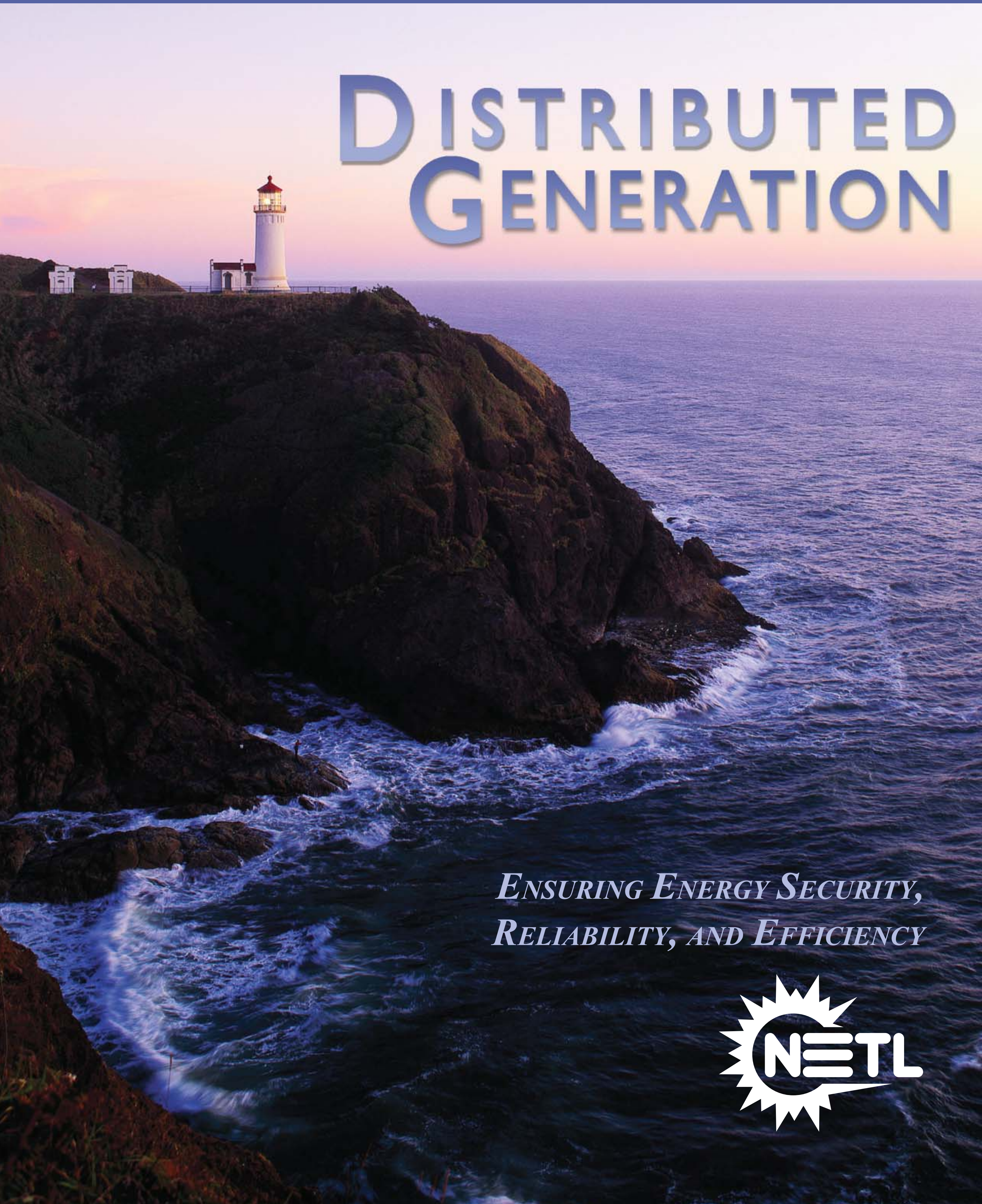
U.S. Department of Energy • Office of Fossil Energy
National Energy Technology Laboratory



DISTRIBUTED GENERATION

ENSURING ENERGY SECURITY, RELIABILITY, AND EFFICIENCY

NETL

The U.S. Department of Energy (DOE) Office of Fossil Energy, through the National Energy Technology Laboratory (NETL), is taking the lead in forging government/industry partnerships to develop a portfolio of new power systems that will forever change the way energy is viewed. Fuel cell and novel generation systems are being pursued that are compact and quiet and offer unsurpassed efficiencies and environmental performance. These characteristics allow them to be strategically placed almost anywhere, including customer sites, in what is called distributed generation (DG).

DG is becoming an essential option as our nation enters a new energy era marked by utility restructuring, the digital revolution, escalating environmental concerns, and threats to our energy security. Currently available technology limits DG to niche applications. NETL's portfolio of technologies will enable application of DG in mainstream markets. One primary barrier remains in the path to commercialization – cost. To remove that barrier, NETL has structured unique alliances to mobilize the nation's scientific community and government and industry resources.

Introduction

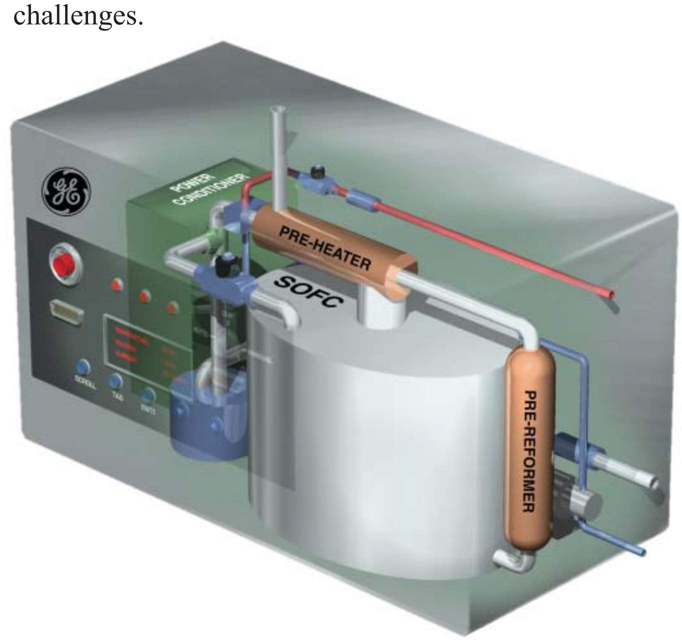
As the 21st century unfolds, changing market forces, energy security issues, and evolving technologies herald a new age in electricity production — distributed generation (DG). Much like the shift from mainframe to personal computers, DG places power at the customer site, tailors the power to specific needs, and places control in the hands of the customer.

Driving forces for DG are many. The digital revolution requires ever increasing amounts of electric capacity at installation rates and levels of reliability and power quality that are beyond traditional central power system capabilities. The nation's transmission and distribution (T&D) grid is already overburdened, and the time and cost for upgrades or capacity additions to keep pace with demand at present are prohibitive. The transition to utility restructuring along with regulatory uncertainty are making power producers averse to the major financial exposure associated with central power plant construction. Our economy is threatened by overdependence on unstable foreign sources of energy and terrorist attack. Energy security countermeasures require efficient use of domestic resources and reduced vulnerability of our electric delivery infrastructure to terrorist attack. Environmental criteria demand near-zero emissions and ultra-high efficiency from new electric generating capacity.

