U.S. Department of Energy · Office of Fossil Energy

National Energy Technology Laboratory

Hybrid Power Systems Program Plan

NETL

Applying Synergy to Double Power Generation Efficiency

Availability Note:

The following draft document is undergoing stakeholder review. Until this review is complete, the document is available in electronic format only. If you have comments about the content of this document, please reply to the NETL Fuel Cell Product Manager, Dr. Mark Williams, at: mark.williams@netl.doe.gov

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Introduction

> "This new [hybrid] technology has the potential to alter the landscape of tomorrow's power industry. It offers a preview of the day when more of our electricity will be generated by super-clean, high-efficiency power units sited near the consumer ... strengthening the security and reliability of our power supply...."
>
> Secretary of Energy
>
> March 2002

Hybrid power systems hold promise for a future where energy production and use threaten neither the environment nor our economy. Research to date shows that emerging high thermal output fuel cell technology combines synergistically with gas turbine heat engines to produce hybrids that far exceed the cost and performance potential of either component alone. The Hybrid Power Systems program presents a plan for developing fuel cells/turbines (FC/T) hybrids, and explores the development potential of emerging innovative hybrid concepts. Innovative hybrid concepts are those that show promise for further enhancing power generation cost and performance or expanding capabilities. The FC/T program presented in this document is based on prior research, as well as workshops attended by the scientific community and power industry representatives. The program is designed to fully develop the FC/T hybrid potential and to realize the benefits by surmounting technical and market entry hurdles. Innovative hybrid concepts being explored go beyond fuel cell/heat engine hybrids to include fuel cell/fuel cell hybrids that can produce both electricity and hydrogen — a possible bridge to a hydrogen economy.

As the 21st century unfolds, the nation faces potential shortages in electricity generation, a strained electricity transmission and distribution (T&D) grid, growing environmental concerns associated with energy production, and increasing dependence on foreign oil. As reflected in the National Energy Policy and the U.S. Department of Energy (DOE) Strategic Plan, the President is seeking to ensure secure, reliable, affordable, and clean electricity generation and fuels for our nation's future. This goal requires the technological means to meet our nation's energy and environmental demands with primary reliance on abundant domestic resources, and to strategically place power sources.

To meet the challenge, the DOE Office of Fossil Energy is developing a new generation of central and distributed generation power plants. This development ultimately will lead to essentially zero-emission power plants (Zero Emission Systems) offering ultra-

Emission Systems) offering ultra-high efficiency, fuel and product flexibility, and ease of carbon capture for sequestration. These Zero Emission Systems will provide: (1) competitive cost, (2) electric power generation efficiency nearly double that of today's plants, (3) virtually pollution-free performance, (4) operation on abundant domestic fuels, (5) coproduction of electricity and clean fuels or chemicals, and (6) carbon dioxide emissions in a form that is readily captured for recycle or sequestration. These attributes, in turn, allow such plants to be strategically located, further enhancing energy security and reliability by alleviating congestion on the T&D grid and reducing infrastructure vulnerability.

Hybrid power systems offer a path to achieving Zero Emission Systems and a distributed generation capability. These hybrid power systems leverage the inherently benign environmental characteristics and high fuel-to-electricity efficiency of emerging solid oxide and molten carbonate fuel cells, and squeeze out additional energy through synergistic integration. Hybrids can operate on a variety of fuels, including natural gas, coal, biomass, and other hydrocarbon resources; and hybrids can be placed where needed with essentially no environmental impact.

While the body of evidence gathered over the past five years strongly supports the performance potential of hybrids, significant technical challenges remain, requiring mobilization and merging of the nation's scientific and engineering communities. The structure to merge the talents of industry and the research community are in place through DOE's Fuel Cells and Turbines programs, which embody the research and development (R&D) needed to integrate the individual power components of the hybrid power systems. The risks and potential payoff warrant a federal role in pursuing hybrid development. By leveraging government, industry, and scientific resources through effective partnerships, hybrids can soon put the nation on a path toward eliminating environmental concerns associated with the use of our abundant domestic resources, and ensuring low energy costs requisite to a strong economy.

PROGRAM VISION

By 2015, commercially viable, cost-competitive hybrid power systems will be ready for deployment in a range of sizes for mainstream distributed generation, aggregated customer, and central power station applications. These hybrid power systems will offer electrical efficiencies nearly double those of today's technologies and virtually pollution-free performance, operating with emissions orders of magnitude less than current standards. Hybrid power systems also provide fuel flexibility, operating on natural gas, coal, biomass, and wastes. Greenhouse gas issues are addressed through high efficiency, production of sequestration-ready carbon dioxide, and the capability to use biomass.

Hybrid and high-quality electric power systems provide high quality, reliable power in off-grid applications and introduce options for a hydrogen-based economy. Fuel cell/fuel cell hybrid power systems configured with energy storage and management devices generate hydrogen and quality electric power, and provide a framework for ahydrogen-based economy.

Ultimately, wide spread application of hybrid power systems forever changes the way the nation views energy, by eliminating environmental concerns associated with energy production and use, and by ensuring secure, reliable, and affordable energy delivery.

Zero Emissions Systems

- Pollution-free
- 75% efficiency on natural gas
- 60% efficiency on coal
- Coproduction of chemicals and clean fuels (including hydrogen)
- Sequestration ready

Benefits

Successful development of hybrid power systems benefits the nation by:

- Offering virtually pollution-free performance through the use of a fuel cell rather than combustion to synergistically power an integrated heat engine or fuel cell component(s);

- Providing the only known technology option to nearly double coal- and natural gas-based electric power generation efficiencies in both the distributed generation (kilowatts to several megawatts) size range, and central power generation (tens to hundreds of megawatts) size range, essentially halving CO_2 emissions and concentrating the CO_2 emissions to enable capture and sequestration;

