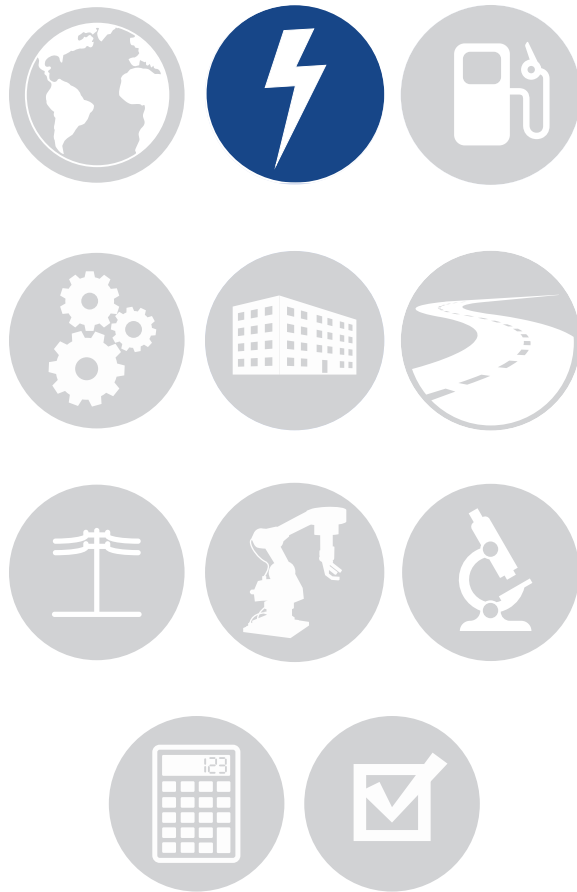




Quadrennial Technology Review 2015

Chapter 4: Advancing Clean Electric Power Technologies

Technology Assessments



Advanced Plant Technologies

Biopower

*Carbon Dioxide Capture and Storage
Value-Added Options*

*Carbon Dioxide Capture for Natural Gas
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Wind Power



U.S. DEPARTMENT OF
ENERGY



Advanced Plant Technologies

Chapter 4: Technology Assessments

Overview of Advanced Plant Technologies for Solid Fuels

Integral to management of carbon emissions from fossil and biomass power generation are efforts to improve base plant costs and efficiencies. The advanced plant technologies are combined with carbon capture and storage (CCS) technologies to minimize both emissions and costs. The non-capture components of a power plant offer opportunity for improving fuel conversion efficiencies, increasing plant availability, reducing water consumption, and achieving ultra-low emissions of traditional pollutants. For gasification technologies, this includes lower cost oxygen separation membranes, high efficiency hydrogen turbines, more efficient gas cleanup, and high temperature fuel cells. For pulverized coal plants it includes advanced turbines, supercritical CO₂ (sCO₂) power cycles, and high temperature durable materials. In addition, alternative combustion processes for coal that can generate a highly concentrated stream of CO₂ and minimize CO₂ separation costs, such as oxy-combustion and chemical looping, are being explored.

Turbomachinery and turbine-based cycles which operate at temperatures up to 3100°F and at high mass flow rates have the potential to achieve 65% integrated combined cycle efficiencies for natural gas plants. These technologies require advanced materials, system modeling for pressure gain combustion, advanced transition designs enabling higher turbine inlet temperatures, and low NO_x combustion. In addition, sCO₂ power cycles have the potential to reduce the cost of coal-based power generation by 5-15% (see Technology Assessment 4.R Supercritical Carbon Dioxide Brayton Cycle). Solid oxide fuel cells, when integrated with carbon capture, have the potential for >60% efficiency and >97% carbon capture, while using one-third the water and reducing the cost of capturing carbon with CCS technologies compared to conventional systems.