Technologies that hold the promise for enabling widespread application of DG and addressing expressed market and energy security issues are poised to become a commercial reality. The Department of Energy's (DOE) Office of Fossil Energy, through the National Energy Technology Laboratory (NETL), has put in place a multi-component program to effect that commercialization. These components are Fuel Cell Systems, Innovative Systems Concepts, Vision 21 Hybrids, Novel Generation Concepts, and Advanced Research. The power systems targeted for future research are solid oxide fuel cells (SOFC), fuel cell/turbine (FC/T) hybrids that integrate SOFCs and gas turbines, and a novel generation technology called the Ramgen Turbine.

This portfolio of technologies has the potential to revolutionize the energy industry. The fuel cell-based systems offer virtually pollution-free performance at unsurpassed efficiencies on a range of domestic fuels. Together with compact modular construction and quiet operation, these fuel cell-based systems can be installed almost anywhere and match specific power demands. Ramgen Turbines apply rocket engine science to significantly advance gas turbine performance and enable operation on low-energy-density waste-derived fuels.

Presented here is an overview of NETL's efforts to make DG a readily available energy option. Included is a look at the technologies, the challenges that must be overcome to achieve market entry, and the strategies for overcoming the challenges.



STRATEGIC PERSPECTIVE

NETL's DG program focuses on stationary fuel cell-based power systems that can meet market entry criteria envisioned in the next decade. Environmental hurdles for new capacity are certain to be essentially zero pollutant emissions and ultra-high efficiency, as evidenced by proposed regulations and the President's Climate Change and Clear Skies initiatives. These environmental characteristics are inherent in fuel cell systems. The primary market hurdle is cost, and here the challenge is significant. Current fuel cell capital costs range upwards of $4,000/kilowatt (kW). To ensure entry into mainstream markets will require an estimated $400/kW. If this can be accomplished, DG transcends niche market status and becomes a preferred option in a broad range of energy applications, strengthening energy security and reliability.

DOE has established the following program strategic performance goal for NETL's fuel cell R&D portfolio:

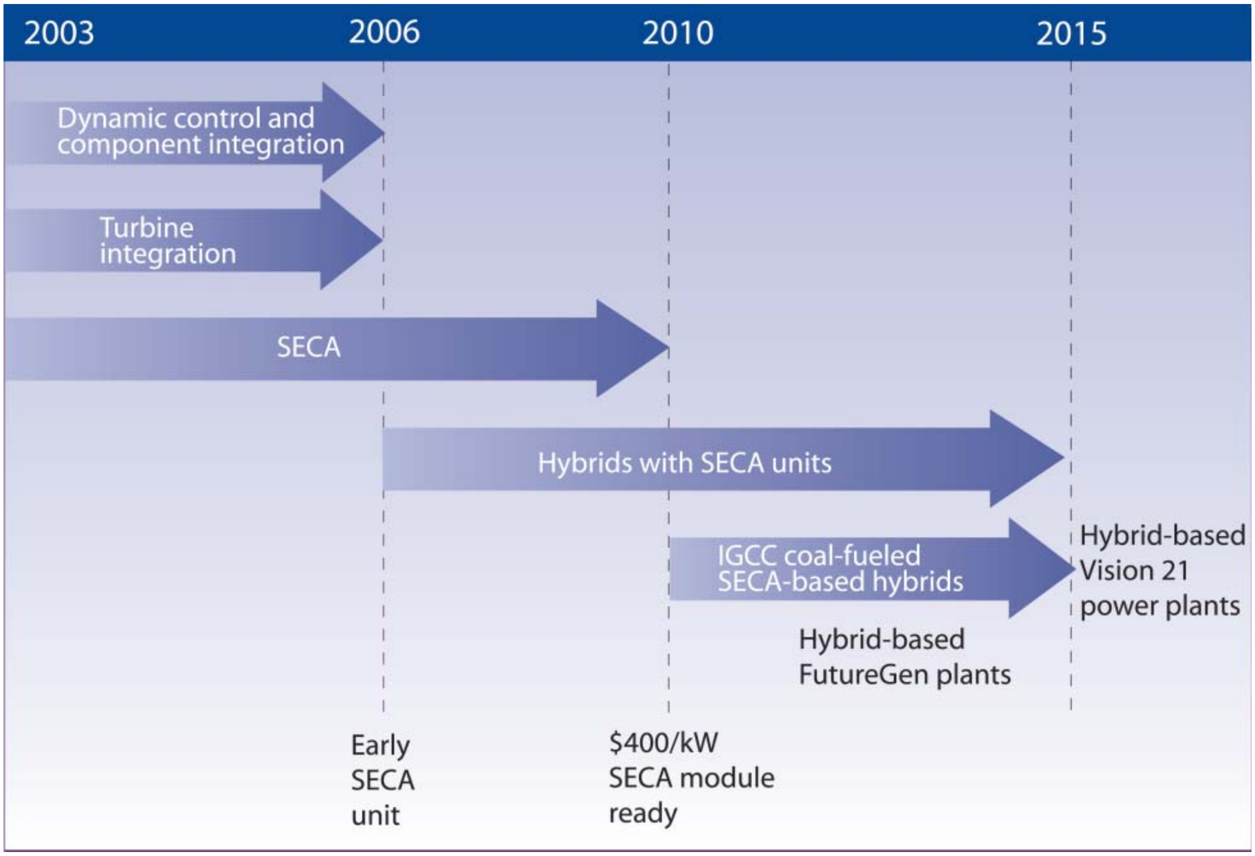
- By 2010, increase the robustness of distributed generation and thereby lower vulnerability of the electricity grid by introducing prototypes of: a) modular fuel cells with 10-fold cost reduction ($400/kW) with 40–50% efficiency; and b) fuel cell-turbine hybrids with 60–70% efficiency adaptable for coal gas.

SOFC compositions and inherent power densities suggest that they hold the greatest promise for meeting cost targets; and SOFCs are compatible with natural gas, transportation fuels, and coal-, biomass-, and waste-derived synthesis gas. As a result, SOFCs are the focus of NETL fuel cell development efforts under the Solid State Energy Conversion Alliance (SECA). Also, SOFCs offer the highest fuel cell operating temperatures and can sustain moderate pressures, making them ideal for synergistic integration with gas turbines into FC/T hybrids. NETL FC/T hybrid efforts are concentrated on using SOFCs emerging from SECA. Achieving the 2010 goal in turn supports the following overarching Office of Fossil Energy Coal & Power Systems goal, which is Vision 21:

- By 2015, provide zero-emission plants (including carbon) that are fuel-flexible, and capable of multi-product output and efficiencies over 60% with coal and 75% with natural gas.

By virtue of the goals established, the SECA SOFCs and FC/T hybrids will play a central role in the President's vision of a new hydrogen economy, and will support the President's Climate Change and Clear Skies initiatives. These systems are considered key enabling technologies for FutureGen — a DOE demonstration of advanced power systems that emit zero emissions, double today's electric generating efficiency, coproduce hydrogen, and capture and sequester carbon dioxide (CO_2).

Technology Roadmap for Distributed Generation Systems



Dynamic control and component integration deals primarily with developing the instrumentation, physical controls, and control logic to effectively operate FC/T hybrids.

Turbine integration involves developing turbine systems compatible with fuel cells in FC/Ts, which entails meeting fuel cell flow and pressure requirements.

SECA's goal is the development of a $400/kW SOFC module, with early prototypes becoming available around 2005 to 2006.

Hybrids with SECA units embody the development of a natural gas-based FC/T hybrid.

IGCC coal-fueled SECA-based hybrids are the integration of FC/Ts into large coal-fueled integrated gasification combined-cycle (IGCC) central power plants, with the focus on providing FC/Ts for FutureGen.