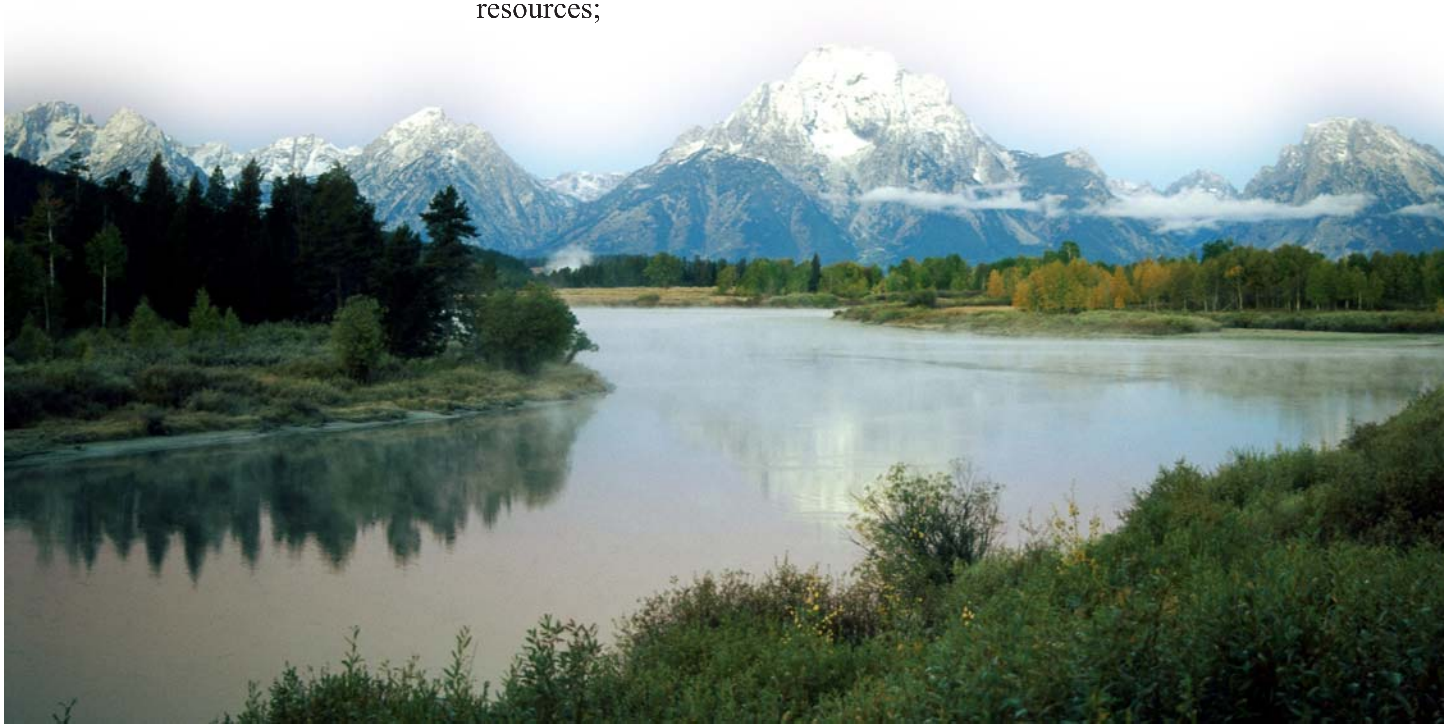
- Affording the flexibility to operate on natural gas, gasoline, diesel fuel, alcohol fuels, and synthesis gas derived from coal, biomass, and industrial and municipal wastes;

- Positioning U.S. industry to export a premium power generation commodity in a burgeoning world energy market, addressing both central power and distributed generation needs in developing countries that face the greatest energy growth and have modest or nonexistent T&D grids;

- Providing a bridge to a hydrogen economy by using hydrogen to produce power efficiently and by offering the potential to produce hydrogen, as well as electricity, from abundant domestic resources;

- Strengthening energy security by enabling operation on low-cost domestic resources, reducing consumption of premium fuels through major efficiency gains, and reducing infrastructure vulnerability through distributed generation applications; and

- Strengthening energy supply reliability by alleviating strain on the T&D grid, providing the performance characteristics and modular construction conducive to rapid deployment, and affording on-site distributed generation options conducive to tight power quality control and enhanced efficiency by avoiding line losses and using process heat.



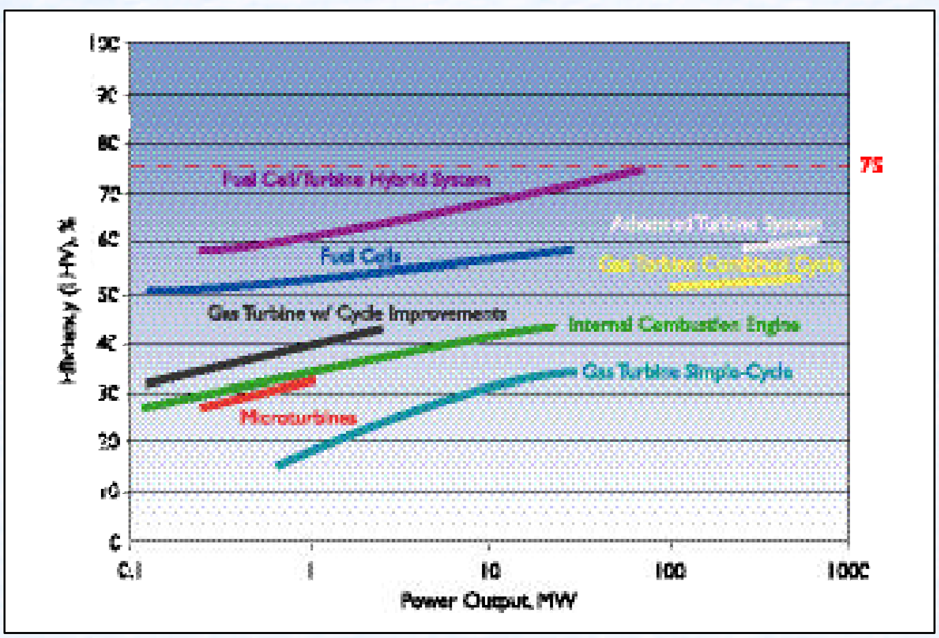
Hybrid Power Systems

The heart of hybrid power systems is the high-temperature fuel cell. High-temperature fuel cells are the products of years of development through partnerships between DOE, industry, and the research community. Emerging from the development are commercially ready solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC).

The high thermal output of SOFCs and MCFCs make possible the hybrid cycle, where the combined performance potential of the power components far surpasses that of individual components alone. Coproduction of electricity and hydrogen also are achievable. As shown in ***Figure 1***, hybrids have the potential for fuel-to-electricity efficiencies of 75% or more, far exceeding that of other known high-performance natural gas-based power systems. And, hybrids produce near-zero emissions, which is characteristic of the fuel cell. The high efficiency results in relatively low emissions of the greenhouse gas, carbon dioxide. Emissions of nitrogen oxides are negligible.

Cost reduction, efficiency, and pollution-free performance were the major factors driving development of the MCFC and SOFC. Over the past five years, capital costs have been halved for some

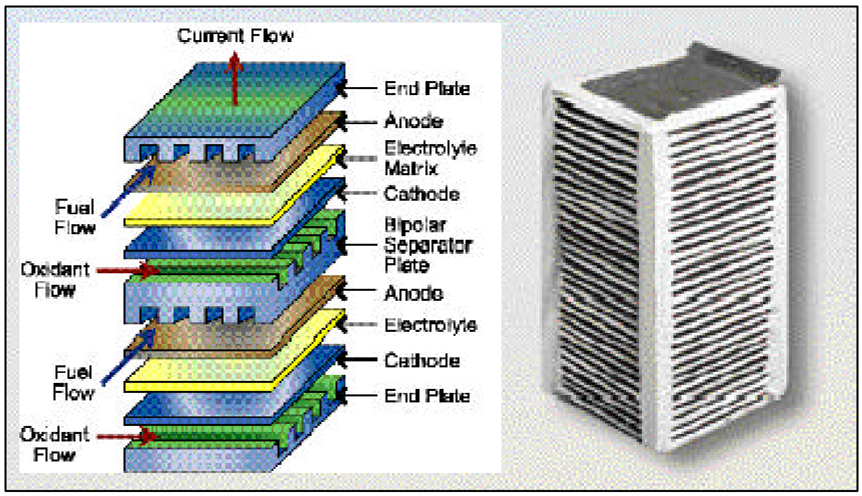
Figure 1. Comparison of Fuel-to-Electricity Efficiencies



of the key SOFC and MCFC subsystems. These subsystem accomplishments put them on a track to potentially bring capital costs down to $1,500–2,000/kW at high production rates, within the next few years. SOFC and MCFC systems realized efficiency gains over existing technology, raising efficiency from 42% to 55%. Performance enhancements supporting both capital and operating cost reduction include: (1) increased fuel-to-electricity efficiency; (2) more tolerance of fuels used; (3) operating temperatures sufficient for supporting fuel "reforming" (processing to free the hydrogen for fuel cell use); (4) high-volume production; and (5) high-value process heat sufficient for leveraging thermal efficiency in combined heat and power and combined cycle applications.

