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Journal of Power Sources 143 (2005) 191–196

JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Short communication

The U.S. Department of Energy, Office of Fossil Energy Stationary Fuel Cell Program

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Received 23 November 2004; accepted 15 December 2004
Available online 20 February 2005

Abstract

The U.S. Department of Energy (DOE) Office of Fossil Energy's (FE) National Energy Technology Laboratory (NETL), in partnership with private industries, is leading a program for the development and demonstration of high efficiency solid oxide fuel cells (SOFCs) and fuel cell/turbine hybrid power generation systems for near-term distributed generation markets, with emphasis on premium power and high reliability. NETL is partnering with Pacific Northwest National Laboratory (PNNL) in developing new directions for research under the Solid State Energy Conversion Alliance (SECA) initiative to develop and commercialize modular, low cost, and fuel flexible SOFC systems. Through advanced materials, processing and system integration research and development (R&D), the SECA initiative will reduce the fuel cell cost to \$400 kW^{-1} for stationary and auxiliary power unit markets. The SECA industry teams and core program have made significant progress in scale-up and performance. Presidential initiatives are focusing research toward a new hydrogen economy. The movement to a hydrogen economy would accomplish several strategic goals, namely that SOFCs have no emissions, and hence figure significantly in DOE strategies. The SOFC hybrid is a key part of the FutureGen plant, a major new DOE FE initiative to produce hydrogen from coal. The highly efficient SOFC hybrid plant will produce electric power while other parts of the plant could produce hydrogen and sequester CO_2. The produced hydrogen can be used in fuel cell cars and for SOFC distributed generation applications.

Keywords: Fuel cell program; Solid oxide fuel cells; SOFCs; Fuel cell/turbine hybrid; Distributed generation

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1. Public benefits and DOE policy initiatives

Presidential initiatives are focusing research toward a new hydrogen economy to accomplish several strategic goals: the U.S. can use its own domestic resources—solar, wind, hydroelectric, and coal to reduce greenhouse gas emissions. To this end, the U.S. government has proposed several major initiatives, such as Clear Skies and Climate Change, which aim to reduce CO_2, NO_x, and SO_2 emissions. As shown in Figs. 1 and 2, SOFCs have large economic benefits and no emissions, which figure significantly in these DOE strategies.

Distributed generation—SOFCs, reforming, and energy storage—provides significant benefit for enhanced security and reliability. The use of fuel cells is expected to bring about the hydrogen economy. However, commercialization of fuel cells is expected to proceed first through portable and stationary applications, by developing SOFCs for a wide range of stationary and APU applications, which will initially use conventional fuels, then eventually migrating to hydrogen. Like all fuel cells, the SOFC will operate even better on hydrogen than conventional fuels [1].

Near-term natural gas reforming is the most likely route of hydrogen production, from nuclear, coal, natural gas, and renewable sources. Considering the properties of hydrogen, it is likely to be produced locally and used immediately. One scenario would be a large local hydrogen plant supplying fuel to the automobile and bus fleet of a major metropolis. Ultimately, hydrogen is expected to be produced from renewable sources: wind and solar with electrolysis [2–4].

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doi:10.1016/j.jpowsour.2004.12.003

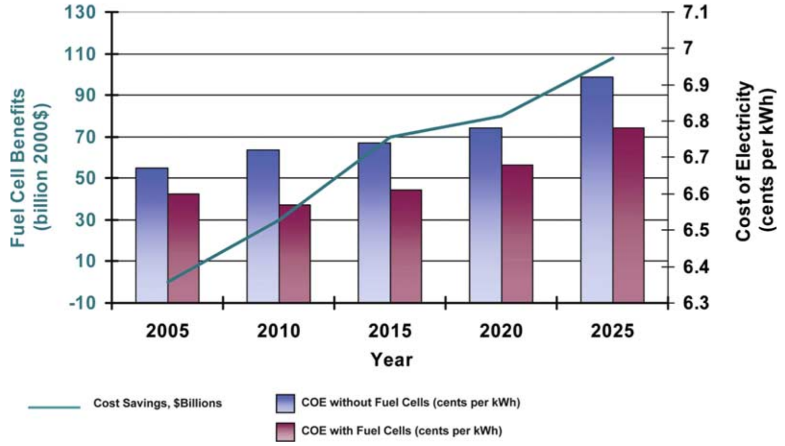

Fig. 1. Cost benefits of SOFCs.