National Benefits

Achieving the goals set for NETL's DG program will result in the following national benefits:

Environmental

- A bridge to a pollution-free, hydrogen economy is provided by operating cleanly and efficiently today on abundant hydrogen-rich fossil fuels, and by offering even better performance in the future on pure hydrogen.

- Environmental concerns associated with fossil fuel use are eliminated by producing negligible pollutant emissions; and by providing ultra-high, stand-alone efficiency and further efficiency gains through avoidance of T&D grid line losses and use of high-quality waste heat. The DG systems comply with all known pollution regulations and have the potential to double power generation efficiency in many applications, which halves CO_2 emissions. High-quality heat on-site can be used for heating, air conditioning, and other processes.

Energy Security

- Energy security is strengthened by enabling use of a variety of low-cost domestic energy resources, by reducing fuel use through major efficiency gains, and by reducing electricity delivery infrastructure vulnerability to terrorist attack. The DG systems are fuel flexible, capable of operating on natural gas, transportation fuels, and synthesis gas derived from coal, biomass, or wastes. Ultra-high efficiency is inherent in these systems and they can be strategically dispersed anywhere because of their compactness and quiet, environmentally benign operation.

Energy Reliability

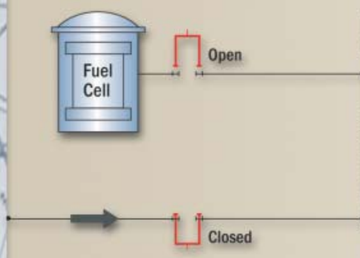
- Reliability of energy supply is ensured by enabling rapid deployment where needed (without long delays associated with building large central plants), by providing on-site, grid-independent service, and by consistently meeting power quality needs. The compact, quiet, essentially zero-emission DG systems can be readily installed almost anywhere, without protracted permitting. On-site power eliminates service disruptions caused by grid damage or adjustments to overloads, and provides the power quality needed in many industrial applications dependent upon sensitive electronic instrumentation and controls. Power quality shortfalls and service disruptions currently cost industry billions of dollars a year.

Economic

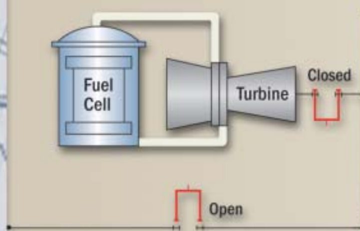
- Utility restructuring is assisted by providing more power choices for residences and businesses.

- U.S. industry is positioned to export highly cost-competitive DG commodities in a rapidly growing international energy market, the largest portion of which has modest or non-existent T&D grids.

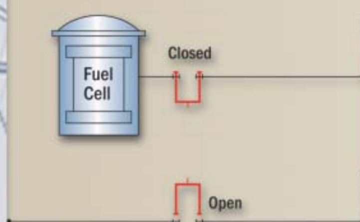
DISTRIBUTED GENERATION APPLICATIONS

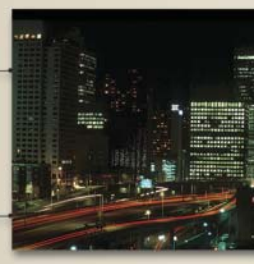


STANDBY POWER is used where electric service interruption either impacts public health and safety or causes irreparable economic loss. Examples are hospitals, water pumping stations, and computer chip manufacturing facilities.

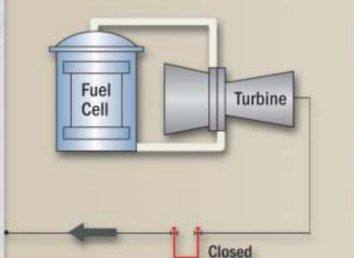


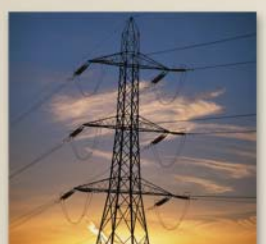
PEAK SHAVING is the use of on-site power during relatively high-cost peak periods of uti lity power generation to reduce cost and alleviate grid congestion. Examples are office buildings, schools, and hotels.





COMBINED HEAT AND POWER is the application of waste heat energy derived from an on-site power source to power heating-ventilation-and-air conditioning (HVAC), or provide process heat. Examples are large commercial buildings and process industries.





GRID SUPPORT is the strategic placement of power where the grid has problems sustaining power delivery due to the length or configuration of the T&D grid.

STAND ALONE DG is used where T&D grid service is not an option. Examples are lighthouses and other remote stations, auxiliary power units for emergency services or military applications, and manufacturing facilities using delicate electronics.

Addressing Market Needs

Affordable, reliable, and secure electricity supplies underpin and integrate our nation's economy. Changing market forces and security issues threaten to disrupt this supply. DG holds the promise for removing the threat, but technology development is required to field the needed DG systems.

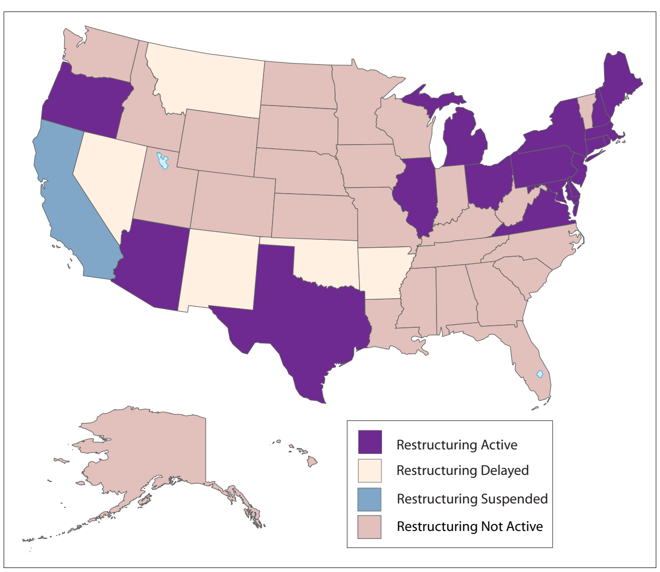
Electricity Needs. Electricity is central to our nation's economy. With the advent of the digital revolution in the 1990s, electricity has accounted for more than 80% of the total growth in U.S. energy demand. To keep pace with electricity demand and plant retirements, DOE's Energy Information Administration estimates that 428 gigawatts (GW) of new U.S. generating capacity will be needed by 2025. In this time frame, demand for electricity is expected to increase by approximately 55% while plant retirements from our aging generation fleet, averaging 39.5 years of service, are projected to be 82 GW.

Market Status. After a lull through much of the 1990s, electric generation capacity rapidly expanded from 1999 to 2002 to backfill need sparked by the digital revolution. The Energy Information Administration (EIA) estimates that during this period power producers installed 72 GW of natural gas-fired turbine combined-cycle units, 66 GW of simple-cycle natural gas-fired turbines, 5 GW of wind power, and 1 GW of coal-fired capacity.

A pause in capacity additions marked the onset of 2003. Power producers are now pondering the options for dealing with future demand under significantly different market conditions. Cost as always is the overriding consideration. Continuing to build central power plants may no longer be the preferred cost option. Large central plants require major outlays, lengthy engineering-procurement-construction (EPC) periods, and adequate T&D grid capacity for delivery. Power producers are averse to the financial exposure associated with these actions. Adding to the investment risk is regulatory uncertainty, and the uncertainty surrounding deregulation of retail electric power generation and the ensuing utility restructuring and associated competitive environment.