Current fuel cell development efforts are focused on bringing fuel cell costs down to $400/kW — a cost that would enable fuel cells to find applications in a large variety of power markets. This effort is being undertaken by the DOE National Energy Technology Laboratory (NETL) Fuel Cell program's Solid State Energy Conversion Alliance (SECA). SECA leverages previous work on the SOFC with the objective of developing a next-generation, mass produced, 3-kW to 10-kW SOFC module that can be combined like batteries to meet a broad range of applications. This "mass customization" approach resolves the dilemma of initial costs being high, because limited markets don't warrant mass production. Increasing power density and reducing material and fabrication costs of the SOFC are key technical developments requisite to meeting cost targets.

A number of hybrid cycles offering synergistic operation are possible and being explored. These include hybrid combinations of fuel cell/turbine, fuel cell/fuel cell, fuel cell/reciprocating engine, and fuel cells with other heat engines. The focus of present



Generic planar SOFC configuration

efforts is in developing the fuel cell/turbine hybrid because the technology database and components are the most mature. Supporting this development is the Turbines program. A major thrust in the Turbines program is to leverage current gas turbine technology and advancements, and to develop the design modifications needed for optimum turbine synergy when integrated with a high-temperature fuel cell.

In the near to mid-term, fuels used with the hybrids will be natural gas and transportation fuels, and sizes will be up to several megawatts, which are capable of supporting distributed generation applications. In the longer term, the hybrids will be linked to gasification technologies capable of converting coal, biomass, and solid waste feedstocks to clean synthesis gas. These gasification-linked hybrids will support central power applications.

Hybrid Concepts

Several hybrid concepts are described here in simple form to provide some understanding of the synergy offered and the basic relationships of components, as a backdrop for the ensuing discussion.

Fuel Cell/Turbine Hybrid

The fuel cell/turbine (FC/T) hybrid, which currently is receiving the greatest attention, combines a high-temperature fuel cell and a gas turbine in one of two basic operating modes — direct or indirect. In the direct mode, shown in ***Figure 2***, the fuel cell serves as the combustor for the gas turbine. Residual fuel in the already high-temperature fuel cell exhaust mixes with the residual oxygen in an exothermic oxidation reaction to further raise the temperature — a temperature below the thermal NO_x formation temperature. Both the fuel cell and the gas turbine generate electricity, and the gas turbine provides some balance-of-plant functions for the fuel cell, such as supplying air under pres-

