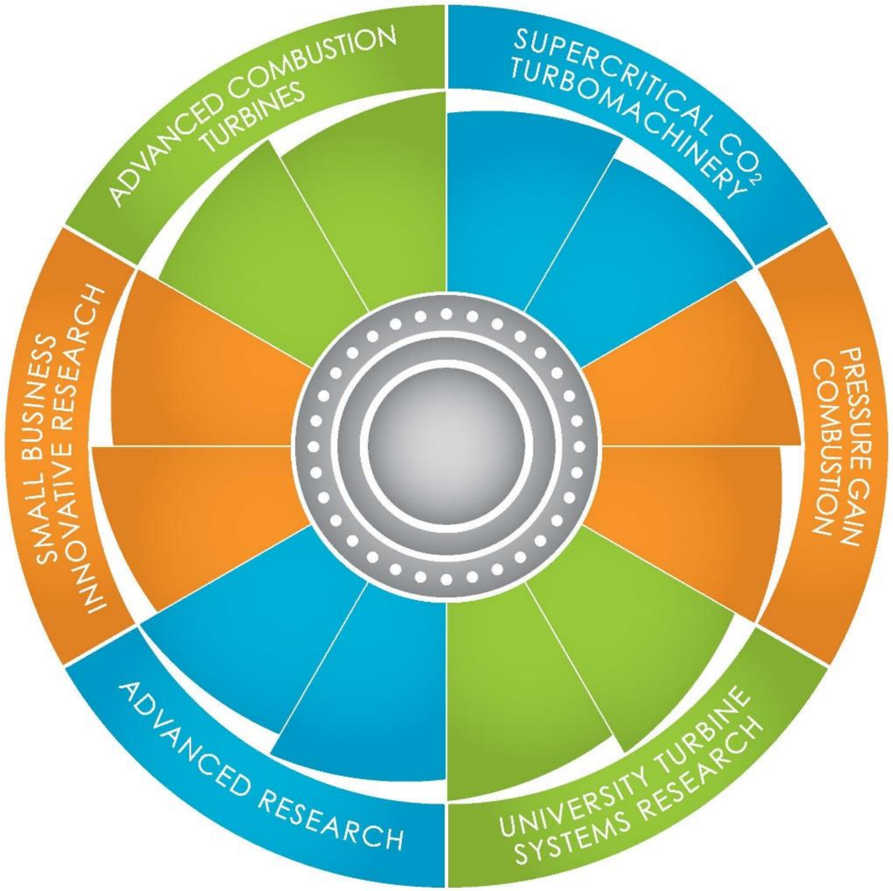
Overview of the US DOE Advanced Turbines Program

Keynote Session 3: National and Regional Markets: Opportunities and R&D Challenges for Gas Turbine Stakeholders

NATIONAL ENERGY TECHNOLOGY LABORATORY



The Future of Gas Turbine Technology

9th International Gas Turbine Conference

October 10 – 11, 2018
La Plaza Hotel
Brussels, Belgium

Rich Dennis
Technology Manager
Advanced Turbines and
SCO2 Power Cycles
U.S. Department of Energy
National Energy Technology Laboratory

Presentation Overview

Overview of the US DOE Advanced Turbines Program

- **Overview of NETL**
- **Market Data for US Turbine Based Power Generation**
- **Overview of the US DOE Advanced Turbines R&D Program**
  - Advanced combustion turbines for syngas, NG and H_2 fuels
  - Pressure gain combustion for combustion turbines
  - Modular turbine based hybrid heat engines
  - Supercritical carbon dioxide (sCO_2) based power cycles
- **Conclusions & Summary**

Department of Energy

Organizational Structure

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **OFFICE of the SECRETARY**
  - Secretary
  - Deputy Secretary
  - Boards & Councils
  - Federal Energy Regulatory Commission
  - Inspector General
  - Ombudsman
  - Chief of Staff

Office of the Under Secretary for Nuclear Security and National Nuclear Security Administration
Under Secretary for Nuclear Security Administrator (S5)/ Administrator, NNSA

- Deputy Administrator for Defense Nuclear Nonproliferation
- Deputy Administrator for Naval Reactors
- Associate Administrator for Defense Nuclear Security
- Associate Administrator for External Affairs
- Associate Administrator for Management & Budget
- Office of General Counsel
- Deputy Administrator for Defense Programs
- Deputy Under Secretary for Counter-terrorism & Counter-proliferation
- Associate Administrator for Emergency Operations
- Associate Administrator for Safety, Infrastructure & Operations
- Associate Administrator for Acquisition & Project Management
- Associate Administrator for Information Management & Chief Information Officer