Utility restructuring creates a new market, providing flexibility for customers to choose their energy provider and method of delivery. Under utility restructuring, many of the institutional barriers to adopting DG are removed. Power producers rather than customers shoulder investments in new capacity. The uncertainty lies in the policies each state applies to utility restructuring. According to EIA, as of the end of 2002, 17 states and the District of Columbia had operating, competitive retail electricity markets. Texas and Virginia had opened their markets to competition, and Oregon restarted its restructuring process. Five states with restruc-

Status of State Electric Industry



turing legislation on the books (Montana, Nevada, New Mexico, Oklahoma, and Arkansas) have delayed opening competitive retail markets. California's competitive retail market was suspended throughout 2002.

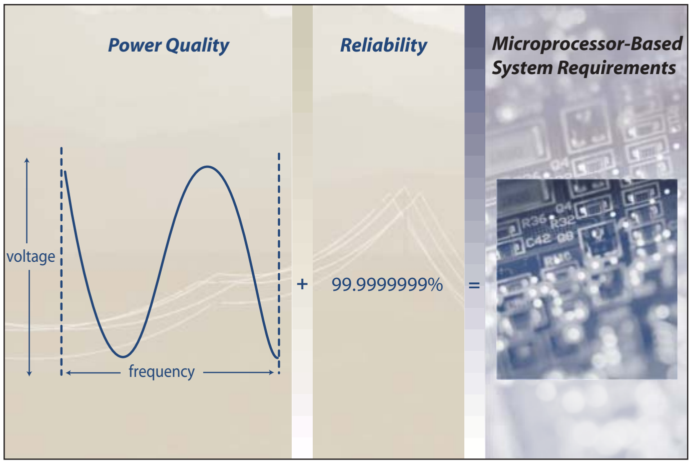
Moreover, the state of much of the nation's T&D grid represents a major issue for those contemplating large central plant capacity additions. The nation's T&D grid is largely strained to capacity in dealing with existing demands. Large capital costs, low return on investment, regulatory complexity and public opposition have combined to block major T&D grid upgrades and expansion. Construction costs average an estimated $1.5 million per mile, and it typically takes 28 years to recover those costs. Maintaining T&D grids is also expensive. One utility company estimates that it spends $1.50 to deliver power for every $1.00 spent for production. Power transmission also incurs electricity losses; the EIA estimates that approximately 9% of the power produced at central power plants is lost in delivery.

The need for rapid response to market needs is another consideration. The digital revolution introduced a whole new set of criteria for the speed with which new capacity must come online.

Locating power generating units at or near customer sites in DG applications is an obvious option to consider. T&D costs and line losses are avoided and process heat may be used to boost efficiency in CHP applications. As of 2002, the World Alliance for Decentralized Energy (WADE) estimated that DG accounts for 6% of U.S. electricity generation and 7% worldwide, with central power accounting for the balance. Growth beyond that portion of the generation capacity will in all likelihood require systems with significantly better environmental and operating performance than current DG systems. Diesel engines dominate DG in the <10 MW range and simple-cycle gas turbines prevail in the >10 MW range. Diesels offer electric generation efficiencies up to 40% and simple-cycle natural gas turbine efficiencies are typically 30%. Considering the fuels involved, these efficiencies translate to high operating costs; and environmental performance is marginal. Also, noise levels and size make them difficult to intimately integrate into many potential on-site applications.

Environmental Considerations. In supplying electricity for the future, it is clear that there is little or no room for additional pollutant emissions; and, CO_2 emissions, which are linked to global climate change, must be minimal. Regulatory actions (proposed and enacted) establish emission caps that barely allow for continued operation of existing plants. Concerns over global climate change and energy security serve as strong drivers for new systems to incorporate ultra-high efficiency. The environmental performance bar is raised even more for DG systems, which must operate anywhere, including highly sensitive environments.

Reliability and Power Quality Implications. Reliability of electricity delivery and power quality have increased economic and security implications. The dependence on computer networks and electronic equipment has grown so great that even momentary outages can result in widespread disruption ranging from the mere inconvenience of a frozen cursor to multimillion dollar losses caused by damaging sensitive and extremely expensive equipment. Power quality, or distortions of the alternating current wave delivering the power, has similar effect. These are brought on by changing the demand placed on the generation and transmission system, or by external influences such as lightning strikes or downed power lines. With the advent of microprocessor-based equipment, even a one-sixteenth of a second interruption in power can cause many devices to malfunction. On an an-



Compared to a central systems approach, such DG systems require relatively small capital investments, short EPC schedules, and no T&D grid upgrades or additions. DG modules can be installed rapidly to match specific incremental increases in power demand, either independent of the grid or to support the grid. Off-site modular construction and pollution-free performance contribute to abbreviated EPC schedules. Such applications are not subject to grid-induced interruptions in service or distortions of delivered power. DG systems can be used as auxiliary power units for emergency response teams; and they are not vulnerable to attacks on the T&D grid. The DG systems being developed by NETL are designed to operate on a range of fuels including natural gas, transportation fuels, and coal- and waste-derived gases. Essentially zero-emissions performance and ultra-high efficiency make these DG systems an integral part of achieving environmental initiatives and responding to regulatory actions.

nual basis, this means that electricity must be available 99.9999999% of the time; that is, it must have what is called 9-nines reliability. Electric utilities traditionally have assured reliability to 4-nines, or 99.99% of the time. A *Business Week* study suggests that power failures nationally cost more than $50 billion a year in lost productivity.

Energy Security Implications. As our nation enters an age of ongoing terrorist threats, it is imperative that our emergency response capability be enhanced and our vital electricity infrastructure be maintained. Moreover, energy independence becomes increasingly important as instability escalates in energy-producing regions of the world.

Importance of Advanced DG Systems. The portfolio of fuel cell-based and novel generation technologies being developed have the potential to: (1) provide future electric power needs; (2) meet reliability and power quality requirements; (3) ensure energy security; and (4) eliminate environmental concerns over energy use. These systems are characterized by compact, high-energy-density power modules that offer near-zero emissions, ultra-high efficiency, fuel flexibility and mainstream market entry costs.

Challenges. Significant technical challenges must be overcome to bring the envisioned DG systems into commercial reality. Key among them are reducing cost and achieving true synergistic integration of fuel cells and turbines. Reducing cost opens the door to mainstream markets. Achieving FC/T synergy represents a quantum leap in efficiency to levels yet unreached by any of the fossil fuel technologies. The following sections provide an overview of NETL's DG system development efforts and a glimpse into the future.

Fuel cells are like a continuously fueled battery, converting chemical energy directly into electricity. Hydrogen-rich fuel is directed to an anode; and an oxidant, usually air, is directed to a cathode. Both anode and cathode are porous, electrically conducting electrodes that are placed on either side of a non-conducting electrolyte material. The chemical affinity of hydrogen for oxygen causes ionization of one or the other to occur, depending on the materials used. And, the chemical affinity causes the electrically charged ions to pass from one electrode to the other through the electrolyte. The porosity of the electrodes allows transport of the hydrogen, oxygen, and ions. The electrolyte selectively permits ions to move through the material and react with the gas on the other side. Electrons build up on the anode, producing an electrical potential called voltage. Connecting a device across the electrodes causes these electrons to flow like water down a hill, actuating the device.