Figure 2. Direct-Fired Fuel Cell/Turbine Hybrid

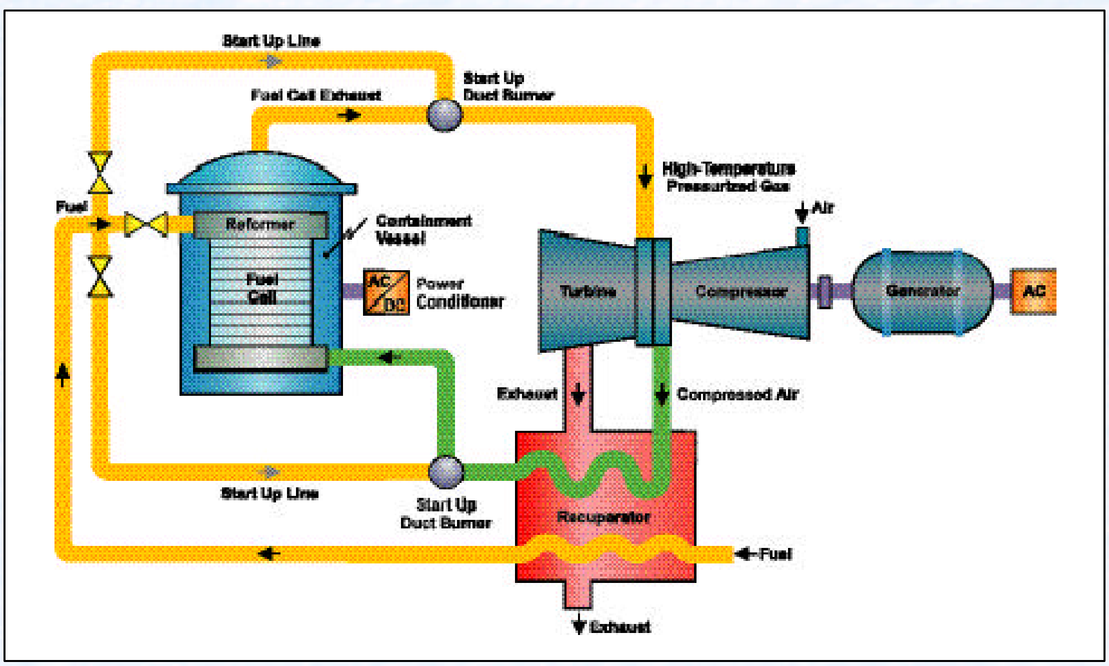


Figure 3. Indirect-Fired Fuel Cell/Turbine Hybrid

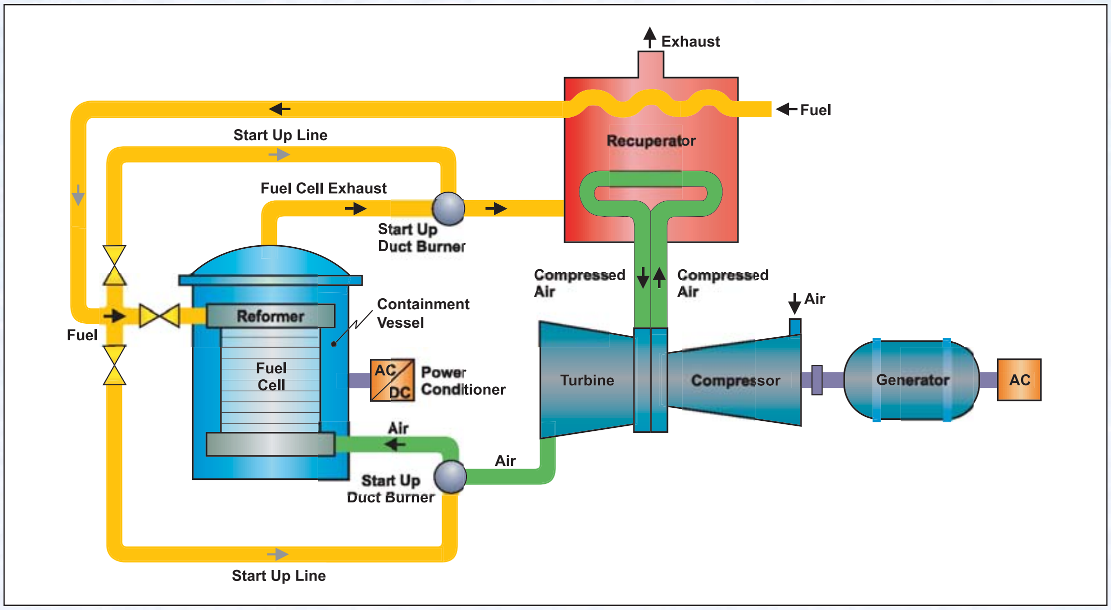
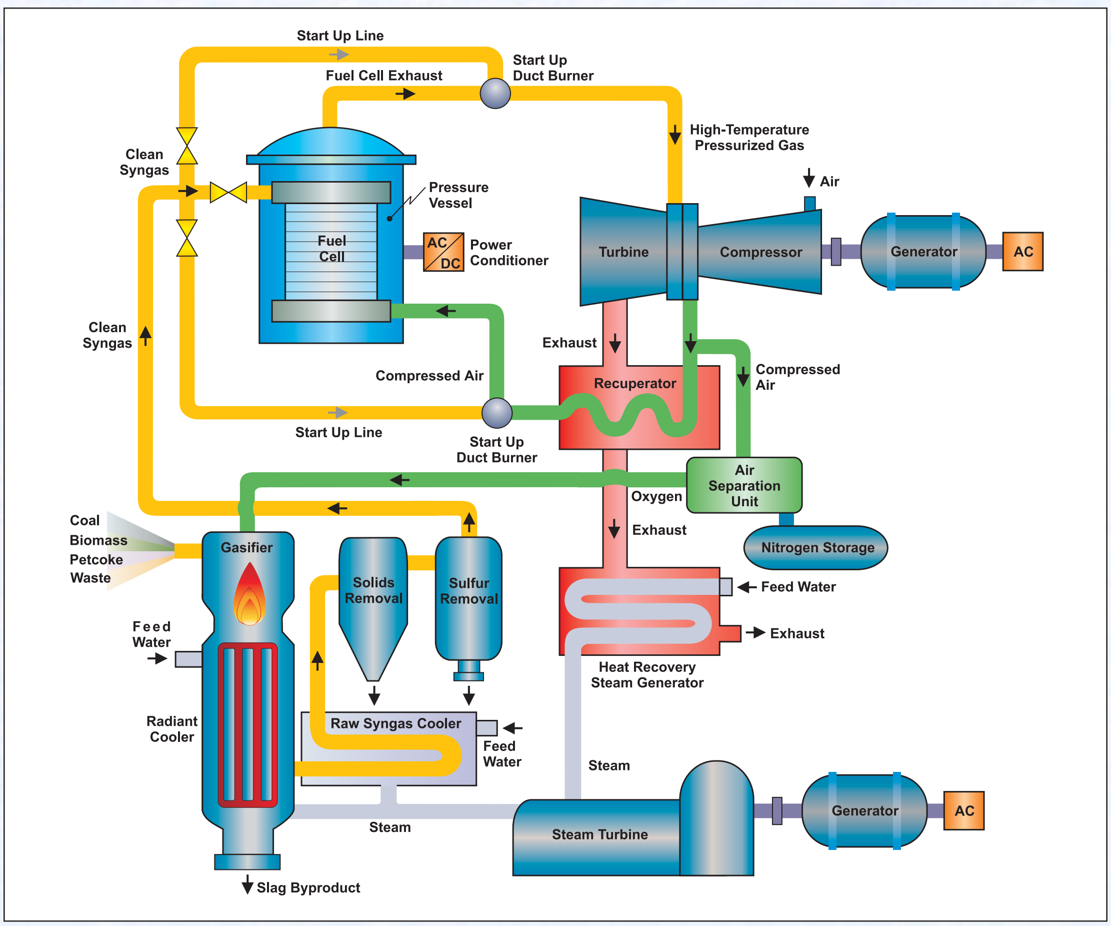


Figure 4. Advanced Coal-Fueled Energy Plant



sure and preheating the fuel and air in a heat exchanger called a recuperator. In the indirect mode, shown in ***Figure 3***, the recuperator (in this case a high-temperature heat exchanger) transfers fuel cell exhaust energy to the compressed air supply, which in turn drives the turbine. The expanded air is supplied to the fuel cell. The indirect mode uncouples the turbine compressor pressure and fuel cell operating pressure, which increases flexibility in turbine selection.

The schematic of an advanced coal-fueled energy plant in ***Figure 4*** shows that 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 fuels (such as coal) and wastes to a syngas (primarily composed of hydrogen and carbon monoxide), which is compatible with high-temperature fuel cells. These gasification systems can be configured with either direct or indirect FC/T hybrid technology. By performing the reforming function, the gasifier enables the fuel cell portion of the hybrid to operate at the highest possible efficiency.

Innovative Hybrid Concepts

Hybrid concepts beyond FC/T systems are being evaluated that show promise for effective synergistic integration. Among these are hybrids combining a high thermal output fuel cell with other heat engines such as reciprocating engines, which function in much the same manner as FC/T hybrids. Another concept of particular interest is a fuel cell/fuel cell (FC/FC) hybrid. The FC/FC hybrid appears to perform well in both power generation and hydrogen coproduction modes.

Addressing Market Needs

While hybrids clearly offer superior efficiency and environmental performance, realization of these inherent benefits can occur only if market entry cost and performance criteria are met. Recognizing this reality, the Hybrid Power Systems program continually assesses the electric power market as it is today and is forecast for the future to assure that the program is focused on market needs consistent with a federal role. The market entry criteria are continually factored into the performance objectives driving the R&D.

Electricity Demand

The U.S. DOE Energy Information Administration (EIA) estimates that 374 gigawatts (GW) of added capacity are needed through 2020 to meet new electricity demand and accommodate plant retirements. Moreover, EIA predicts that over the period 2003 to 2020, between 0.5 GW and 1.0 GW of domestic distributed generation (DG) capacity will be added per year just to avoid T&D congestion. Avoiding T&D through DG not only relieves congestion, but represents a significant cost saving because T&D costs are typically 26% of the cost of electricity, or on average $0.02 per kilowatt-hour.

A confluence of utility restructuring, the combination of growing electricity demand and an already burdened T&D grid, and a mandate for reliability and quality electric power have created a major domestic DG market — power generation at or near a user site. Utility restructuring has opened the market for relatively small, modular, usually natural gas-fueled power systems. Gas turbines and reciprocating engines currently dominate the DG market, with fuel cells finding niche applications where superior performance and quiet operation are primary requirements. Currently, cost is limiting fuel cell penetration into mainstream markets. SECA is addressing the cost factor by developing an advanced SOFC. Integration of the SOFC with a gas turbine into a FC/T hybrid has the potential to further enhance economics, and therefore, market penetration.

