit, O_2 is removed from the already vitiated air and exits the unit at sub-atmospheric pressure. The 100% O_2 is cooled and compressed to gasifier pressure with a small side stream going to the catalytic “cleanup” burner. The non-permeate, now reduced in mass flow and pressure, is expanded in the turbine and exhausts to an HRSG where it is cooled to 66 °C.

4. High Temperature Electrochemistry Center (HiTEC)

The High Temperature Electrochemistry Center is a research collaboration focused on understanding the scientific and technical breakthroughs needed to accomplish DOE’s vision for energy plants for the future, such as FutureGen. HiTEC applies advanced high temperature electrochemistry so that fossil fuels can be used efficiently while producing fewer pollutants.

HiTEC was established at PNNL as part of the Advanced Research Program for fuel cells to support FE’s FutureGen Initiative. Satellite research centers have been established at Montana State University (MSU) in Bozeman and at the University of Florida in Gainesville. Focused on long-term basic research, HiTEC’s mission is to advance high temperature solid oxide electrochemical technologies, such as solid oxide high temperature electrolyzers, reversible or regenerable fuel cells, energy storage devices, gas separation membranes, low temperature SOFC concepts, and sensors, and to conduct fundamental research that aids the general development of all solid oxide technology. HiTEC also has two major contracts in place: University of Utah for active cathodes through modification of space charge effects and California Institute of Technology for enhanced power stability.

An initial solicitation was issued in 2005, and it focused on the following topics:

- energy storage utilizing high temperature electrochemical processes;
- revolutionary high temperature electrochemical power technology;
- thermoelectric-SOFC hybrid energy conversion;
- effect of coal contaminants on SOFC system performance and service life.

Awards were made to five new HiTEC Participants: University of Utah, Massachusetts Institute of Technology, Northwestern University, United Technologies Research Center, and SRI International. The selected projects focus primarily on SOFCs for use in large central coal-fired power plants. Coal-based power production systems that incorporate SOFCs have the potential for significantly higher efficiencies and lower emissions than conventional technologies. In addition, high temperature electrochemical systems can enhance energy storage in central coal power plants, reducing the impact felt during hours of peak demand and making the plants more cost effective.

Energy storage technologies enable central coal plants with load leveling and peak load electricity supply capabilities to satisfy daily and seasonal peak load periods between 3 and 10 h in duration. This investment in large energy storage technologies for central coal power plants is anticipated to result in spin-off products for smaller scale power generation systems. For example, high temperature energy storage technology developed could serve regional and local needs when integrated with high temperature power generation units, such as molten carbonate fuel cells and SOFCs, as well as waste heat from microturbines.

Reversible fuel cells are another important topic of study under HiTEC. Reversible fuel cells can take advantage of excess electrical grid capacity during off-peak hours to produce hydrogen fuel to be utilized later during periods of high electrical demand. The power unit (fuel cell) is sized for the peaking load. To minimize cost, the electrolyzer is rated at a power that can produce sufficient hydrogen to recharge the hydrogen storage capacity over the remaining hours of the day. A new all-ceramic fuel electrode has been developed at PNNL that shows high activity for steam electrolysis. The ceramic electrode is actually a composite of two oxide phases—doped strontium titanate and doped ceria. Because this electrode is composed of metal oxides, it shows less susceptibility than nickel/zirconia to degradation by intermittent exposure to air. Lower polarization losses associated with the ceramic composite electrode can lead to more efficient hydrogen production by steam electrolysis.

5. Solid oxide fuel cells

SOFCs use a ceramic electrolyte that results in a solid state unit, an important aspect. The conduction mechanism is solid state conduction of O^{2-} ions. The reaction is completed by the reaction of oxygen ions and hydrogen to form water. SOFCs can extract hydrogen from a variety of fuels using either an internal or external reformer. They are also less prone to CO poisoning than other fuel cells and thus are attractive for coal-based fuels. SOFCs work well with catalysts made of nickel, which is much less expensive than platinum. SOFCs can achieve efficiencies of 55% stand-alone, or over 80% (net) if the waste heat is used for cogeneration. SOFC challenges include power

Table 2
Solid oxide fuel cells—attributes

Attribute	Application
High electric conversion efficiency	Demonstrated, 47%
	Achievable, 55%
	Hybrid, 65%
	CHP, 80%
Superior environmental performance	No NO_x
	Lower CO_2 emissions
	Sequestration capable
	Quiet; no vibrations
Cogeneration—combined heat and power (CHP)	High quality exhaust heat for heating, cooling, hybrid power generation, and industrial use
	Co-production of hydrogen with electricity
	Compatible with steam turbine, gas turbine, renewable technologies, and other heat engines for increased efficiency
Fuel flexibility	Low or high purity H_2
	Liquefied natural gas
	Pipeline natural gas
	Diesel
	Coal synthesis gas
	Fuel oil
	Gasoline
	Biogases
Size and siting flexibility	Modularity permits wide range of system sizes
	Rapid siting for distributed power
Transportation and stationary applications	Watts to megawatts

density improvement, cost reduction, and the development of improved seals and metallic interconnects [10].

For SOFCs, conventional fuels can be used at present, while hydrogen may be used in the future. Like most fuel cells, SOFCs will operate better on hydrogen than on conventional fuels; therefore, the commercialization path for fuel cells is through portable and stationary markets using today's conventional fuels, transitioning to transportation markets using hydrogen. Each market offers potential for progressively lower hardware costs [11,12].

In the U.S., the market makes the eventual choice between viable technology alternatives. Less expensive materials, simplified stack and system designs and high volume markets are the three criteria that must be met by a fuel cell system to compete in today's energy market. These criteria form the basis for SECA's goal of lowering fuel cell costs.

High temperature SOFC systems possess numerous attributes for various applications: high electrical efficiency; superior environmental performance; combined heat and power (CHP), fuel, size and siting flexibility; transportation and stationary application potential (Table 2). These attributes hold promise for SOFC use in worldwide stationary industrial and residential power generation applications, as APUs in trucks and cars, and in myriad military applications.

6. Summary

The prototype of the first SECA-type fuel cell capable of being manufactured at a cost approaching that of conventional stationary power technology has been successfully tested by GE. The vision of an economy driven by pollution-free, low-cost fuel cells has taken a major step toward reality through this successful prototype. SECA fuel cells and FCT hybrids are essential to meet DOE's goals for zero emissions, high efficiency, sequestration ready advanced coal-based power plants. High temperature electrochemical systems can also enhance energy storage in central coal power plants, reducing the impact felt during hours of peak demand and making the plants more cost effective.

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