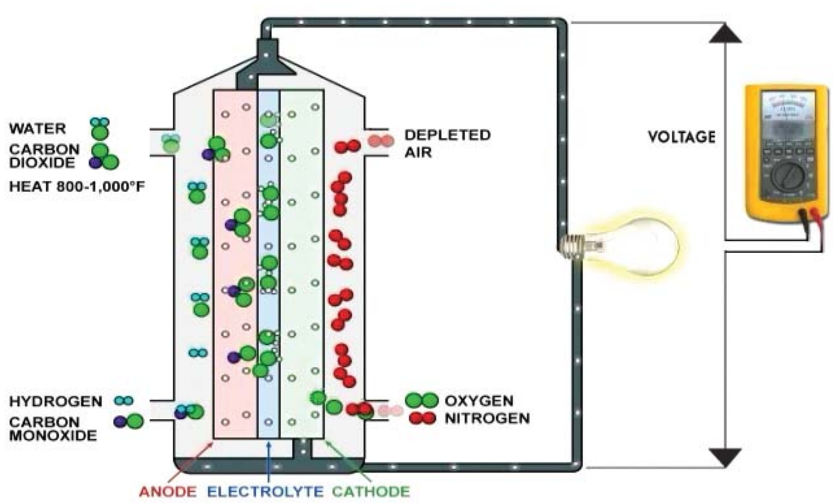
For solid oxide fuel cells, as depicted in the diagram, carbon monoxide (CO), as well as hydrogen, serve as process fuels. This feature gives SOFCs advantage over many other fuel cells that are poisoned by CO — a major fuel processing component.

The by-products of the electrochemical conversion are heat, carbon dioxide, and water. The high-quality heat from emerging fuel cells is used to free hydrogen and produce CO from a wide range of hydrocarbon fuels in a fuel processing step. Application of heat and steam, in the presence of a catalyst, enables fuel cells to use any hydrocarbon material as fuel. In order to use solid hydrocarbons (including coal), a similar process called gasification is used, along with a cleanup step to remove contaminants from the gas.

In practice, the electrodes and electrolytes, which constitute a cell, are sandwiched between plates that serve to direct fuel and oxidants, and to electrically connect the cells into stacks. These stacks are then electrically connected to meet practical power demands. The DC, or direct current, electricity produced is usually converted to alternating current, or AC electricity, typically used in homes, businesses, and commerce.

Fuel cells are categorized (or "named") by their electrolyte. Five classes of fuel cells are generally considered. They are alkaline or AFCs, phosphoric acid or PAFCs, polymer proton exchange membranes or PEMs, molten carbonate or MCFCs, and solid oxide or SOFCs. With successful completion of MCFC development under NETL's Fuel Cell System DG program component, SOFCs are now the current focus of NETL development efforts.

SOLID OXIDE FUEL CELL



Fuel Cell Systems — "Second Generation" Systems

MCFCs

In 2003, installation of a 250-kW commercial MCFC in downtown Los Angeles successfully culminated a 27-year DOE partnership with FuelCell Energy to develop a "second generation" advanced, high-temperature fuel cell.

The MCFC uses nickel catalyst electrodes in lieu of far more expensive precious metals, such as platinum in the lower temperature PEM and PAFC. MCFC operating temperatures of 650 ˚C support internal reforming and effective CHP application, both of which enhance efficiency.

The MCFC electrolyte is a mixture of molten alkali metal carbonates, which are contained within a ceramic matrix. In operation, oxygen and carbon dioxide supplied at the cathode are incorporated into, and transported across the electrolyte as carbonate ions. The carbonate ions react with either hydrogen or carbon monoxide fuel at the anode. This is another important advantage over current low-temperature fuel cells, which cannot tolerate carbon monoxide.

Fuel Cell Energy's MCFC technology evolved from the first experimental test unit, which generated one watt, to the 250,000-watt commercial offering — the Direct FuelCell® Power Plant or DFC 300A. In 2003, the California Energy Commission certified the DFC 300A for grid interconnection under the state's "Rule 21" that specifies standard requirements for DG applications.

With the conclusion of MCFC development, crosscutting research will be carried out under this program component. The research will support further advancements in fuel cell system development and testing in a variety of areas.

FuelCell Energy Molten Carbonate Fuel Cell

SOFCs

In a parallel effort, Siemens Westinghouse pioneered the development of a "second generation" SOFC. This effort led to the production of the first commercial SOFC units, which employ a tubular construction. The potential demonstrated by these early SOFC units spurred the current DOE research designed to further SOFC technology, because the technology holds the greatest promise for achieving $400/kW capital costs.

In the 1960s, NASA leveraged the inherent efficiency and reliability of fuel cells to open new frontiers in space. Likewise, today, NETL is engaged in a mission to open new frontiers in terrestrial power generation by making fuel cells affordable.

Cost is the one remaining barrier that must be overcome for fuel cells to reach their full potential. A recent convergence of technological know-how and market forces now makes it feasible to effectively address this cost issue. Emerging SOFC technology and remarkable advances in solid state manufacturing provide the technical tools. Utility restructuring and increasing demand for clean, reliable power provide the market pull.

The SOFC cost reduction potential lies in their high power-density potential and solid-state composition. High power density drives down material usage, which is the major fuel cell cost component. Solid-state composition enables leveraging of advanced mass production manufacturing techniques emerging from the semiconductor industry. Also, high SOFC operating temperatures support effective fuel processing and thermal efficiencies of 85 percent in CHP applications, and make SOFCs desirable in hybrid applications where the fuel cell serves as the turbine combustor. Moreover, SOFCs tolerate and use the carbon monoxide constituent of synthesis gas.

SECA — TARGETING $400/kW SOFC TECHNOLOGY BY 2010

Industry Teams

- ➔ Competitively selected to develop proposed SOFC technology concept
- ➔ Have ready access to markets
- ➔ Understand end-user specifications
- ➔ Coordinate with manufacturing
- ➔ Supply input to shape Core Technology Program

Core Technology Program

- ➔ Provides problem-solving R&D
- ➔ Consists of universities, R&D companies, and National Laboratories
- ➔ Focuses on fuel processing, manufacturing, controls and diagnostics, power electronics, modeling and simulation, and materials R&D

Federal Government

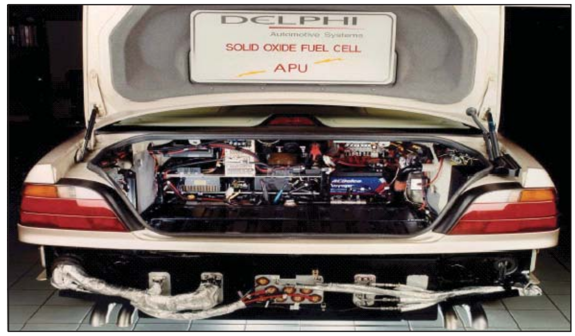
- ➔ Leverages federal R&D investments across multiple agencies
- ➔ Encourages broad national perspective to SOFC technology development beyond company-specific interests
- ➔ Integrates and manages Industry Team projects with Core Technology Program

The challenge to achieving mainstream market penetration is significant. Fuel cell costs must be brought down from thousands of dollars per kilowatt to $400 per kilowatt. This will require merging our nation's scientific, engineering, and manufacturing communities for a common cause.

The Solid State Energy Conversion Alliance, SECA, has been forged to bring about that merger.