A recent market study suggests that, by 2005, FC/T hybrids could capture over 8 GW of the domestic DG market share currently projected for gas turbines, reciprocating engines, and stand-alone fuel cells. In the longer term, a FC/T hybrid market share of 60–90 GW is estimated, with a successful R&D effort building first on available technology, and progressing toward more intensive activities to optimize hybrids. The 8-GW market share is based on R&D effectively modifying existing fuel cell and turbine technology, and developing hybrid power systems having 63–70% efficiency and installed costs of $1,060–1,620/kW. The 60-GW market share is based

on R&D achieving efficiencies of 70–74% and, more importantly, reducing installed costs to $630–1,070/kW. The 90-GW market share is based on reducing installed costs to $560–780/kW for a FC/T hybrid system. A recent analysis showed that incremental increases in efficiency beyond the inherently high efficiency of hybrids influence market share far less than installation cost. ***Table 1*** summarizes cost and performance values used in the market analysis as a function of hybrid capacity, along with the potential market share.

In the market study, the size of the market and the size of the appropriate system are based, in large part, on a concept that aggregates customers who can take advantage of shared installation and capital costs to counter historically high prices for grid-based electricity and associated service interruptions. Local distribution costs for servicing aggregated markets were factored into the analysis. While there is some market potential in the 300-kW to 1.5-MW size range, the primary market appears to be in the 15-MW to 40-MW range, particularly in the post-2010 timeframe.

While hybrids will find initial application in the DG market, they must ultimately be integrated into coal-based, 100+ megawatt central power generation systems to fully realize their efficiency and environmental performance potential. Largely due to DOE/industry R&D partnerships, coal-, residual oil-, and petroleum coke-based integrated gasification combined-cycle (IGCC) technology is beginning to penetrate the baseload power generation market, with efficiencies of 40% and capital costs of $1,200–1,300/kW. By 2008, ongoing R&D under the DOE Gasification Technologies program is expected to provide the impetus for IGCC to become the baseload power technology of choice by increasing efficiency to 52% and reducing capital costs to less than $1,000/kW. Parallel FC/T hybrids R&D is needed to further enhance IGCC performance, culminating in a 60% efficient coal-fired plant by 2015.

Globally, the demand for electricity is expected to double in the next 20 years, with the bulk of that demand coming from developing nations whose electric power infrastructure is modest or nonexistent. The market for distributed

TABLE 1. FC/T HYBRID INSTALLED COST TARGETS, PERFORMANCE, CAPACITY, AND PROJECTED MARKET SHARE

	0.3 MW Output	1.5 MW Output	25 MW Output	40 MW Output	
Year	Installed Cost $/kW (Efficiency%)				*Market Share*
2005	1,620 (63%)	1,400 (66%)	1,090 (70%)	1,060 (70%)	8 GW
2010+	1,070 (70%)	940 (71%)	660 (74%)	630 (74%)	60 GW
2015+	780 (70%)	700 (71%)	570 (74%)	560 (74%)	90 GW

Source: "Fuel Cell Hybrids: Market Assessment and Early Adapter Study," prepared by Resource Dynamics Corporation for the U.S. Department of Energy, National Energy Technology Laboratory. October 2001.

power generation, which requires no T&D infrastructure, is expected to be quite large in remote areas. This market represents a major opportunity for U.S. manufacturers, suppliers, and developers of hybrid power systems. Moreover, there is a continuing worldwide need for natural gas- and coal-based central power generation systems that can allay concerns over pollutant emissions and global climate change associated with fossil fuel use.

Energy Security and Reliability

Reliability in electric power supply has become a paramount issue for power providers and consumers as electricity underpins and integrates the entire U.S. economy. No one can deny the role electricity plays in day-to-day life. Since 1990, electricity accounts for more than 80% of total U.S. energy demand growth. Computers, the Internet, fiber optics, and wireless communications — just some of the technologies underlying the digital economy — will transform electricity use in the new millennium. Advances will include web-connected household appliances, “smart” houses, recyclable cell phones, advanced automated manufacturing, self-diagnosing and self-repairing equipment, and real-time, off-site process control. And all of these advances, at one time or another, will tap into the nation’s electric power system.

The issue, however, is broader than just the increase in electricity demand created by the digital economy. The new importance attached to the quality of power and the economic costs associated with interruptions is a testament to the impact of the new economy in terms of demands placed on the electric power industry. The dependence on computer networks has grown so great that even momentary outages can result in widespread disruptions ranging from the mere inconvenience of a frozen cursor to multi-million dollar losses caused by damage to sensitive and hugely expensive equipment. One study suggests that power failures nationally cost more than $50 billion a year in lost productivity. This pervasive dependence on electricity means that a disruption in the system can easily ripple through the economy. Yet, investment in new T&D capacity has not kept pace with growth in demand and changes in the electric power industry. And, siting concerns for new fossil-fueled electricity generation perpetuate the geographic mismatch between where electricity is generated and where it is needed.

The superior environmental performance of hybrids can remove siting constraints and allow them to be strategically located to alleviate strain on the T&D grid. Hybrids also can be used in on-site applications for further power service insurance, and for enhanced efficiency through avoidance of line losses and use of residual heat. Strategically dispersed power not only reduces the vulnerability of the T&D grid to functional breakdown, but to unanticipated disruptions. Also, hybrids have the potential to reduce United States’ dependence on politically unstable countries for oil supplies — current imports are over 50% and are projected to rise to 62% by 2020. Hybrids operate on low-cost domestic fuels, reduce use of premium fuels such as natural gas through extremely high efficiency, and provide a pathway to a hydrogen economy by operating on hydrogen, and having the potential to produce hydrogen.

Program Structure

The Hybrid Power Systems program is carried out by the NETL Strategic Center for Natural Gas under the auspices of the DOE Office of Fossil Energy. NETL is providing the appropriate federal role of mobilizing and merging government, industry, and scientific resources to achieve difficult technical and cost goals clearly in the public interest and validated through public process.

The NETL will competitively select and forge cost-shared partnerships with industry teams seeking to develop hybrid power systems. These teams will include members who will take the end product into the marketplace and provide needed market entry criteria. Through a separate process, NETL will tap into an existing structure of supporting technology programs engaging universities, national laboratories, and other research organizations to address cross-cutting R&D needs identified by the industry teams. These existing supporting technology programs include those already underway in the Fuel Cells, Turbines, Gasification, and Advanced Research & Technology Development (AR&TD) programs. NETL, as program manager and coordinator, will communicate identified R&D needs to existing supporting technology programs to take advantage of ongoing efforts. Technology needs unique to hybrid power systems that remain unresolved through existing programs will be addressed through competitively solicited, selected, and awarded research contracts.

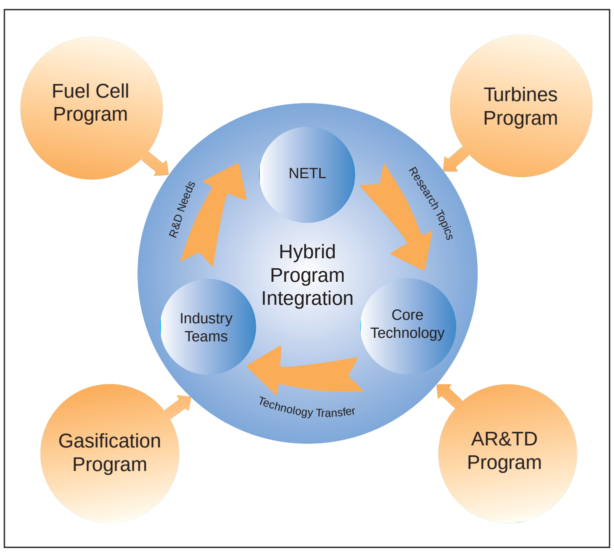
The Fuel Cells and the Turbines programs support the R&D needed to integrate the individual hybrid components. Hybrid activities within these product lines identify integration issues and develop the hardware needed to achieve optimum synergy between fuel cells and heat engines. The fuel cells, turbines, and hybrid products emerging from these efforts are designed for stand-alone operation on natural gas and transportation fuels.