Office of the Under Secretary for Science
Under Secretary for Science (S4)

- Office of Science
- Office of Technology Transitions
- Office of the Assistant Secretary for Environmental Management
- Office of Legacy Management
- National Laboratory Operations Board

Office of the Under Secretary for Energy
Under Secretary (S3)

- Office of Policy
- Office of the Assistant Secretary for Electricity
  - Bonneville Power Administration
  - Southwestern Power Administration
  - Southeastern Power Administration
  - Western Area Power Administration
- Office of the Assistant Secretary for Nuclear Energy
- Loan Programs Office
- Office of the Associate Under Secretary for Environment, Health, Safety & Security
- Office of Assistant Secretary for Energy Efficiency and Renewable Energy
- Office of the Assistant Secretary for Fossil Energy
  - NATIONAL ENERGY TECHNOLOGY LABORATORY
- Office of Indian Energy Policy and Programs
- Office of Project Management Oversight & Assessments

Staff Offices

- U.S. Energy Information Administration
- Office of the Assistant Secretary for International Affairs
- Office of Enterprise Assessments
- Office of the General Counsel
- Office of the Chief Human Capital Officer
- Office of Management
- Office of Intelligence & Counterintelligence
- Advanced Research Projects Agency - Energy
- Office of the Assistant Secretary for Congressional & Intergovernmental Affairs
- Office of Public Affairs
- Office of the Chief Financial Officer
- Office of Chief Information Officer
- Office of Small and Disadvantaged Business Utilization
- Office of Economic Impact & Diversity
- Office of Hearings & Appeals

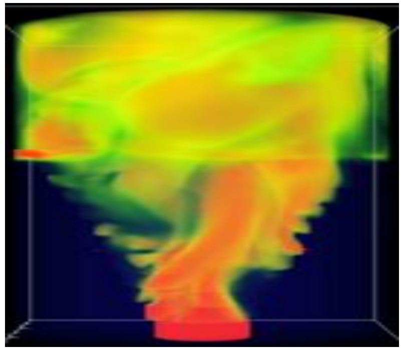
U.S. DEPARTMENT OF ENERGY

Updated: July 2018

NETL Core Competencies

NATIONAL ENERGY TECHNOLOGY LABORATORY

Effective Resource Development • Efficient Energy Conversion • Environmental Sustainability

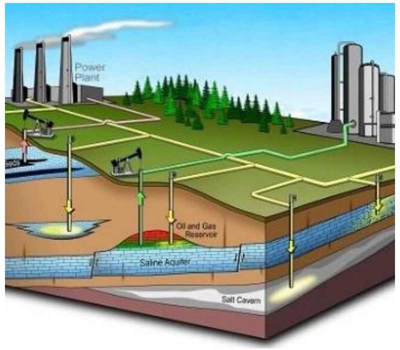


Computational Science & Engineering

- High Performance Computing
- Data Analytics

Materials Engineering & Manufacturing

- Structural & Functional
- Design, Synthesis, & Performance



Geological & Environmental Systems

- Air, Water & Geology
- Understanding & Mitigation

Energy Conversion Engineering

- Component & Device
- Design & Validation

Systems Engineering & Analysis

- Process & System
- Optimization, Validation, & Economics

Program Execution & Integration

- Technical Project Management
- Market & Regulatory Analysis

U.S. DEPARTMENT OF ENERGY

DOE FE NETL Program Areas

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Advanced Energy Systems

- Transformational Power Generation
- Advanced Combustion, Gasification, Fuel Cells, and Gas Turbines
- Efficient Energy Conversion
- Coal Beneficiation

Carbon Capture

- Cost-Effective Capture Systems
- Minimize Energy Penalty for Capture and Compression
- Smaller Capture System Footprint

Carbon Storage

- Safe, Effective, Long-Term Storage
- Monitoring, Verification, Accounting, and Assessment
- Demonstrate Storage Infrastructure
- Utilization of Captured Carbon Dioxide

Crosscutting Research & Analysis

- High-Performance Materials
- Sensors and Controls
- Simulation-Based Engineering
- Water Management
- University Training and Research