Key Technologies

Key technologies and research opportunities include the following:

- **Hydrogen Turbines** - Develop turbo-machinery and turbine-based cycles that will improve the efficiency and reduce the cost of coal-fueled power plants with carbon capture.^{1,2}
- **Oxy-Combustion** - Develop oxy-combustion and chemical looping technologies to combust coal in a high oxygen environment to generate power with greater than 90% carbon capture.^{3,4}
- **Gasification** - Develop advanced gasification systems⁵ and coal-biomass to liquids (CBTL) technologies^{6,7} to reduce the cost and increase the efficiency⁸ of converting coal into power and transportation fuels with near zero carbon emissions.
- **Supercritical CO₂ Power Cycles** - Develop turbomachinery, recuperators, and syngas-oxyfuel combustors in both direct and indirect supercritical CO₂ systems and assess the cost-performance benefits.⁹
- **Solid Oxide Fuel Cell** - Develop novel atmospheric and pressurized Solid Oxide Fuel Cell (SOFC) powered systems that produce electric power from coal using integrated coal gasification with carbon capture.



Hydrogen Turbines

Advances in turbine technology provide some of the most significant contributions to projected cost and efficiency improvements in both combustion and gasification applications. Furthermore, by increasing the conversion efficiency of fuel gas or boiler heat to electric power, advanced turbine technologies also reduce fuel requirements, the cost and size of equipment, and overall emissions. Advanced combustion turbines currently provide technology solutions for large-frame combustion turbines for coal-based Integrated Gasification Combined Cycle (IGCC) systems that can operate on pure hydrogen with a turbine inlet temperature approaching 2600°F. Components and subsystems for turbines that will operate on pure hydrogen (derived from coal) with a turbine inlet temperature approaching 3100°F will include additional advances in pressure gain combustion. Table 4.A.1 lists some of the challenges and desired outcomes for hydrogen turbines, and Table 4.A.2 summarizes their state-of-the-art, current R&D activities, and key R&D opportunities.

Table 4.A.1 Challenges and Desired Outcomes for Hydrogen Turbines

Hydrogen Turbines - Develop turbomachinery and turbine-based cycles that will improve the efficiency and reduce the cost of coal-fueled power plants with carbon capture.^{1,2}

Major R&D Challenges

- Elevated firing temperatures in order to improve cycle efficiency
- Advanced material systems for high temperature environments (up to 3100°F) with elevated mass flows (over 1000 kg/s) and increased moisture content (up to 15%) and with component lifetimes on par with conventional technologies
- Advanced cooling and leakage control strategies for reduction of parasitic losses that, if unabated, can result in an excessive airflow as high as 25% of the total airflow
- Fundamental and applied combustion of H₂ with improved NO_x emissions control through combustion geometry and downstream strategies that integrate the combustion transition with the first stage of the turbine hot gas path

Desired Outcomes:

- Demonstration of turbomachinery components to successfully point toward 65% integrated combined cycle efficiencies by attaining turbine inlet temperatures up to 3100°F, higher ramping rates, and lower minimum generation levels.
- Industry led component technology field demonstrations that support product initiation
- Demonstration and commercialization² of combustor technology, and associated advanced materials and coatings, and enhanced cooling technology.



Table 4.A.2 Technical Assessment and Opportunities for Hydrogen Turbines

Hydrogen Turbines - Develop turbo-machinery and turbine-based cycles that will improve the efficiency and reduce the cost of coal-fueled power plants with carbon capture.^{1,2}