A third ongoing development pathway, the Gasification Technologies product line, provides the means to enable fuel cells, heat engines, and hybrids to operate on coal and other solid fuels. The Gasification Technologies program will provide efficient gasifiers to convert solid fuels, such as coal, into synthesis gas (syngas), which is primarily hydrogen and carbon monoxide. This program also will provide gas separation and cleanup technologies to reduce gasification costs and condition syngas for hybrid use. The Fuel Cells and Turbines programs provide continuing input to the Gasification Technologies program to ensure product compatibility.

The AR&TD program supports all three power systems programs in development of instrumentation and controls needed to achieve integration of the major power components. Each component must sense and adjust to changes in outputs from the other components, such as gas composition, flow rate, pressure, and temperature to truly perform in a synergistic manner.

Figure 5 shows how hybrid product development draws upon other programs and integrates hybrids activities to effectively carry out the requisite R&D.

Figure 5. Hybrid Power Systems Program Structure



Program Approach

The Hybrid Power Systems program targets: (1) development of FC/T hybrids capable of serving the needs of aggregated customers in distributed generation applications and the needs of power generators in central power applications; and (2) evaluation of the development potential of innovative hybrid concepts that show promise for enhancing power generation cost and performance or expanding capabilities.

FC/T Hybrids: Goals

- Between 2003 and 2006, identify and resolve near-term integration, control, and component issues using sub-MW MCFC and tubular SOFC-based hybrids. (These systems will be applicable to early adapter and niche markets.) It is expedient to use these existing systems in support of achieving the goals for SECA-based hybrids.
- By 2006, complete conceptual designs and initiate testing of SECA-based SOFCs and optimized turbines to address follow-on integration issues, and scale-up and aggregation issues.
- By 2010, demonstrate aggregated SECA-SOFC stack design concepts that are capable of: (1) being scaled to MW-class FC/T hybrids, using an optimized turbine; (2) operating on natural gas and coal derived syngas at electrical efficiencies of 70% (lower heating value (LHV)) and 55% (higher heating value, (HHV)), respectively; and (3) offering a competitive cost of electricity and essentially pollution-free performance.
- By 2015, demonstrate MW-class FC/T hybrids based on optimized turbines and aggregated SECA fuel cell modules; and develop detailed designs for advanced zero emissions fossil fueled hybrid power systems capable of dominating both the aggregated DG and central power generation markets, by having capital costs of $400/kW, efficiencies up to 75% (LHV) on natural gas and 60% (HHV) on coal, and essentially pollution-free performance.

FC/T Hybrids: Approach

To meet the FC/T hybrid program goals, activities in the Fuel Cells and Turbines programs will be closely coordinated. These activities will include the optimization of existing turbines and components to match necessary pressure ratios and mass flows, address control issues, and optimize hybrid-specific components and other critical operating parameters for synergistic integration with SECA-based fuel cells emerging from the Fuel Cells program. SECA-related hybrid efforts will leverage SOFC cost reduction measures and refine designs to optimize hybrid performance. Important SECA-based hybrid design considerations are aggregation of the 3-kW to 10-kW modules to achieve multi-megawatt capacity, and operating temperature. Parallel activities in the Gasification Technologies program will pave the way for hybrid linkage to coal-, biomass-, and waste-derived fuels, as well as entry into the central power systems market.

Siemens Westinghouse near-200-kW FC/T hybrid at National Fuel Cell Research Center

Current hybrid activities are leveraging FC/T hybrid demonstrations using first-generation SOFC and MCFC fuel cells with off-the-shelf micro-turbines to provide data needed to address key integration and system control issues. DOE has supported key system studies and the development of fuel cell stacks in heavily cost-shared, small-scale (less than 0.3 MW) demonstrations with Siemens Westinghouse and FuelCell Energy. Testing of a near-200-kW FC/T hybrid at the National Fuel

FuelCell Energy's 280-kW FC/T hybrid

Cell Research Center by Southern California Edison and Siemens Westinghouse succeeded in revealing and defining the challenges of effectively integrating fuel cells and turbines and the associated limitations of existing gas turbines and control strategies. Likewise testing of a 280-kW FC/T hybrid power system at FuelCell Energy's research facility in Danbury, Connecticut has been successful in identifying control issues, component needs and turbine requirements.

Other current hybrid activities include General Electric's efforts to integrate their high power density SECA SOFC into a small hybrid configuration. This sub-scale activity will help to identify early SECA related hybrid issues. The National Fuel Cell Research Center is currently assessing system configurations and component improvements needed to achieve Zero Emission System performance goals.

The NETL on-site research group is completing construction of an experimental hybrid project called HYPER (Hybrid PERformance) to develop and test control strategies for hybrid systems. HYPER is a simulated fuel cell configured into a representative hybrid system using an actual 75-kW gas turbine. This project was designed to test system models, control strategies, and advanced sensors in a generic hybrid system.

Milestones for the near term include the following:

- By 2004, DOE's Advanced Combustion program is scheduled to complete development of a high-temperature, alloy-based heat exchanger capable of operating at temperatures of 2,300 °F, which could be added to the hybrids cycle development arsenal.
- By 2006, the combined Turbines and SECA hybrids activities are to culminate in a demonstration of a SECA SOFC/optimized turbine hybrid to resolve fuel cell scale-up, integration, and aggregation issues for SECA hybrids in the 200-kW to 2-MW range.

In the mid-term (2007–2010), FC/T hybrids will continue to incorporate SECA products and optimized turbine technology from the Turbines program. SECA has the succinct objective of producing high power density 3-kW to 10-kW SOFC modules at a manufactured cost of no more than $400/kW by 2010, with power densities greater than 0.6 W/cm_2. Ultimately, the success anticipated in the SECA program will facilitate the cost and performance goals envisioned for the FC/T hybrid power system. Throughout this mid-term period, the aggregating (or "ganging") of SECA modules and scale-up will be pursued to develop the technology for MW-class power blocks. The Turbines program, planned for conclusion in 2008, will be completing work to provide the necessary turbine designs and controls for multi-megawatt FC/T hybrids. During this period, the Gasification Technologies program will provide design criteria to the FC/T design teams; and gasification technology developments will provide the pathway for hybrid linkage to coal-, biomass-, and waste-derived fuels, and entry into the central power systems market.

Milestones for the mid-term include the following:

- By 2008, the Gasification Technologies program is to have developed and demonstrated a gasification-based power system capable of operating on coal and blends of coal and biomass or wastes, realizing efficiencies of 52% or more, costing $1,000 or less to install, and achieving NO_x, SO_2, and PM emission rates of 0.06 lb/106 Btu, 0.06 lb/106 Btu, and 0.003 lb/106 Btu, respectively.
- By 2010, the SECA program is to have reached the goal of making 3-kW to 10-kW SOFC modules with power densities greater than 0.6 W/cm_2 commercially available at a manufacturing cost of no more than $400/kW.