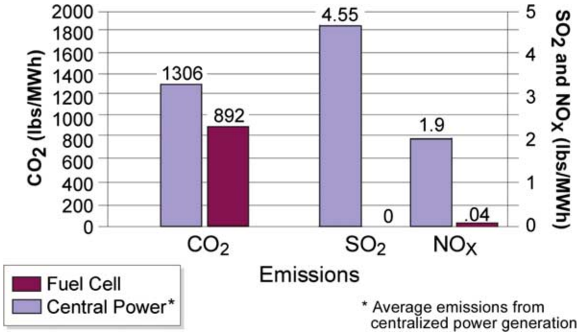

Fig. 2. Environmental benefits of SOFCs.

Coal may be a possible fuel for producing hydrogen; over 50% of the electricity in the U.S. comes from coal, and coal use is on the rise. Coal is a very abundant resource, and could become the primary fuel for energy independence in the U.S. Coal is poised to play an important role in the future of independence and security of the U.S. energy needs.

The president recently announced the 275 MW FutureGen project to produce hydrogen from coal. This is a $1 billion presidential initiative leading to a 10-year demonstration project to create the world's first coal-based zero-emissions power plant with over 1 million tons per year of CO_2 sequestered.

2. Technology and status high-temperature fuel cells

High temperature fuel cells include solid oxide and molten carbonate fuel cells. SOFCs use a ceramic electrolyte which 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. In a molten-carbonate fuel cell (MCFC), molten carbonate salts are the electrolyte. At 650 °C, the salts melt and conduct carbonate ions $(CO_3)^{2-}$ from the cathode to the anode. At the anode, hydrogen reacts with the ions to produce water, CO_2, and electrons that flow through the external circuit. At the cathode, the electrons react with oxygen from air and CO_2 recycled from the anode to form carbonate ions that replenish the electrolyte and transfer current through the fuel cell. SOFCs and MCFCs 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 and MCFCs work well with catalysts made of nickel, which is much less expensive than platinum. SOFCs and MCFCs can achieve an efficiency of 60% stand-alone, or over 80% (net) if the waste heat is used for cogeneration. Currently, demonstration units exist up to 2 MW. Challenges with SOFCs are development of high power density, reducing cost, and better seals and metallic interconnects. Significant technical challenges with MCFCs are the complexity of working with a liquid electrolyte rather than a solid, and the relatively inherent low power density, as well as high cost. Advantages of both fuel cells are the fuel flexibility, using coal, natural gas, or heavy fuels with small modification. R&D funding by the public sector for MCFC has been concluded as is not discussed. Research is continuing by industry to optimize costs of materials and production processes to enable market entry [1].

3. Solid State Energy Conversion Alliance SECA

In the United States, SECA is a major national stationary fuel cell program, and comprises the main thrust of the Distributed Generation Fuel Cell Program [5–10]. Achieving SECA goals should result in the wide deployment of the SOFC technology in high volume markets. Near zero emissions, fuel flexibility, modularity, high efficiency, and simple CO_2 capture will provide a national payoff that increases as these markets expand. The SECA program is dedicated to developing innovative, effective, low cost ways to commercialize solid oxide fuel cells. The program is designed to move fuel cells out of limited niche markets into widespread market applications by making them available at a cost of

Fig. 3. SECA industry teams.

\$400 kW^{-1} or less through mass customization of common modules [11,12]. SECA fuel cells will operate on conventional fuels, such as natural gas, diesel, coal, and gas, and will move to hydrogen. The program will provide a bridge to the hydrogen economy, beginning with the introduction of SECA fuel cells for stationary (both central generation and distributed energy) and auxiliary power applications [13,14].