State-of-the-Art	Current R&D	Opportunities and Future Pathways
<ul style="list-style-type: none"> ■ Full scale hydrogen combustion was demonstrated with single digit parts per million NO_x emissions.¹⁰ ■ Thermal barrier coating systems were demonstrated to enable hot gas path component operation at targeted turbine inlet temperatures.¹¹ ■ Advanced manufacturing techniques have been applied to reach cooling improvement goals through implementation of complex internal component features.¹¹ ■ The advances in H₂ turbines—including firing temperature, compressor and turbine efficiencies, and reduced cooling requirements—led to predicted efficiency improvements of 3 percentage points, a ~15% COE reduction, and cost of capture reduction of ~\$19/tonne. 	<ul style="list-style-type: none"> ■ Component-level demonstrations of 2nd generation H₂ turbine technologies at targeted inlet temperature (2650°F)^{12,13} include: <ul style="list-style-type: none"> - system modeling, - combustion development, - advanced coating and substrate materials development, and - aerodynamics and heat transfer improvements for optimized turbomachinery systems ■ System-level research for turbine component technologies include the following: pressure gain combustion, advanced transition designs enabling higher turbine inlet temperatures, CLC component material systems, low NO_x combustion at 3100°F, and more.¹⁴ ■ University Turbine Systems Research (UTSR) Program is a collaborative research effort involving universities and industry to focus on the areas of combustion, aerodynamics/heat transfer, and materials, in support of the Advanced Turbine Program goals.^{15,16} 	<ul style="list-style-type: none"> ■ Design and testing of cutting edge turbomachinery components, such as pressure gain combustion systems, advanced transition designs, novel internal cooling features and flow strategies, and hot gas path components.^{2,9} ■ Innovative materials, methods or concepts for gas turbine system operation at high temperatures (up to 3100°F), and high efficiency (65% integrated combined cycle system).

Oxy-Combustion and Chemical Looping Technologies

Advances in oxy-fuel combustion systems can decrease the mass and volume of flue gas, and hence reduce equipment size and system cost. When coupled with existing technologies, this can dramatically reduce the emissions of conventional pollutants. At the same time, oxy-fuel combustion flue gas is rich in CO₂, making separation of CO₂ from this concentrated stream much simpler than for more dilute air-fired combustion systems, which has the potential to increase efficiency. The formation of nitrogen compounds is nearly eliminated through the exclusion of air from the boiler, negating the need for nitrogen oxides control technologies. The capability to produce low-cost, coal-based electricity while eliminating nearly all air pollutants and potential greenhouse gas emissions makes advanced combustion one of the most promising technology areas for coal power plants of the future.

Two key oxy-fuel combustion technologies include pressurized oxy-combustion (POC) and Chemical Looping Combustion (CLC) - each with its own advantages and challenges. These technologies are focused on development of high-efficiency oxy-combustion and chemical looping technologies and novel concepts optimized for coal-fueled power plants with carbon capture.

Development of POC power generation systems is based on Pressurized Fluidized Bed technology and a novel staged oxy-combustion approach. Capital cost, energy consumption, and operational challenges of oxygen separation are among the most significant barriers to the use of oxy-combustion technology and the advancements in oxygen separation technology being pursued under the gasification program are critical to the success of the oxy-combustion program.¹⁷

Chemical Looping Combustion includes technologies that generate oxygen for combustion in situ, introducing oxygen to the system via oxidation-reduction cycling of a solid oxygen carrier between separate air and fuel reactors.¹⁸ This eliminates the need for conventional oxygen production. Current CLC research efforts are focused on development and refinement of high-capacity oxygen carriers that can withstand the harsh environment associated with CLC operation; development of effective and sustainable solids circulation and separation techniques; reactor design to support fuel and oxygen carrier choices; effective heat recovery and integration; and overall system design and optimization. Chemical looping and pressurized oxy-combustion have the potential to reduce the COE for coal-based power generation with CO₂ capture by more than 20% compared to today's technology with capture.¹⁹ Integration of supercritical CO₂ power cycles will further improve efficiency and COE.

Several atmospheric oxy-combustion systems have been operated at the pilot scale (1-10 MWe), leading to the generation of commercial-scale designs. The 1 MWe pilot scale systems aim to resolve technical gaps including stable long-term operation and to verify heat transfer characteristics. In addition, data such as a) equipment sizing parameters; b) gas and solids flow rates; and c) heat transfer rates and reactivities are needed for scaling up to large pilots. Table 4.A.3 describes some of the challenges and desired outcomes for oxy-combustion, and Table 4.A.4 summarizes the State-of-the-Art, current R&D activities, and key R&D opportunities for these technologies.