- By 2010, the combined SECA and Turbines program hybrid efforts are to achieve the Hybrid Power Systems goal of introducing into the marketplace a MW-class FC/T hybrid, using an optimized turbine and aggregated SECA fuel cell modules, that is capable operating on natural gas and coal-derived syngas at electrical efficiencies of 70% (LHV) and 55% (HHV), respectively; and that offers a competitive cost of electricity and essentially pollution-free performance.
- By 2010, the Gasification Technologies program is to further enhance efficient linkage of FC/T hybrids to gasifiers by developing hydrogen gas separation membrane-based systems, chemical and physical CO_2 absorption and adsorption technologies, and advanced pollutant controls.

In the long term (2010–2015), the thrust of activities will be to initially scale up the FC/T hybrids to larger systems (e.g., 20–40 MW) for an expanded DG market, and to move toward 100-MW systems for coal-, biomass-, or waste-fueled central power applications. Supporting this thrust will be development of advanced hybrid cycles, integrating multiple fuel cells and turbines to squeeze the maximum amount of energy out of the fuels used. A portfolio of advanced instrumentation and controls will be developed to handle numerous parameters and optimize environmental and operational performance of complex systems, incorporating gasifiers, fuel cells, and gas turbines. On the Gasification Technologies side, efforts will continue to develop by-product processes to efficiently convert constituents resulting from gasification into high-value products in lieu of wastes, essentially eliminating waste streams. A key enabling project, FutureGen, is designed to bring Gasification Technologies and advanced systems like FC/T hybrids together into Zero Emission Systems. The $1-billion FutureGen project is scheduled to take place over the next 10 years. The culmination of these activities will be the realization of the 2015 Hybrid Power Systems goal. ***Figure*** *7* (on page 18) provides a summary of near-term, mid-term, and long-term goals for the hybrids development.

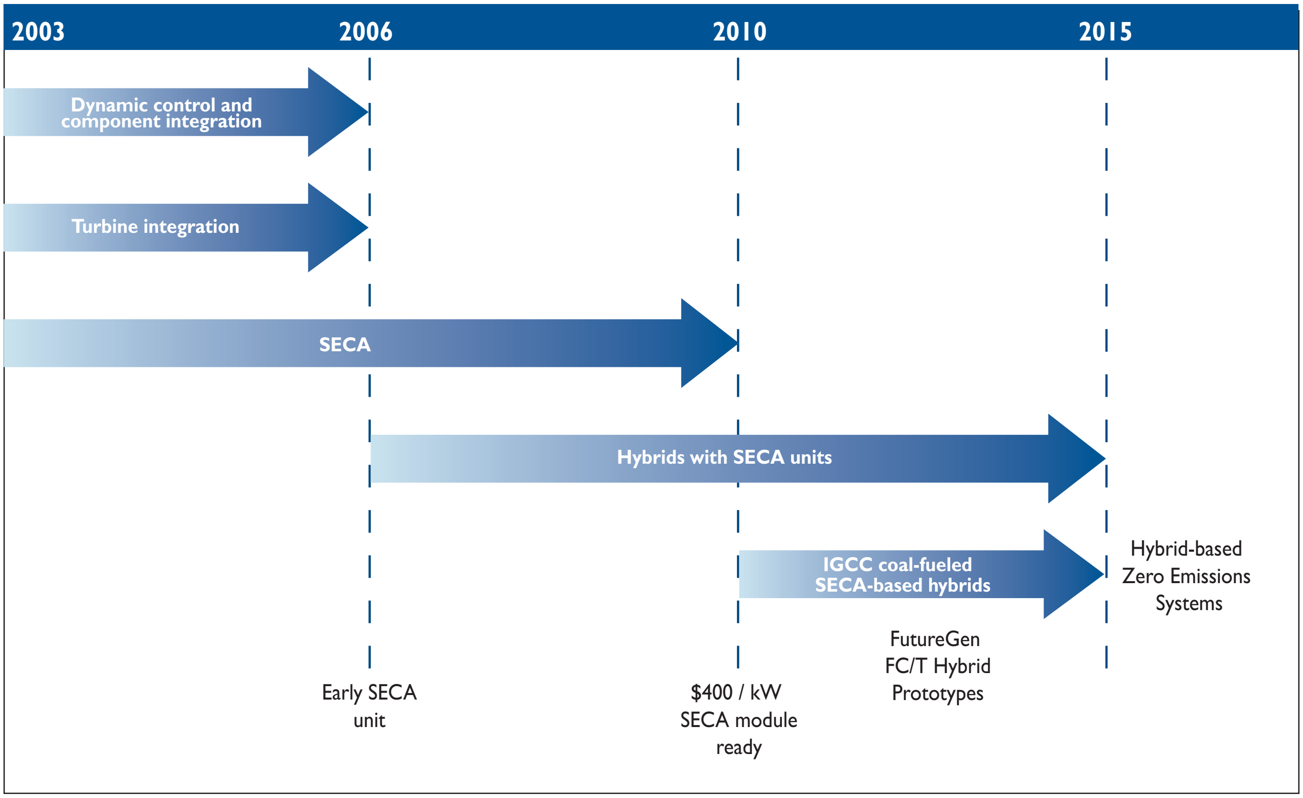
Innovative Hybrid Concepts

The "innovative hybrid concepts" element serves as a breeding ground for new hybrid concepts that have the potential to contribute toward achieving Zero Emission System goals. This element explores new concepts, nurtures those showing particular promise, investigates paths to commercialization with industry and the scientific community, and develops plans for realizing commercialization. Goals for the meritorious innovative concepts will be established through collaboration between the public and private sectors.

The approach is a generic one that actively seeks new concepts on an ongoing basis. Mechanisms and resources are provided for both in-house and outside public and private entities to explore the technical and economic feasibility of promising new concepts. Once basic technical and economic analyses establish the viability of a concept, more in-depth thermodynamic system assessments, modeling, and financial analyses (including market analyses) are conducted on the concept. Laboratory and bench-scale testing follow to investigate critical process steps, and the data are fed back into the technical and economic analyses to determine development potential. Throughout, information derived from the studies conducted on new concepts is made available to potential customers of the advanced technology, the technology developers, and the scientific community. The private sector is encouraged to unilaterally undertake development of specific designs based on the promising concepts, and establish the associated intellectual property. The Hybrid program engages with

Microturbine generator for the Siemens Westinghouse 300-kW pressurized hybrid

FIGURE 7. SUMMARY TIME LINE FOR HYBRIDS DEVELOPMENT



industry and the scientific community to explore paths to overcome impediments to commercialization of those concepts that demonstrate strong development potential, yet carry too much technical risk to achieve market entry. This dialog usually begins with participant workshops. The eventual outcome is a program plan for moving new concepts into the marketplace.

The FC/T hybrids program is a result of the generic approach to bringing next-generation concepts into being. The FC/FC hybrid is nearing the stage where paths to commercialization will be explored. Other concepts, such as fuel cell/reciprocating engine hybrids, are in the pipeline.