SECA is employing four basic strategies to achieve cost objectives:

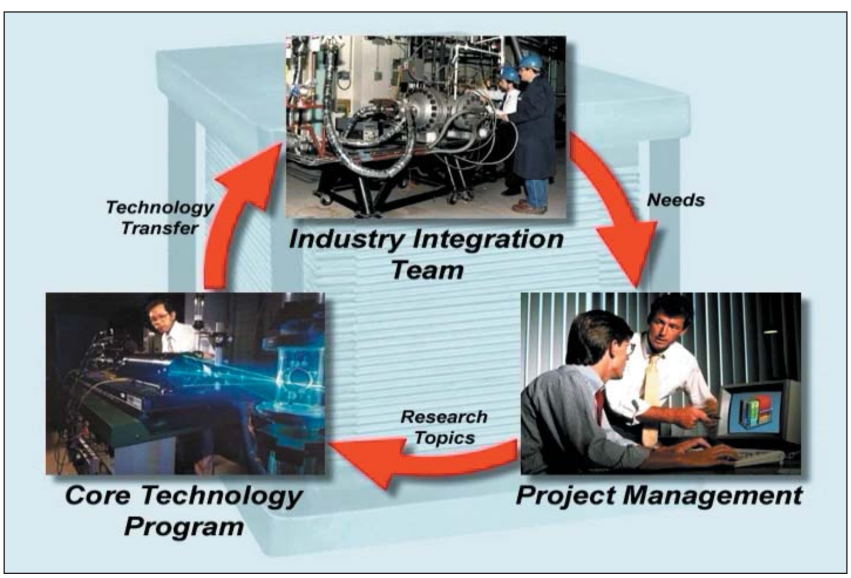
- A "mass customization" approach to resolve the market entry dilemma of initial costs being too high to sell in volume, while needing high-volume production to reduce costs;
- Integrating government, industry, and scientific resources; and leveraging their respective skills by placing them in appropriate roles;
- A common "Core Technology" R&D program that reduces redundancy by making results available to all selected "Industry Teams" developing SOFC hardware; and



- Intellectual property provisions that enhance technology transfer by enabling all "Industry Teams" to benefit from scientific breakthroughs in the "Core Technology" program.

Under SECA, NETL establishes performance-based criteria for the program and competitively selects Industry Teams that show the greatest promise for producing SOFCs that meet the criteria. Industry Teams carry out the hardware development, factor in market entry criteria, input manufacturing knowledge, and identify longer-term research needed to overcome critical technical barriers. NETL assesses the industry research needs, develops research topics, and competitively selects those in the scientific community best able to address the needs. Selected universities, R&D companies, and National Laboratories constitute the Core Technology program. Results of the Core Technology program are made available to all Industry Teams. Any intellectual property arising from the research is made available on a non-exclusive license, which allows Industry Teams to collaborate with researchers on what can be breakthrough technology.

SECA Process



To achieve cost targets, multiple Industry Teams are engaged in developing 3-10 kW SOFC modules that can be mass produced and aggregated like batteries, to meet a broad range of applications. This "mass customization" approach leverages the economies of high-volume mass production and requires reaching a full spectrum of large markets, such as residential-commercial-industrial power, auxiliary power for mobile applications, telecommunications, battery replacement, and similar and specialized applications for the military. Producing a common module for these vast markets will create the requirement for high volume needed to reduce costs.

As of 2003, six industry teams have been selected to carry out a phased program approach and form the foundation for a competitive commercial industry. These teams were selected on the basis of technology promise and the diversity they bring in terms of technical approach, market focus and market access, and unique technical skills. The adjacent table lists the six teams and delineates the technical approach, manufacturing method, and markets targeted. All teams are on track to demonstrate prototype, pre-com-

SECA Industry Team Projects

Team	Approach	Manufacturing	Markets
Delphi/Battelle	5-kW module Anode supported Low temperature Ultra compact system 50 liter envelope Rapid transient capability cPox reformer	Tape casting Screen printing Two-stage sintering	Automotive/heavy truck APUs Stationary DG Niche military applications
General Electric	5-kW module Anode supported Low temperature Hybrid compatible Internal reforming	Tape calendering Two-stage sintering	Residential applications FC/T hybrid applications Eventual tie-in to coal-based systems
Cummins Power Generation/ McDermott	4-kW module Electrolyte supported Intermediate temperature Unique co-sintered design Thermally matched materials Seal-less (co-sintered) stack	Tape casting Screen printing Co-sintering	RV APUs Commercial vehicle APUs Emergency telecommunication APUs
Siemens Westinghouse	5- to 10-kW module Cathode supported High temperature Redesigned tubular Reduced manufacturing steps Seal-less stack	Extrusion Plasma spray	Residential CHP Automotive APUs
Acumentrics	10-kW module Anode supported Intermediate temperature Soda straw sized tubes	Extrusion	Residential applications Military applications Broadband communications APUs for heavy trucks
FuelCell Energy	10-kW module Anode supported Low temperature MCFC seal and interconnects Novel non-YSZ materials	Tape Casting Screen Printing	Target stationary power first Expand to military and APU markets

mercial modules in 2005 under Phase 1 of a three-phased effort. Subsequent phases will entail the engineering, testing, and design refinements requisite to producing commercial modules in 2010.

The Core Technology program began in earnest in 2002 with nineteen contractors being selected to address six thrust areas: materials, manufacturing, fuel processing, modeling and simulation, power electronics, and controls and diagnostics. The structure and provisions in place reduce costs by avoiding all six teams engaging in separate fundamental research programs and ensure that only major issues are addressed.

The figure below shows an estimated cost breakdown for a 5-kW SECA system meeting the $400/kW goal. The predominance of research is in stack design, which impacts all other elements.

Technical Challenges

The technical challenges facing SECA are significant. However, recent development efforts leading to the first commercial SOFC offerings suggest that significant cost reduction is possible.

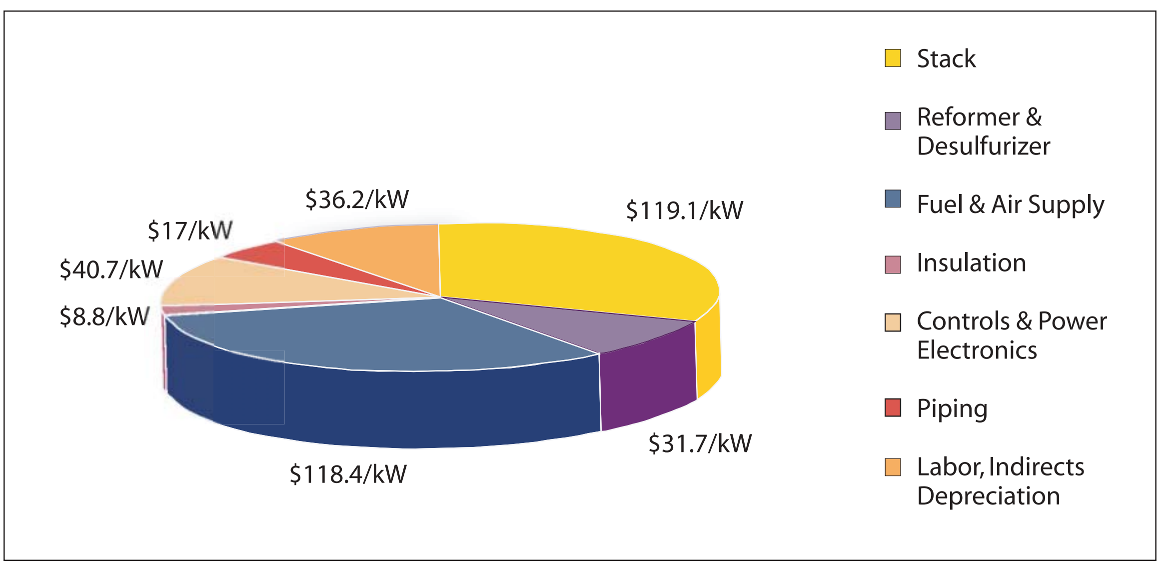
The following summarizes the major technical challenges:

- Development of low-cost materials that work cohesively as temperatures range from ambient to as high as 1,000 ºC while providing low electrical and ion transport resistance;

- Effective integration of fuel processing and stack operation to optimize thermal management; and

- Development of efficient, low-cost mass production manufacturing techniques, which require tailoring new solid-state fabrication procedures to specific fuel designs.