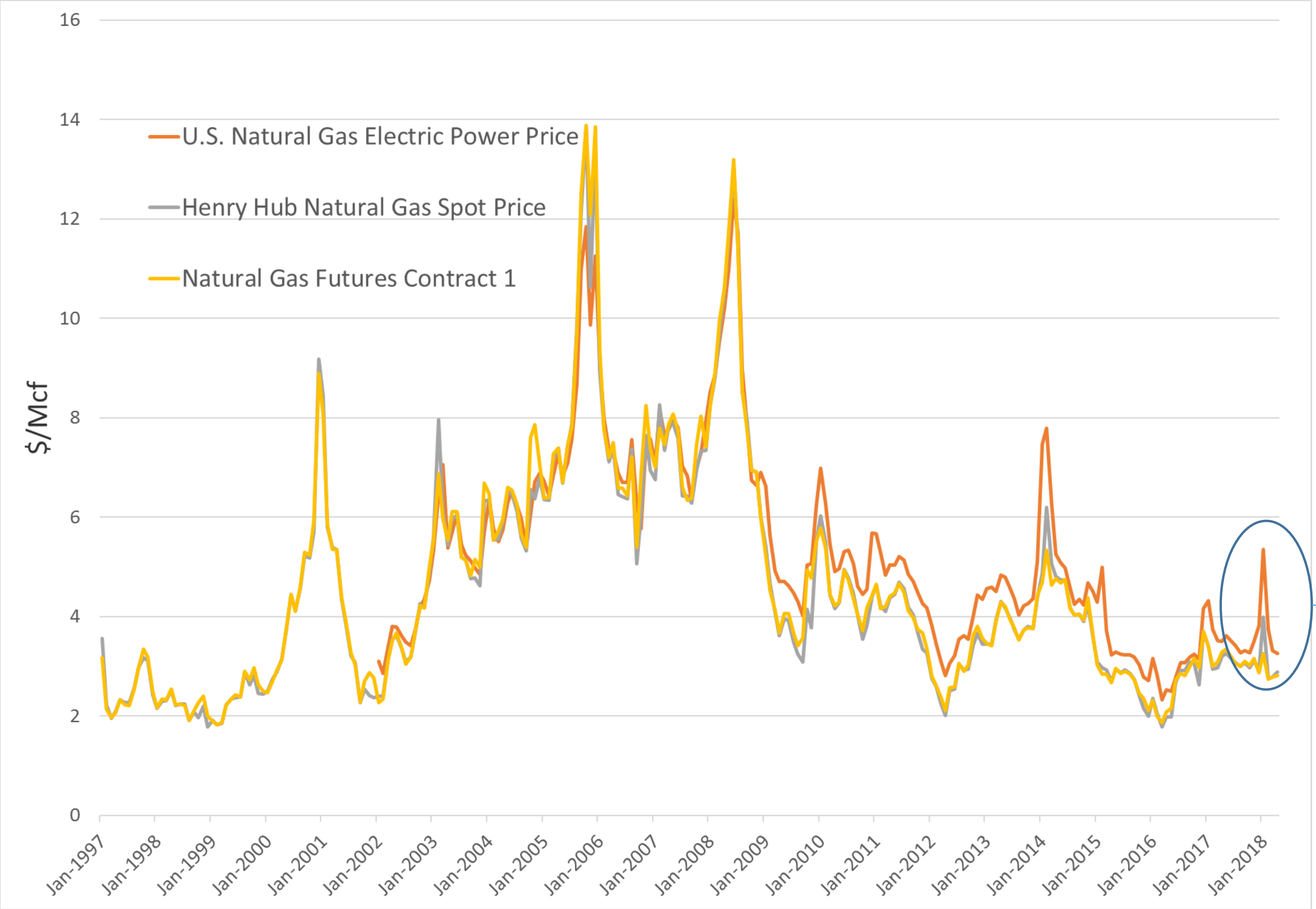
STEP (Supercritical CO_2)

- High-Efficiency Power Cycle
- Reduced Water Consumption and Air Emissions
- Reduced Power Cycle Footprint

Rare Earth Elements

- Efficient Rare Earth Element (REE) Recovery
- Cost-Competitive Domestic Supply of REEs