Table 4.A.3 Challenges and Desired Outcomes for Oxy-Combustion

Oxy-Combustion - Develop oxy-combustion and chemical looping technologies to combust coal in a high oxygen environment to generate power with greater than 90% carbon capture.

Major R&D Challenges

- Pressurized Oxy-Combustion
 - Controlling cost and complexity of pressurized operation
 - Ensuring materials strength, stability, manufacturability, and cost at high temperature and pressure conditions
 - Verifying heat transfer rates and optimal extraction methods under pressurized operation
 - Reducing cost and energy demand of CO₂ purification and compression over SOTA
- Chemical Looping
 - Identifying oxygen carriers with sufficient reactivity, stability, and longevity at an appropriate cost
 - Maintaining consistent controlled solids circulation which affects the optimal operating regime
 - Generating reactor designs to support consistent and controlled operation
 - Engineering a well-integrated system through system development²⁰

Desired Outcomes:

- Oxy-combustion technologies achieve efficiencies greater than 40% and cost reductions greater than 20% relative to today's IGCC with CCS^{14,21,22}
- Chemical looping technologies achieve efficiencies greater than 35% and cost reductions greater than 30% relative to today's IGCC with CCS^{14,23}
- Second generation technologies prepared for demonstration and commercialization leading to NOAK performance that decrease the COE of today's coal-fueled power plant with CCS by 20% when integrated with other second generation technologies¹⁵
- Technologies prepared for subsequent demonstration and commercialization leading to NOAK performance that decrease the COE of today's coal-fueled power plant with CCS by 30% when integrated with other second generation technologies¹⁵
- Integration of higher efficiency advanced power cycles such as advanced ultra-supercritical (AUSC) and sCO₂ steam cycles.²⁴ See also the Tech assessment on sCO₂, QTR TA 4.R.



Table 4.A.4 Technical Assessment and Opportunities for Oxy-Combustion

Oxy-Combustion – Develop oxy-combustion and chemical looping technologies to combust coal in a high oxygen environment to generate power with greater than 90% carbon capture.		
State-of-the-Art	Current R&D ¹³	Opportunities and Future Pathways
<ul style="list-style-type: none"> ■ Component level testing indicates that potential COE reductions of >20% are possible compared to today’s technology with capture.¹⁶ Integration of supercritical CO₂ power cycles can provide further gains. ■ Several atmospheric oxy-combustion systems have been operated at the pilot scale (1-10 MW_e), leading to the generation of commercial-scale designs, including performance and cost analyses.¹³ ■ Continuous operation of chemical looping systems was shown to be technically feasible at the small pilot (8kWe-1 MW_e) scale.²⁵ 	<ul style="list-style-type: none"> ■ Pilot scale (1 MW_e) systems are being developed to resolve technical gaps: <ul style="list-style-type: none"> - stable long-term operation - verification of heat transfer characteristics ■ Data are being collected for scaling up to large pilots: <ul style="list-style-type: none"> - equipment sizing parameters - gas and solids flow rates - heat transfer rates - reactivities ■ Projects on compact heat exchangers and recuperators for high-efficiency sCO₂ power cycles addressing cost efficient production, efficiency and plant optimization. 	<ul style="list-style-type: none"> ■ Large-scale pilot testing to evaluate performance and cost potential, retire risk, and collect engineering data prior to commercial scale demonstration. ■ Evaluate load-following capabilities, impacts, and solutions. ■ Advance development of technologies supporting optimized system integration such as advanced CO₂ purification, advanced compression, advanced oxygen production.¹⁹ ■ Identify and evaluate new concepts for efficient and effective conversion of coal to power via oxy-combustion, including pressurized oxy-combustion boilers and integrated oxygen production technologies. ■ Integrate high-efficiency supercritical CO₂ power cycles with coal-based power systems through modeling and testing at large-pilot scale.