Cost Breakdown for $400/kW Fuel Cell



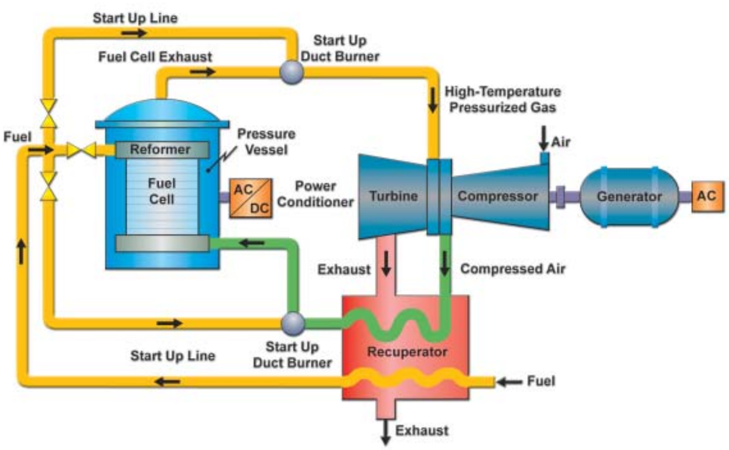
To reach the ultimate performance goals established by Vision 21, additional leaps in efficiency are needed beyond those available through even the most advanced technologies. Today, SOFCs and advanced gas turbine systems vie for the efficiency title. In exploring means of reaching higher efficiency plateaus, researchers found synergy in linking high-temperature fuel cells and gas turbines. In effect, the fuel cell serves as the gas turbine combustor and the turbine provides air under pressure to the fuel cell while both produce power. The resulting 60–70% efficiency is roughly 10 percentage points greater than either stand-alone component.

There are at least two basic FC/T concepts from which actual advanced systems will derive — direct and indirect. In the direct FC/T, the fuel cell delivers the heat energy directly to the hot gas path section of the gas turbine. A recuperator transfers residual heat from the turbine to incoming fuel and air from the turbine compressor. Other concepts being explored may eliminate the need for a recuperator.

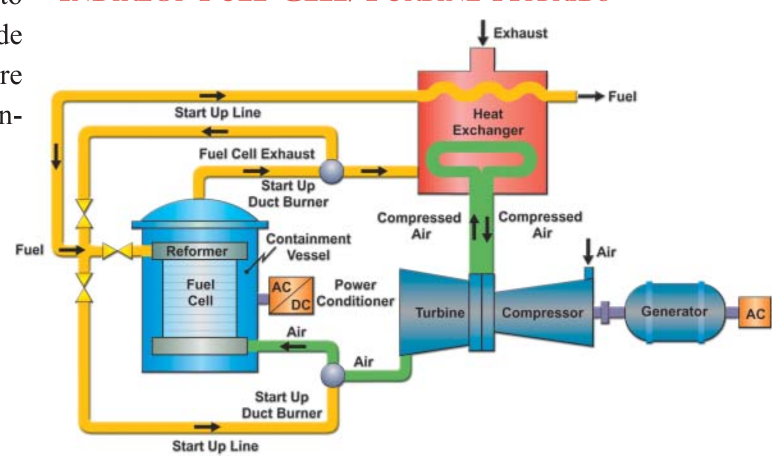
In the indirect FC/T, the recuperator transfers fuel cell heat energy to the compressed air supply, which in turn drives the turbine. The expanded air is supplied to the fuel cell. The indirect operating mode decouples the turbine compressor pressure and fuel cell operating pressure, which increases flexibility in turbine selection.

FC/T hybrids represent a superior power module option for gasification-based systems. Gasification extends the range of fuels that can be used by the hybrid, converting solid feedstocks, such as coal, biomass, and wastes to a usable synthesis gas. By performing the reforming function, the gasifier enables the fuel cell portion of the hybrid to operate at the highest possible efficiency.

DIRECT FUEL CELL/TURBINE HYBRIDS



INDIRECT FUEL CELL/TURBINE HYBRIDS



FC/T Program Focus

NETL's FC/T hybrids development efforts are focused on integrating low-cost SECA SOFCs with turbines. These turbines, which offer capacities far above emerging microturbine capacities, are not only going to be compatible with FC/T hybrid applications, but will provide high, simple-cycle efficiency. High simple-cycle efficiency supports hybrid efficiency goals and provides the market pull needed for development. Turbine development for the FC/T will take place under NETL's Turbines program.

Technical Challenges

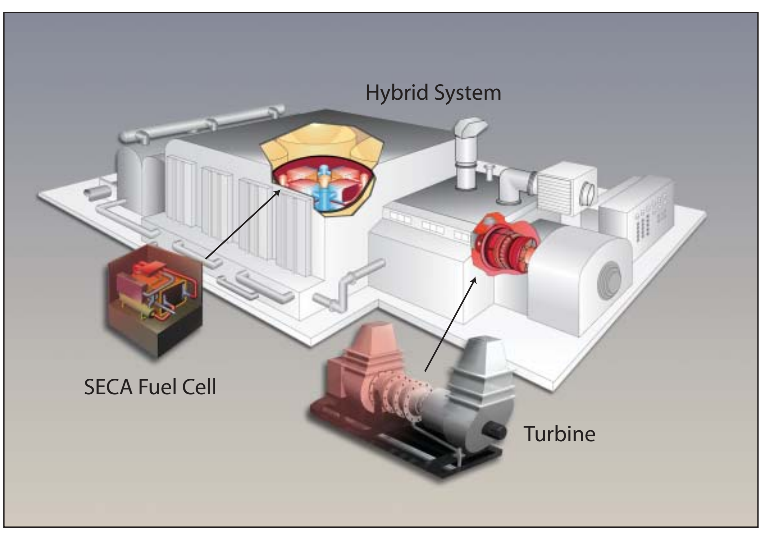
The technical challenges associated with developing a truly synergistic FC/T hybrid primarily reside in achieving compatible operating characteristics between the fuel cell and turbine and controlling the FC/T under dynamic operating conditions.

Existing gas turbine compressor pressures and air flows are not compatible with any of the high-temperature fuel cells considered for FC/T hybrids. Conventional gas turbines in size ranges sought for FC/Ts produce air pressures too high for the fuel cells to endure, and the air flows are too low to support efficient system performance. The fuel cells tolerate only moderate pressures at best. High air flow is needed to provide high mass flow for the hot gas path power section of the gas turbine. This air flow offsets relatively low firing temperatures produced by fuel cells in meeting power generation targets. Modified turbines are needed that provide effective balance-of-plant support for candidate SOFCs.

Under dynamic operating conditions, such as start-up, shutdown, and load following, control issues arise because the coupled components have significantly different operating characteristics and response times. The issue is best illustrated by a sudden loss-of-load situation. Upon loss of load, the fuel cell almost instantaneously stops reacting the hydrogen because electrons are not available to support electrochemical conversion. Although reacting in fractions of a second, the fuel shut-off control is much slower than the cessation of hydrogen conversion. This can result in a significant hydrogen buildup and uncontrolled, damaging combustion upon contact with air from the turbine. The turbine continues to run on the residual thermal energy from the fuel cell, and air shut-off controls suffer the same time lag as fuel controls. Control logic and the physical sensors and controls must be developed to handle the full range of operating conditions in a fail-safe manner.