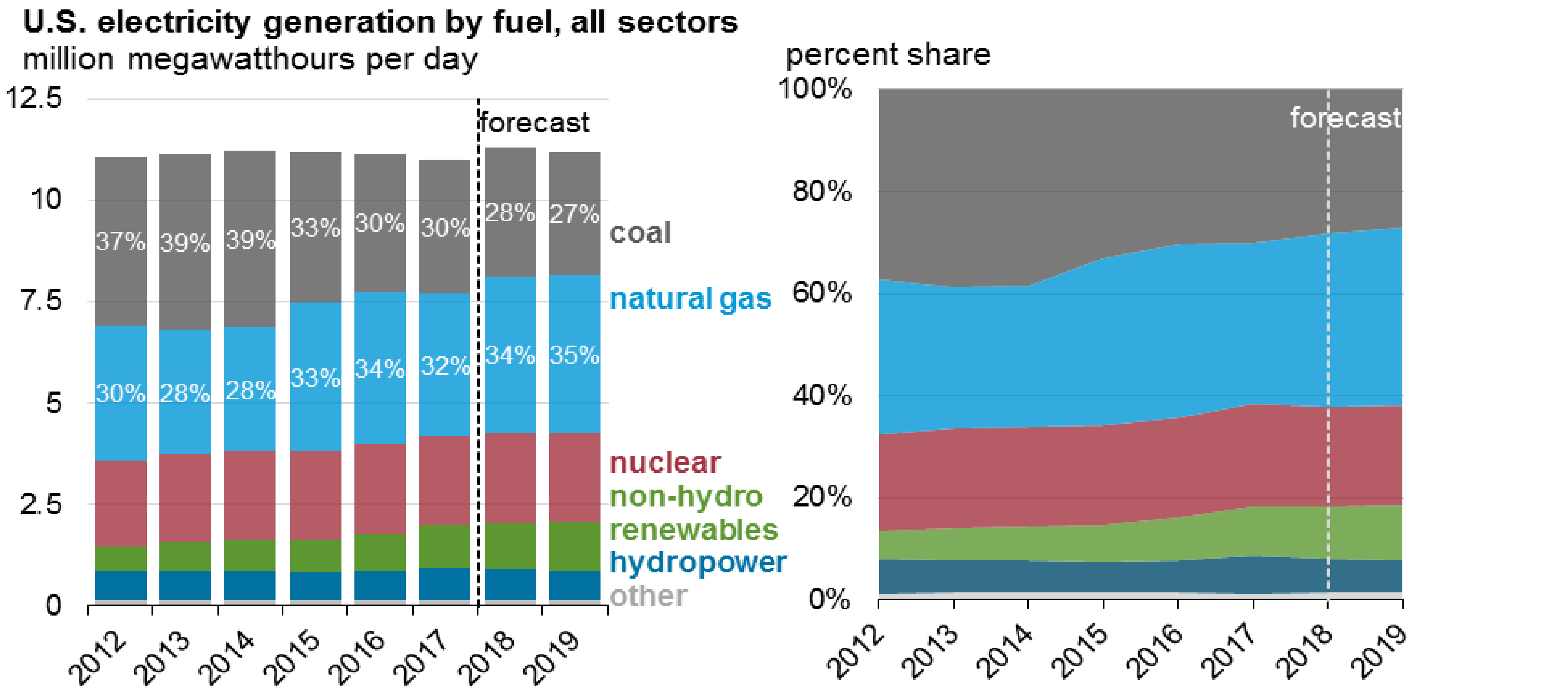
Historical US Natural Gas Prices



Abnormally cold weather Dec/Jan 2018

Source: EIA

Electricity Generation Mix (Short Term)