Gasification

Gasification RDD&D emphasizes development of technologies that can be efficiently integrated into the plant, optimized with the temperature and pressure requirements of other systems, and meet product delivery specifications. A major cost element in gasification plants is converting raw syngas into a pure and specific gas used to create the plant’s target product suite. High-hydrogen, low-methane, ultraclean syngas is versatile and can be used for power production with CO₂ capture, and for fuels or chemicals production. RDD&D includes reducing the energy requirement for hydrogen production, and warm syngas cleanup. Other applications with simultaneous on-site generation of electric energy, process steam or heat, and products from the same plant include coal and coal-biomass gasification and the production of affordable liquid fuels and hydrogen. The technologies being developed are focused on attaining significant improvements in the value of product distribution using catalysts that lead to hydrocarbon mixtures not bound by the Anderson-Schulz-Flory distribution.²⁶ Table 4.A.5 describes some of the challenges and desired outcomes for gasification and CBTL, and Table 4.A.6 summarizes the State-of-the-Art, current R&D activities, and key R&D opportunities for these technologies.



Table 4.A.5 Challenges and Desired Outcomes for Gasification and Coal/Biomass-to-Liquids

Gasification and CBTL - Develop advanced Gasification Systems²⁷ and Coal/Biomass-to-Liquids (CBTL) technologies³⁰ to reduce the cost and increase the efficiency of converting coal into power and transportation fuels with near zero carbon emissions.

Major R&D Challenges

- Identifying materials for high temperature operations
- Integrating numerous interdependent unit operations as advances in cost and efficiency are made
- Developing catalysts and processes with enhanced control of product distributions

Desired Outcomes:

- Second generation gasification and CBTL technologies move to demonstration and commercialization and achieve the projected combined 20% COE reduction relative to today’s coal-fueled power plant with CCS
- Development of advanced in-situ gasification of coal seams that create methane, such as in-situ bio-gasification
- Gasification and CBTL technologies demonstrate their potential as integrated systems with 30% COE reduction relative to today’s coal-fueled power plant with CCS
- Demonstrate production of transportation fuels from coal and/or biomass with cost and greenhouse gas (GHG) emissions acceptable for a broad deployment.

Table 4.A.6 Technical Assessment and Opportunities for Gasification and Coal/Biomass-to-Liquids

Gasification and CBTL - Develop advanced Gasification Systems, and Coal/Biomass-to-Liquids (CBTL) technologies, including coal-to-liquid and co-firing coal and biomass, to reduce the cost and increase the efficiency of converting coal into power and transportation fuels with near zero carbon emissions.

State-of-the-Art	Current R&D ¹³	Opportunities and Future Pathways
<ul style="list-style-type: none"> ■ Early studies of increased operating temperatures between the gasifier and either the turbine or downstream conversion processes have suggested that process efficiency gains are possible.³¹ ■ Advanced process concepts have been individually demonstrated at a component level and are deemed to have synergies that may help drive chemical reactions, reduce capital costs, and increase the efficiency of each.³² ■ Integration of the water-gas-shift (WGS) reaction and CO₂ capture have been modeled to show a reduction in the cost of making steam.³³ 	<ul style="list-style-type: none"> ■ Ion transport membranes are being developed for higher temperature oxygen production.³⁴ ■ Techniques are being developed for sulfur and particulate removal from syngas in high temperature environments.²³ ■ Gasifiers based on rocket technology are being integrated with syngas cleanup and advanced WGS operations.³⁵ ■ A WGS process is being developed to have a greater extent of reaction through the removal of CO₂.³³ ■ A chemical looping process is being developed to remove oxygen from air for a coal gasification process.³⁶ ■ Several small projects are investigating the viability of bio-gasification development.³⁷ ■ Publicly available computational and physical simulations are being used to predict commercial reactor behavior, speed the development of new concepts and optimize commercial operations.³⁸ ■ Research studies in reactor re-design, microwave use, particle size optimization, etc. are being conducted to change gasifier operation limits so that lower temperature coal conversion may decrease operations costs. 	<ul style="list-style-type: none"> ■ Develop advanced technologies for coal and coal-biomass mixtures that are ready for integrated demonstration by 2020. ■ In-situ bio-gasification of coal could be demonstrated in actual coal seams, pending independent verification of DOE systems analysis that shows the cost of the process is competitive with natural gas prices. ■ Develop reactor geometries and chemistry that lower temperature and smaller reactor designs to improve the cost of gasification over current state-of-the-art. ■ Research tight integration of steam-methane-reforming with pyrolysis/mild-gasification for liquids production to realize significant production and cost advantages.