Commercial trucks, military vehicles, aircrafts, and ships are all potential SECA applications. To lower the cost of fuel cells as much as possible, it is important to utilize fuel cells in all of these applications [15]. A number of other federal and state government agencies and offices are directly supporting SECA program efforts [16–21].

The SECA program is currently structured to include six industry teams supported by a core technology program that is working to solve crosscutting issues.

SECA is an \$800 million (MM) program through 2010, with \$375 MM from DOE for the industry teams. SECA has six industry teams working on designs that can be mass-produced at costs that are 10-fold less than current costs. Many alternatives are being pursued, which increases the probability of success of the SECA program. The SECA core technology program is made up of researchers from industry suppliers and manufacturers, as well as from universities and national laboratories, all working to address key science and technology gaps to provide breakthrough solutions to critical issues facing SECA. Fig. 3 shows each team and their working prototype. In fiscal year (FY) 2005 testing of prototypes begins [22].

4. SECA prototypes

General Electric (GE) is developing a compact natural gas 5-kW, planar, 700–800 °C, anode-supported SOFC unit for residential power markets [10,22]. GE is evaluating several stack designs, and is especially interested in extending planar SOFCs to large hybrid systems. GE has already achieved over 400 mW cm^{-2}, exceeding its Phase I SECA targets for stack power density and utilization. Using a planar square SOFC stack, GE has achieved record 238 mW cm^{-2} at 93% fuel utilization and stable operation at 95% fuel utilization.

Delphi is working on a third generation design that has achieved 420 mW cm^{-2} in two 30-cell stacks. Delphi, in partnership with Battelle/PNNL, is developing a compact 5-kW, planar, 700 to 800 °C, anode-supported SOFC unit for the distributed generation and auxiliary power unit markets. Delphi is expert at system integration and high-volume manufacturing and cost reduction. They are focused on making a very compact and light-weight system suitable for auxiliary power in transportation applications [10,22].

Cummins and SOFCo EFS are developing a 10-kW product for recreational vehicles that would run on propane using a catalytic partial oxidation reformer. The team has produced a conceptual design for a multilayer SOFC stack assembled from low-cost building block components. The basic cell is a thin electrolyte layer (50 to 75 μm), fabricated by tape casting. Anode ink is screen-printed onto one side of the electrolyte tape, and cathode ink onto the other. The printed cell is sandwiched between layers of dense ceramic that will accommodate reactant gas flow and electrical conduction. The assembly is then co-fired to form a single repeat unit [10,22].

Siemens Westinghouse Power Corporation (SWPC) is developing 5 to10-kW products to satisfy multiple markets. SWPC has developed a new tube design for their 5-kW units that use flat, high power density tubes. This allows for a shorter tube length with twice the power output, compared to their current cylindrical tube. The Siemens Westinghouse's flattened high power density tubes have achieved a respectable 262 mW cm^{-2} at 85% fuel utilization at 1000 °C [10,22].

Acumentrics uses a micro-tubular design and is already offering early units for field testing. They are interested in the information technology and uninterruptible power supply markets and have conducted over a dozen early unit field tests. The advantages of smaller diameter tubes are higher volumetric power density and rapid start-up because they are less susceptible to thermal shock. Acumentrics units have already achieved 63 thermal cycles [10,22].

FuelCell Energy Inc. (FCE) will bring its long history of fuel cell development to a teaming relationship with Gas Technology Institute (GTI) and VERSA Power, by acquiring Global Thermal Electric, which has a 5-MW per year manufacturing facility and over 25,000 h of testing experience on their RP-2, 2-kW units [10,22].

Finally, the SECA industry teams have surpassed the interim goal of 60% fuel utilization for their short stacks during the first quarter of FY2004.