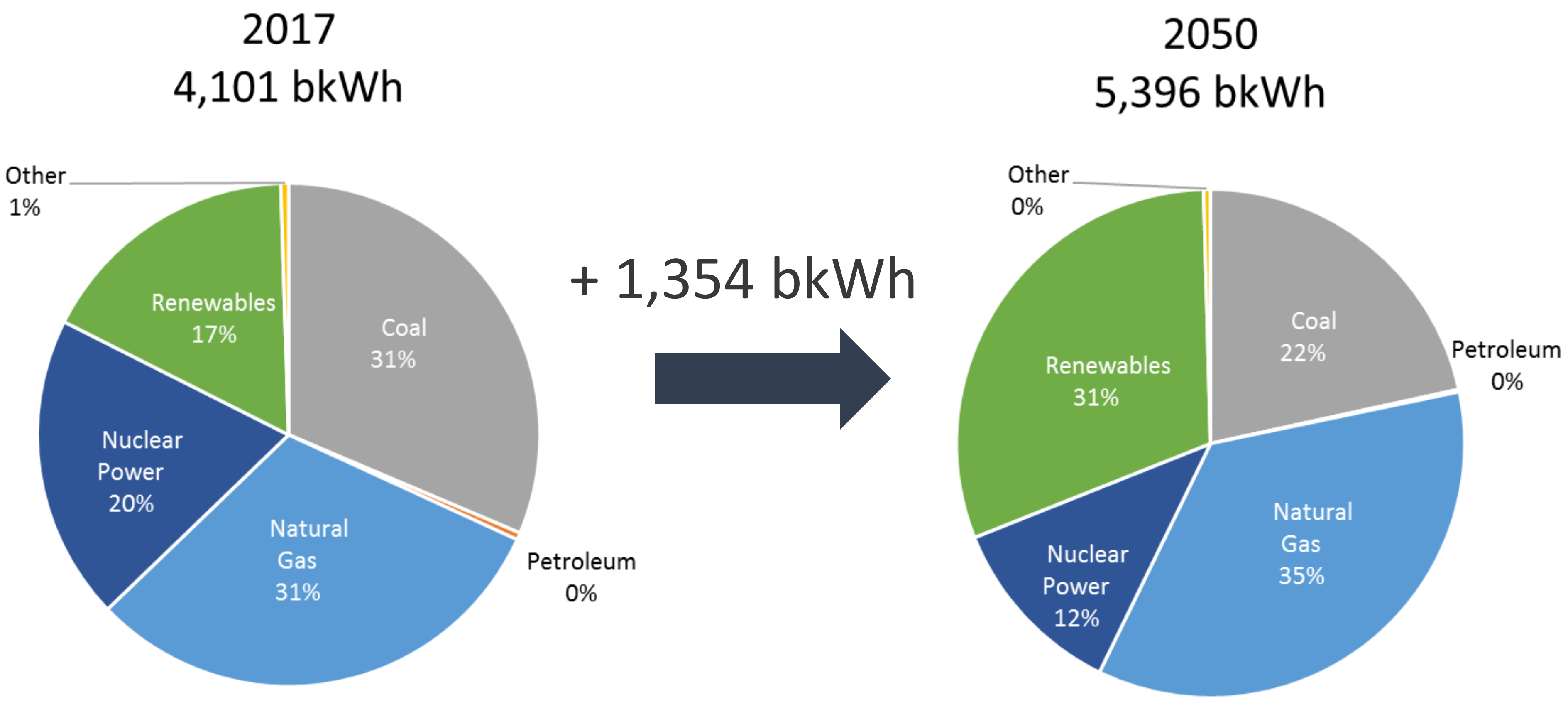
Note: Labels show percentage share of total generation provided by coal and natural gas.