Supercritical CO₂ (sCO₂) Power Cycles

Supercritical CO₂ (sCO₂) based power cycles take on two primary configurations relevant to fossil power generation: 1) an indirectly heated closed Brayton Cycle for advanced combustion applications, and 2) a semi-closed directly heated oxy-fuel Brayton Cycle (see also Technology Assessment 4.R). Developmental challenges common to both applications include turbo-machinery (expanders and compressors) and recuperators. Assuming high-temperature conditions can be achieved (1200-1400°F, (650-750°C) for indirect cycles and 2370°F (1300°C) for direct cycles), transformational benefits will be realized. The IGCC direct fired cycle requires oxy-fuel syngas combustion and turbine integration.

Thermodynamic modeling of sCO₂ power cycles demonstrates better efficiency when compared to traditional steam based Rankine cycle systems, which are used for roughly 80% of the world's electricity generation. The sCO₂ power cycle transforms heat energy to electrical energy through the use of CO₂ as a supercritical fluid rather than through steam and water and has the potential of thermodynamic cycle efficiencies of 50% or greater.^{39,40} The average efficiency of the U.S. fleet is in the low 30 percent range, whereas modern coal power plants using ultra-supercritical (USC) steam cycles have been built in Germany, Japan and China and have achieved thermal efficiencies of 46%. The impact of thermal efficiencies of 50% or greater through either pushing further advancements in USC (Advanced USC or AUSC) or transition to sCO₂ cycles would be transformative. Furthermore the broad application of the sCO₂ cycle and its unique features creates an attractive market for this technology beyond large stationary power generation. Table 4.A.7 describes some of the challenges and desired outcomes for sCO₂ Power Cycles, and Table 4.A.6 summarizes the State-of-the-Art, current R&D activities, and key R&D opportunities for these technologies.

Table 4.A.7 Challenges and Desired Outcomes of sCO₂ Power Cycles

sCO₂ Power Cycles – sCO₂ Power Cycles: Perform R&D on both direct and indirect sCO₂ systems, including the development of turbomachinery, recuperators, and syngas-oxyfuel combustors.

Major R&D Challenges

- Turbomachinery, heat exchanger, and balance-of-plant materials that can withstand 1300°F (700°C) to improve reliability and cycle efficiency
- Control of kinetics in direct-fired sCO₂ environments with suppression of instabilities and undesired products to improve reliability of the system
- Identify system design for optimization of performance and cost
- Develop oxy-combustors for direct cycles to provide a direct-fired system.
- Identify and model control strategies to optimize cycle performance for both indirect and direct-fired systems
- Integrate fossil energy heat sources for indirect cycles⁴¹ to allow integration with existing firing technologies

Desired Outcomes:

- Pilot testing of a pre-commercial sCO₂ power cycle to demonstrate reliable operation and contribution to an integrated goal of a 30% COE reduction at the 50 MWe scale relative to today's coal power plants with CO₂ capture



Table 4.A.8 Technical Assessment and Opportunities of sCO₂ Power Cycles

Supercritical CO₂ Power Cycles - sCO₂ Power Cycles: Perform R&D on both direct and indirect sCO₂ systems, including the development of turbomachinery, recuperators, and syngas-oxyfuel combustors.