- ***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/Ts 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

Technical Challenges

While FC/T hybrids offer a clear pathway to Zero Emission Systems performance goals, the technical challenges that must be overcome along the way are significant. Achieving optimum synergy is critical and requires resolving compatibility issues between the fuel cells and turbines, and using innovative thermal management designs to recover the maximum amount of energy from the fuel. Commercial introduction of hybrids requires resolution of operational and response issues stemming from inherent process mechanisms, primarily in the fuel cells. Producing a high power density, low-cost SECA SOFC (one part of the hybrid system) represents a major developmental challenge. However, studies and workshops strongly suggest that high-efficiency hybrids can be a reality with a balanced and coordinated effort on the part of industry and the scientific community.

Compatibility. There are two basic integration issues associated with the fuel cells and turbines. Existing gas turbine compressor pressures and mass flows are not compatible with the high-temperature fuel cells that are used in the hybrids — the compressor pressures are too high and the mass flows too low for turbines with matching hot gas path power sections. The high-temperature fuel cells deliver a relatively low firing temperature to the gas turbine, 1,500–1,800 °F, which means that more air flow must be provided for a given power output. Parallel efforts are needed to modify existing gas turbines enabling them to deliver lower pressures and higher air flows, and to explore increasing fuel cells pressure tolerance. And, the hot gas path in the gas turbines needs to be modified to adjust for increased mass flow and the absence of on-board combustion.

Dynamic control issues also are important considerations in operation of FC/T hybrids. A successful FC/T hybrid requires synergistic coupling of two components with significantly different operating principals. These components must be controlled in real time through start-up, shutdown, emergency, and load-following operating scenarios. FC/T control problems are introduced in these transient operating scenarios because mass and volumetric flow rates are coupled between two systems with different time constants. Different fuel cell and turbine component response times impact the survivability of both components in dynamic operation. This situation poses major technical challenges from both a control philosophy and instrumentation standpoint.

Cost. In order to meet cost targets identified in ***Table 1*** (page 6), component costs for both the fuel cells and turbines must be reduced. The SECA program is addressing module stack cost. The SECA goal of $400/kW manufactured cost for a 3-kW to 10-kW module requires moderation of temperature to reduce materials costs, more sulfur tolerance, and increased power density. Specific issues being addressed include, but are not limited to, increasing cathode reactivity, development of interconnects that work well at lower temperatures, and the development of thin electrolytes with better ionic conductivity at lower temperatures.

Turbine costs represent a small fraction of the total hybrid power plant costs. This is due to the smaller contribution of turbines to the total power of the hybrid system, coupled with the mature and historically low costs of turbines. Currently, turbines in the 5-MW to 20-MW range are available with a nominal capital cost between $500/kW and $300/kW. As larger sizes are considered, the capital costs will decrease. The emphasis of the NETL turbine program will be to foster optimization of turbines for hybrid integration while maintaining the historically low cost of these machines. One approach to delivering this low-cost and optimized machine will be to utilize existing turbine platforms that are both cost-effective in simple cycle operation and can be modified for hybrid use.

Load Loss. Sudden loss of load presents a problem to FC/T hybrids. Upon loss of load, the fuel cells almost instantaneously stops reacting the hydrogen because the electrons are not available to support chemical conversion. Although reacting in fractions of a second, the fuel shut-off control is much slower than the cessation of hydrogen conversion. This time lag, plus the presence of fuel in the lines and reformer at the time of load loss, can result in a significant fuel buildup. The fuel buildup is a problem because the air supply from the turbine is not shut off instantaneously, which can lead to combustion. The large residual thermal load in the fuel cell continues to drive the turbine even after load ceases, and compressor shut-off controls suffer the same time lag problem as fuel shut-off controls. Solutions to the load loss issue will require some combination of rapid blow-off valves in the turbine compressor circuit, fuel diversion for controlled catalytic oxidation, and bottled nitrogen for fuel dilution.

Load Following. Load following introduces control issues as well. Short-term load excursions of 10–15% are readily handled by the fuel cell as a balance is reached between the brief periods of more fuel being reacted (as load increases) and less fuel being reacted (as load decreases). Short-term decreases in excess of 15% cause power output and turbine speed to drop, resulting in a bit longer response time to upward load swings due to the inherent inertia of the turbine. Longer-term load excursions are handled by simple fuel control to the fuel cell. The control issues occur in turndown conditions — major download adjustments. Fuel cell efficiency increases significantly as load drops significantly. So turndown requires not only fuel control but either reduced air flow or air inlet temperature, or both. Flow controls for the compressor and bypass controls for incoming air around the recuperator are indicated. Another control factor is introduced in direct-fired hybrid cycles, where the fuel cell is pressurized directly by the compressor. Pressure impacts fuel cell performance and must be controlled to avoid pressure surges.

Sensors and Controls. As evidenced by the above discussion, sensors, controls, and control logic will play a critical role in developing a commercial hybrid product. Sensors and controls must be designed and developed to measure and act upon key parameters, such as reformer composition, temperatures, pressures, and fuel and air flows throughout the system. Conditions placed on many sensors and controls are harsh (high temperatures and pressures, and corrosive environments) and functionally demanding (rapid response and tight control). Extensive testing will be required to develop the control logic to ensure safe and operationally sound performance.

Also, the direct current output of the fuel cell and alternating current of the turbine must be integrated and conditioned to meet the power quality specifications of the application. All components need to be better, faster, cheaper, and more tolerant of the high-temperature environment. Again, the potential range of applications includes conditions where the loads are highly variable and the system may be started up and shut down repeatedly over a short period of time. These transient conditions impose a significant burden on the power conditioning and control system, which must deliver the power needed while protecting the integrity of the system.

Thermal Management. Processing fuel for effective conversion to electricity by fuel cells is an integral part of, and critical to, system efficiency and cost. Internal reforming, or using process heat to convert fuels to usable form by the fuel cell, is essential to system efficiency. Moreover, internal reforming is an integral part of thermal management in the fuel cell because it serves to control heat produced in electrochemical reactions. A major thrust under the SECA program is development of a fuel processor that maximizes use of internally generated heat, and also deals with sulfur often contained in the fuels.

Hybrids introduce additional thermal management issues by having both the turbine and recuperator perform integrated heat utilization functions critical to power generation and to sustaining fuel cell operation. Development of efficient high-temperature heat exchangers takes on increased importance.

Modeling. Computer simulations will be developed, leveraging ongoing fuel cells, turbines, and hybrid development activities, to accelerate investigation and resolution of compatibility, operation and control, and thermal management issues. These simulations also document technical understanding and advances, and serve as a foundation for future research.

These technical challenges are being addressed in parallel. Through the Hybrid program and continued participation of industry and the scientific community, Zero Emission System goals can become a reality.

U.S. Department of Energy
National Energy Technology Laboratory

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

National Petroleum Technology Office
Williams Center Tower 1
1 West Third Street, Suite 1400
P.O. Box 3628
Tulsa, OK 74101-3628

Contacts:

Richard Dennis
Turbines Program Product Manager
(304) 285-4515
richard.dennis@netl.doe.gov

Dr. Mark Williams
Fuel Cells Product Manager
(304) 285-4747
mark.williams@netl.doe.gov

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