The funding split for the program's industrial team and core technology areas has been 60/40. The key management tool in the program is a contract clause providing for exceptional circumstances, which encourages sharing R&D solutions with industry teams. The core R&D priorities are based on industry needs and other expert input gathered through workshops. Technology progress is constantly monitored, and priorities are adjusted as needed. The highest research priorities—gas seals and metal interconnects—are critical to stack operation. The industry team R&D must also include lower temperature components, higher power density, insulation, fuel reforming, and power electronics in its research.

5. Central station systems: fuel cell turbine hybrids

All aspects of the DOE FE research and development program now support the FutureGen program and project—including distributed generation fuel cells. Research in distributed generation is developing scaled-up fuel cell and hybrid \$400 kW^{-1} power blocks for FutureGen and other advanced coal-based power systems. Distributed generation systems are critical to achieving cost, efficiency and emissions targets. SOFCs have tremendous cost reduction potential, based on mass customization, or the mass production of common modules for multiple applications. Low-cost, \$400 kW^{-1} SECA fuel cell hybrids are key to achieving 60% higher heating value (HHV) efficiency, low-cost, \$850 kW^{-1} advanced coal-based power systems [22–24]. Fuel cells and fuel cell hybrids have ultra low emissions, produce water, and can be configured to isolate/segregate CO_2—usable features in FutureGen and advanced coal-based systems. SECA fuel cells and hybrids can operate on syngas and hydrogen in FutureGen systems, as well as other conventional fuels.

Fig. 4 is a coal-based fuel cell-turbine hybrid FutureGen-type plant that can achieve 65% HHV efficiency by incorporating solid oxide ITM membranes and hydrogen membranes. The high hydrogen export case results in 65% efficiency, defined on an HHV basis and includes the HHV of the exported hydrogen: thermal efficiency = (net export electric power + HHV contained in exported H2)/(HHV contained in the total coal feed). We are confident that the best FutureGen systems will contain fuel cells [23].

The SOFC SECA-hybrid is a key component of the FutureGen plants. FutureGen is an important new presidential initiative 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