State-of-the-Art	Current R&D ¹³	Opportunities and Future Pathways
<ul style="list-style-type: none"> ■ System studies have shown efficiencies higher than AUSC with reduced plant size and simpler operation, suggesting the potential for a COE reduction of 5-15% relative to coal-based power generation using supercritical steam. ■ Unique system features (e.g., compact turbo machinery), and the potential for lower cost and higher thermodynamic efficiency make sCO₂ power cycles attractive for various heat sources including fossil, nuclear and solar.^{42,43,44} ■ There are sCO₂ power cycle test loops in operation (Bechtel Marine Propulsion Corp., Sandia National Laboratories, Echogen Power Systems) and other DOE-funded test facilities in planning and/or construction phases.^{45,46,47} 	<ul style="list-style-type: none"> ■ Materials testing and characterization are being conducted for high temperature and pressure sCO₂ operation. ■ Measurement of thermodynamic (specific heat, density, and conductivity) and transport properties (viscosity) are being conducted to characterize the sCO₂, and identify ideal CO₂-water mixtures (10 – 20%).^{48,49} ■ Systems studies are underway to establish optimum cycle operating conditions and boundary conditions for components.⁵⁰ ■ Design, construction, and testing of key components, including turbo expanders, compressors, recuperators, and primary heat exchangers, are underway for indirect sCO₂ cycles as well as oxy-combustors for directly heated sCO₂ cycles.⁵¹ 	<ul style="list-style-type: none"> ■ Develop components and technologies and scale them to 10MW_e size as a next phase of development, and if successful, then to the next scaleup step—a 50 MW_e system. ■ Perform component testing and performance evaluation in the 10 MW_e pilot test facility, to then be followed by scaleup to 50 MW and higher. ■ Demonstrate cycle and component performance that will lead to large scale, highly efficient cycles.

Solid Oxide Fuel Cell

Fuel cell technologies are well-suited to stationary applications in view of their low emissions, inherently high efficiencies even at small scales, scalability (kW to multi-MW), high reliability, quiet operation, relatively low maintenance requirements, and ability to handle several types of fuels (natural gas, biogas and higher hydrocarbons, and hydrogen). Unlike heat engines, which are limited by the Carnot efficiency and materials constraints, fuel cells can theoretically achieve > 75% electrical efficiency, though operating efficiency at high loads may be lower.

Solid Oxide Fuel Cell (SOFC) power systems in particular have the potential to achieve greater than 60 percent efficiency (HHV) and more than 97% carbon capture. Their projected cost of electricity is approximately 40 percent below presently available IGCC systems with carbon capture. In SOFCs, power is generated by the migration of oxygen anions from the cathode to the anode to oxidize the fuel gas, which is typically a mixture of hydrogen and CO. The electrons generated at the anode move via an external circuit back to the cathode where they reduce the incoming oxygen, thereby completing the cycle.⁵² Table 4.A.9 describes some of the challenges and desired outcomes for Solid Oxide Fuel Cells, and Table 4.A.10 summarizes the State-of-the-Art, current R&D activities, and key R&D opportunities for these technologies.



Table 4.A.9 Challenges and Desired Outcomes for Solid Oxide Fuel Cells

Solid Oxide Fuel Cell - Develop novel, Solid Oxide Fuel Cell-powered atmospheric and pressurized systems that produce electric power.