Source: Short-Term Energy Outlook, July 2018

EIA = Energy Information Administration

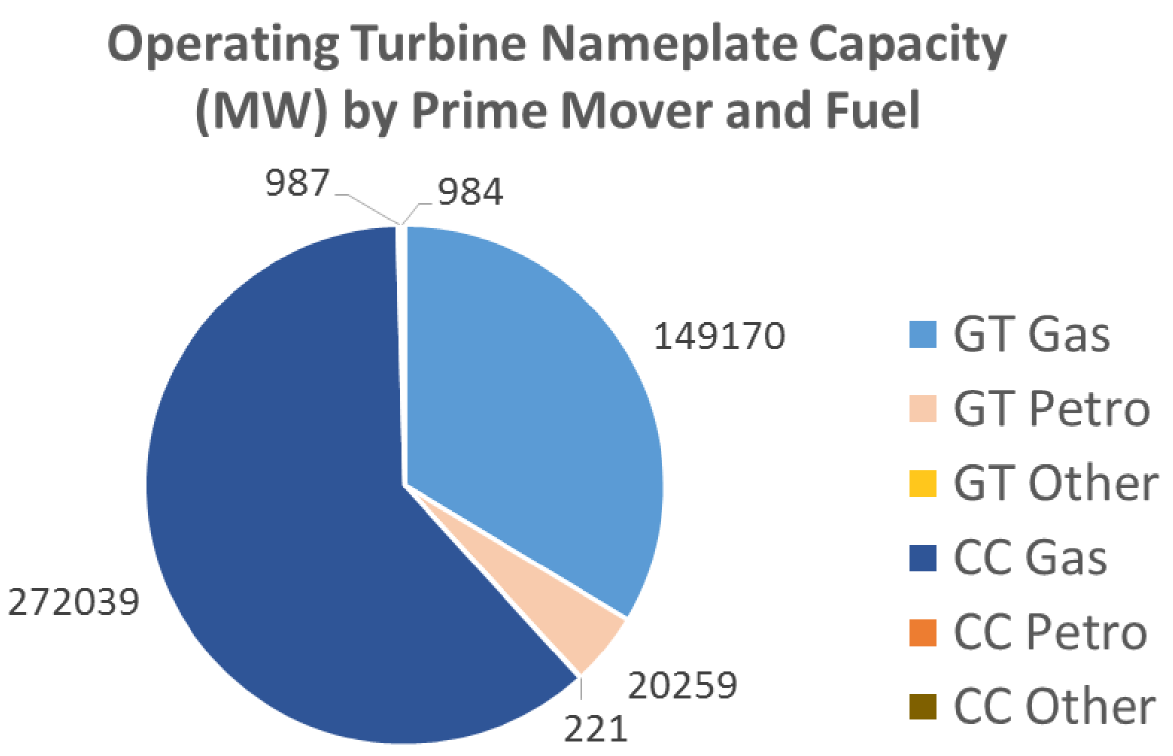
US Electricity Generation by Fuel

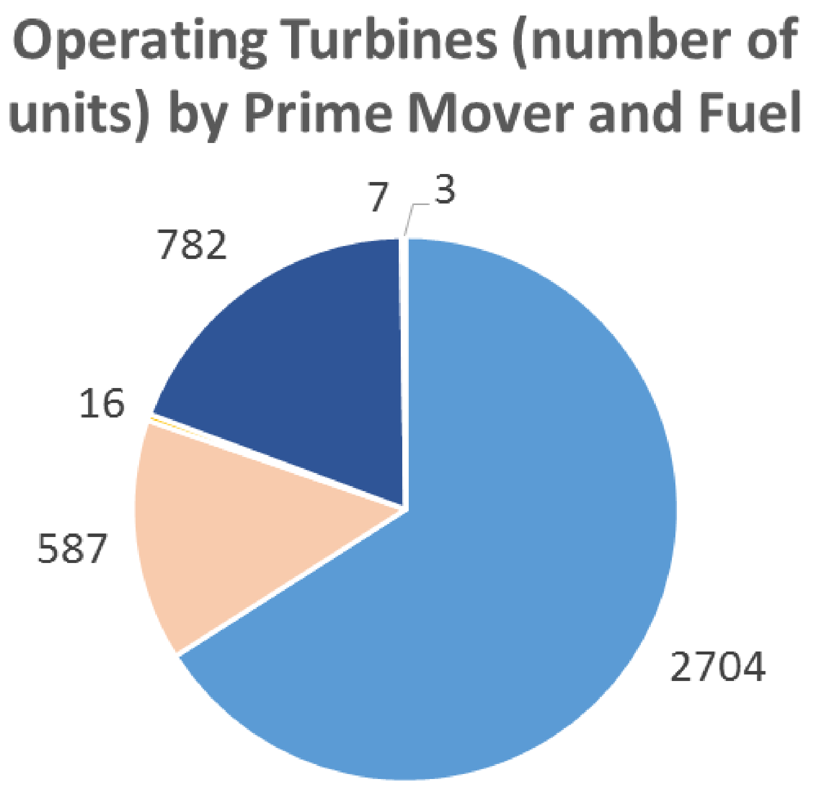
EIA 2018 AEO Reference Case



- NG generation increases by 53%
- Renewable electricity generation experiences the largest growth of 960 bkWh followed by NG generation at 662 bkWh

US Combustion Turbine Fleet by Capacity and Number of Units





- CC units make up the bulk of capacity
- Combined cycle units are larger than simple cycle units