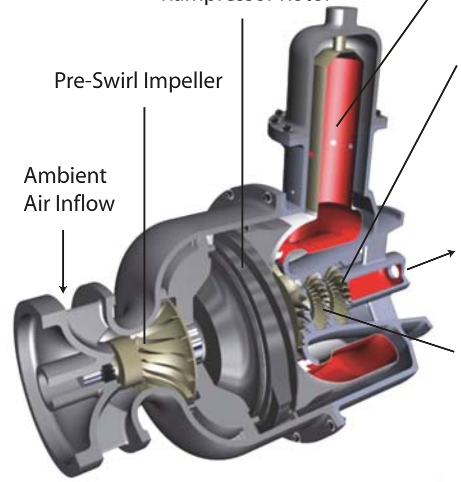
To address these challenges, DOE is leveraging FC/T hybrid demonstrations using first-generation SOFCs and MCFCs with off-the-shelf microturbines to provide data needed to address key integration and system control issues. Also, General Electric is exploring FC/T hybrid integration issues at small scale using their SECA SOFC design.

SECA FC/T Hybrid System



Novel Generation Concepts — Ramgen Turbine

A novel generation technology promising breakthrough cost and performance for small heat engines is the Ramgen Turbine. At the heart of the system is a novel compressor (Rampressor™) that adapts aerospace ramjet technology to stationary power generation. Ramjets use supersonic shock waves, in lieu of direct mechanical means, to rapidly and efficiently compress the large volumes of air needed for high-energy combustion. In the Ramgen power generation technology under development, supersonic shock waves are produced by the interaction of raised sections on the rim of a disk moving at supersonic speeds and a stationary engine case. The raised sections are shaped to most effectively impart the shock waves, much like the stationary nose in a ramjet.



The advantage of the Rampressor™ lies in eliminating aerodynamic losses generated by conventional rotating airfoil profiles. Conventional turbine compressors rely on hundreds of turbine and stator blades to axially compress incoming air through flow turning (50% of the energy) and direct action of the turbine blades on the air. The leading edges of hundreds of turbine and stator blades produce large viscous drag losses. The Rampressor™ does not use flow turning and has few leading edges.

The Ramgen Turbine uses Rampressor™ advanced low-NO_x combustion, employing trapped vortex combustion (TVC) principles, and a conventional hot gas path turbine power section. Efficiency gains of 10% or more over conventional gas turbines are possible, owing primarily to the Rampressor™. For smaller units, the efficiency gain can be far greater because the Rampressor™ can generate high compression ratios even at the smaller sizes, while conventional gas turbines cannot. TVC is projected to reduce NO_x emissions to 5 parts per million.

It is estimated that a 300-kW Ramgen Turbine can operate at nearly 40% efficiency in a simple-cycle mode. Comparably sized commercial gas turbine units have simple-cycle efficiencies of approximately 28%. Moreover, the Ramgen Turbine offers inherent cost and maintenance advantages by replacing hundreds of blades in a multi-stage axial compressor with a single-piece machined disk.

The performance advantages offered by Ramgen Turbines, particularly in the small size range, combine with compactness of the unit and low cost to make it an ideal candidate for DG. A 400-kW Ramgen Turbine is one-third the length and one-half the height of a conventional turbine of comparable capacity, and the projected $300/kW manufacturing cost makes it highly cost competitive. Moreover, Ramgen Turbines offer the advantage of being able to operate on dilute fuels like landfill gas, coalbed methane, and coal- and waste-derived synthesis gas.

Advanced Research

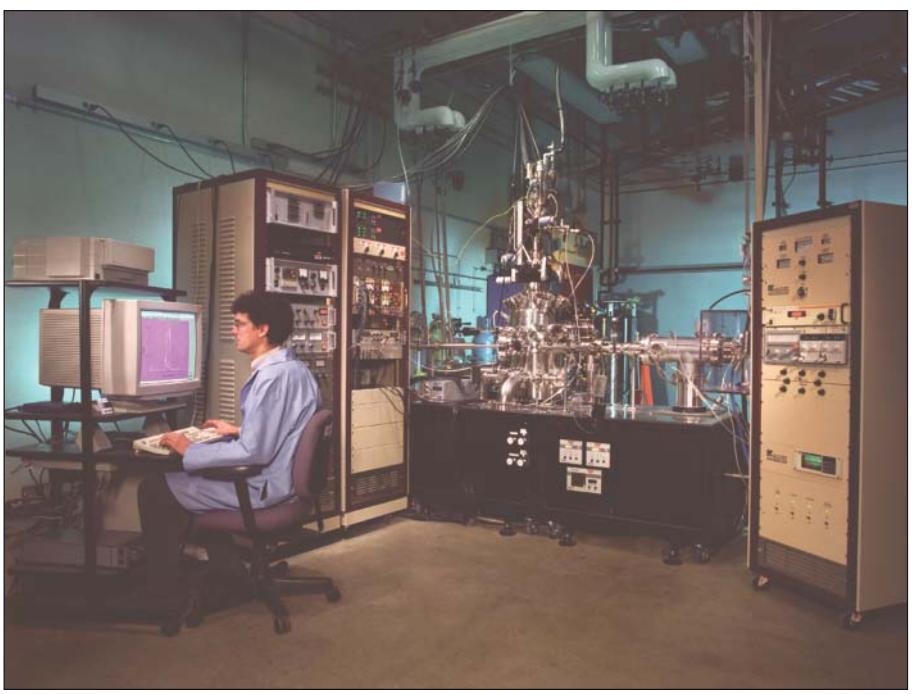
Research is being conducted to develop a fundamental understanding of processes that limit the performance of the high-temperature electrochemical systems that drive advanced fuel cells. This research is designed to both solve fundamental crosscutting issues facing fuel cell developers and identify new, highly innovative electrochemical technology concepts.

For example, researchers are investigating inefficiencies in electrode reactions. These reactions critically affect the performance of high-temperature fuel cells. By building an understanding of electrode reactions, needed improvements can be made in electrocatalytic activity, selectivity, and stability of electrode materials.

Another challenge being addressed is development of sensors to directly measure key parameters in the harsh chemical and physical environment of high-temperature electrochemical systems. Such sensors can significantly enhance fuel cell system operational efficiency. New technologies are being investigated to measure temperatures up to 1,000 °C, pressures up to 500 pounds per square inch, and levels of oxygen, carbon monoxide, hydrogen, hydrogen disulfide, ammonia, water, and hydrocarbons.

An example of a new concept being explored is a "reversible" SOFC. The concept involves production of hydrogen from water using electricity from the grid in non-peak periods and using the stored hydrogen to produce electricity in peak electricity use periods. This leverages the efficient electrolysis inherent in the high-temperature SOFCs. Research focuses on developing the materials and systems tolerant of the high-temperature oxidizing environment.

PNNL's ion accelerator, where collaborators study mechanisms of oxidation of novel electrical interconnect materials



The advent of DG technology envisioned in this document will bring closure to environmental issues ushered in by technologies spawning the industrial revolution over 240 years ago. Environmental, infrastructure, and financial restraints on expanding electric generation capacity will be broken, freeing our economy to reach its full potential. Energy security will be significantly strengthened. Productivity in the workplace will no longer be threatened by disruptions in electric service or poor power quality. And, the United States will be a world leader in DG technology, realizing economic gain from exports but also boosting the standard of living and the economies of developing countries, which have the most to gain from DG technology.

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