Major R&D Challenges

- Increasing fuel cell system power by 10% with no loss of efficiency when operating at normal operating conditions (NOC)
- Reducing system performance degradation from present 1.0 to 1.5 percent per 1,000 hours to less than 0.2% per 1,000 hours
- Improving durability and reliability of a prototypical stack to nominally 5 years of operation from present ~5,000 hours
- Achieving 100% integrated fuel reformation inside the fuel cell stack compared to today's 70%
- Demonstrating thermally self-sustaining operation at NOC of a prototypical stack
- Reducing material and manufacturing costs from today's system cost of ~\$10,000/kW_e to ~\$1,000/kW_e for high volume production

Desired Outcomes:

- Advance current benchscale technologies to demonstration and commercialization, to achieve an integrated NOAK performance having a 30% COE reduction relative to today's coal-fueled power plant with CCS
- Achieve greater than 60% efficiency and over 97% carbon capture for IGFC power systems along with a 40% COE reduction relative to presently available IGCC systems with carbon capture
- Demonstrate SOFC power systems having approximately one-third the amount of water use relative to coal-based power systems

Table 4.A.10 Technical Assessment and Opportunities for Solid Oxide Fuel Cells

Solid Oxide Fuel Cell – Develop novel, Solid Oxide Fuel Cell-powered atmospheric and pressurized systems that produce electric power from coal using integrated coal gasification with carbon capture.

State-of-the-Art	Current R&D ¹³	Opportunities and Future Pathways
<ul style="list-style-type: none"> ■ Single-cell performance and degradation are acceptable; while fuel cell stack and system performance, reliability, and endurance need demonstration.⁵² ■ SOFC technology costs continue to come down with R&D and have the potential for high volume manufacturing in the future. ■ Cathode materials are presently perovskite based, e.g. doped Lanthanum Manganite. Leveraging of advanced manufacturing techniques to reduce stack component and fabrication costs is underway. 	<ul style="list-style-type: none"> ■ Stack tests (60 kW_e class) are in progress. The expected degradation rate is <0.5 percent per 1,000 hours. Planned operation is >1,000 hours. The demonstration is targeted at 100% fuel reformation. ■ System tests (125 kW_e class) are planned to be fueled by pipeline natural gas, to export AC to the grid, and to integrate commercial-scale subsystems. The expected operation is >2,500 hours. ■ Technologies critical to the commercialization of SOFC include approximately 30 projects in areas of cathode materials,⁵³ advanced manufacturing processes, more durable seals⁵⁴ and interconnects.⁵⁵ 	<ul style="list-style-type: none"> ■ The deployment of IGFC systems may be accelerated by leveraging the near-term market opportunities in natural gas fueled distributed generation.⁵⁶ ■ Testing natural gas fueled 400 kW_e SOFC prototype power systems is needed to demonstrate long term operation of the 2nd Generation SOFC technology. ■ MW_e-class demonstration program prototypical of natural gas fueled MWe-class DG systems. Natural gas fueled Multi-MW_e demonstrations with CCS. ■ First-of-a-kind >50 MW_e utility-scale demonstration in the late 2020's, fueled by natural gas or coal derived synthesis gas.

Endnotes

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Acronyms

AUSC	Advanced ultrasupercritical
CBTL	Coal-biomass to liquids
CCS	Carbon capture and storage
CLC	Chemical looping combustion
CO₂	Carbon dioxide
COE	Cost of electricity
cP	Centipoise
EOR	Enhanced oil recovery
H₂	Hydrogen
H₂O	Water
IGCC	Integrated gasification combined cycle
IGFC	Integrated gasification fuel cell
KW_e	Kilowatt electrical (1000 watts)
MEA	Monoethanolamine
MW_e	Megawatt electrical (1,000,000 watts)
NGCC	Natural gas combined cycle
NOAK	Nth of a kind
NOC	Normal operating conditions
PC	Pulverized coal
POC	Pressurized oxy-combustion
RDD&D	Research, development, demonstration, and deployment
ROIP	Residual oil in place
ROZ	Residual oil zone
sCO₂	Supercritical CO ₂
SOFC	Solid oxide fuel cell
SOTA	State of the art
USC	Ultra-supercritical
WGS	Water-gas-shift