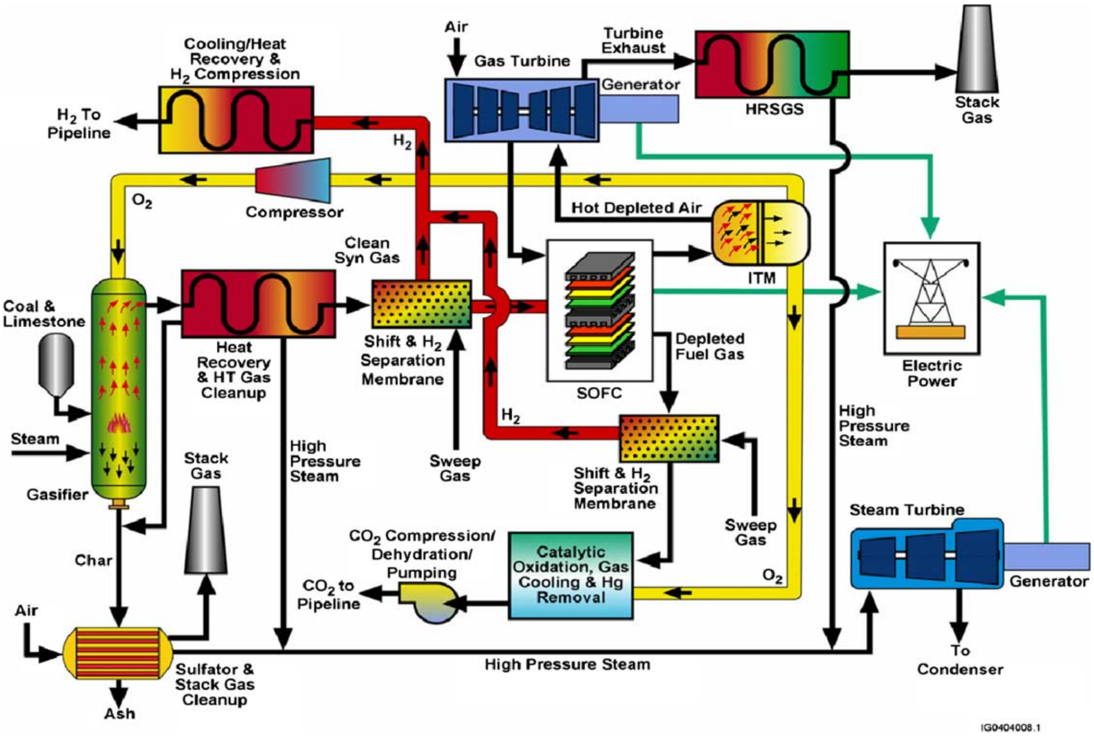

Fig. 4. Possible FutureGen plant.

produce hydrogen and sequester CO_2. The produced hydrogen can be used in fuel cell automobiles and for SOFC distributed generation applications. Early hybrids at SWPC and FCE are being tested to gather information and experience that will lead to SECA hybrid systems for incorporation into FutureGen.

The DOE goal is to demonstrate the fuel cell technology in distributed generation applications before they are used in large-scale central power generation. The first step is demonstration in high volume production, or mass customization. The goal is to develop SECA fuel cells capable of being manufactured at \$400 kW^{-1} by 2010. Simultaneously, the scale-up, aggregation, and integration of the technology are in progress. This will result in commercialization of MW-class intermediary fuel flexible products, such as fuel cell-turbine hybrids ready for demonstration in the 2012 to 2016 timeframe. With further aggregation and integration, SECA designs will ultimately be applicable to 100-MW class, large central generation by 2020.

NETL and FCE are working collaboratively on large-scale expedient testing of an atmospheric Direct FuelCell/Turbine (DFC/T) hybrid system. To date, research and development efforts have resulted in significant progress in validating the hybrid 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 generator. The results of the subMW system tests have accumulated over 6800 h of successful operation with efficiency of 52%.

The Hybrid Power Generation Systems Division of General Electric is collaborating with DOE/NETL to develop SOFC/gas turbine hybrid systems as intermediate products for distributed power generation applications [22]. The objectives for this project are to analyze and evaluate planar SOFC/gas turbine system concepts. Technical barriers in pressurization and scale-up of preliminary design concepts will be resolved for both the feasibility demonstration system and the conceptual system. A preliminary design for high-temperature heat exchangers for hybrid system applications has been developed, and pressurized operation of planar SOFC stacks has been demonstrated. The SOFC is based on the SECA thin-film electrolyte technology fabricated with the tape calendaring method and thin-foil metallic interconnects leading to a low-cost, high-performance, compact planar SOFC. The gas turbine is based on commercial products. The proposed hybrid system has a potential for efficiency greater than 65%.

Researchers in the Combustion and Engine Dynamics Division within the Office of Science and Technology at NETL have completed an experimental facility capable of physically simulating the dynamic operation of a fuel cell-turbine hybrid system. The objective of the hybrid performance 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.

6. High Temperature Electrochemistry Center (HiTEC)

The High Temperature Electrochemistry Center (HiTEC) is pursuing advanced electrochemical solutions to energy problems. HiTEC is developing enabling technologies and innovations necessary in long-term R&D for FutureGen and hydrogen economy programs. In addition, HiTEC is attempting to resolve electrochemical issues that cross-cut all solid oxide technologies, such as patterned electrode work, which allows the role of microstructure and catalytic activity to be distinguished [24].

7. Conclusion

Stationary fuel cells still need a viable distributed generation market and a responsive electric power industry. Residential and commercial fuel cells remain the largest potential market. All fuel cells can use hydrogen, so a hydrogen economy is welcome. The ultimate potential of the fuel cell technology is clear. The SECA program is making excellent progress. We now need a period of intense R&D and public education to resolve the remaining issues in order to reach that potential.

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