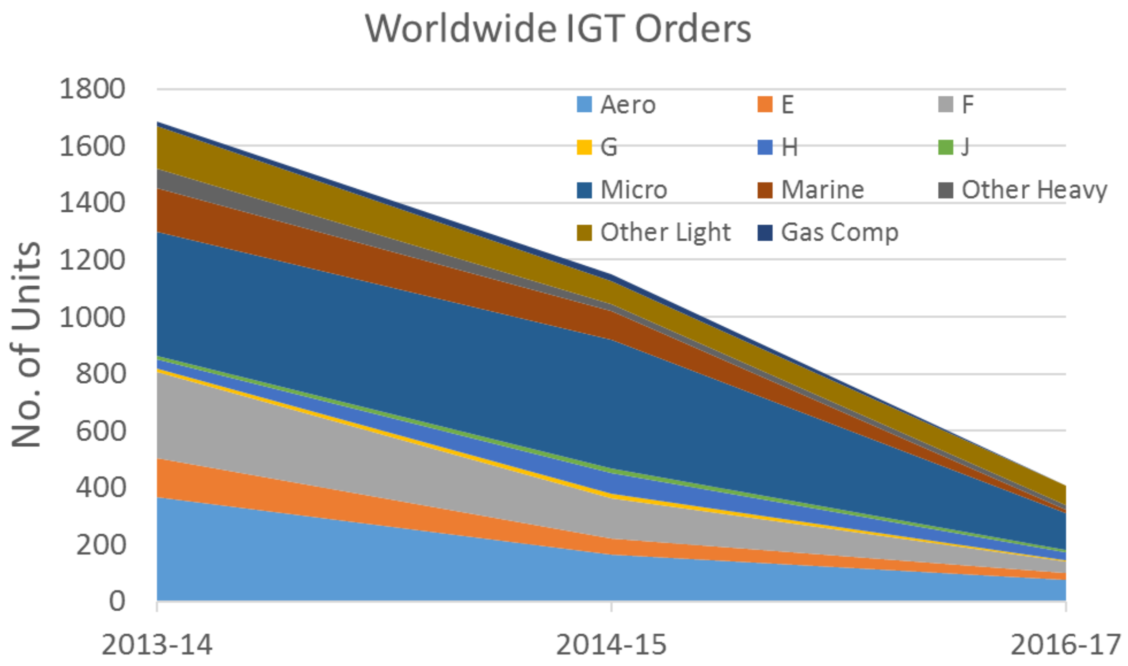
US Combustion Turbine Orders/Installations

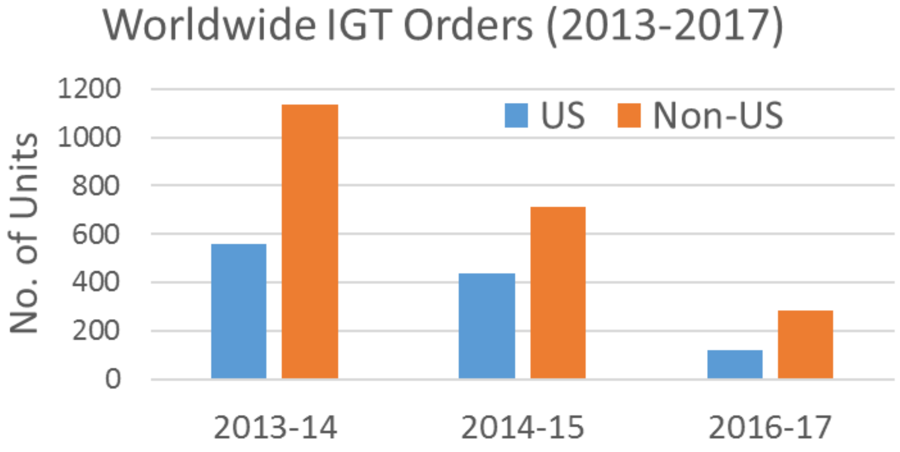
	1/2011-12/2012			1/2013-6/2014			1/2014-12/2015			1/2016-6/2017		
	No. of Units	Average ISO Rating (MW)	Capacity (MW)	No. of Units	Average ISO Rating (MW)	Capacity (MW)	No. of Units	Average ISO Rating (MW)	Capacity (MW)	No. of Units	Average ISO Rating (MW)	Capacity (MW)
Simple Cycle	55	47.1	2,591.4	401	22.5	9,020.9	322	14.1	4,541.1	78.0	17.7	1,383.9
Combined Cycle	36	194.8	7,012.0	85	194.8	16,562.0	102	265.7	27,100	41.0	279.6	11,464.0
Other	21	21.7	456.0	70	16.6	1,158.8	12	1.9	23	1.0	3.5	3.5
Total	112	89.8	10,059.4	675	51.7	34,909.0	436	72.6	31,664.1	120	107.1	12,851.4

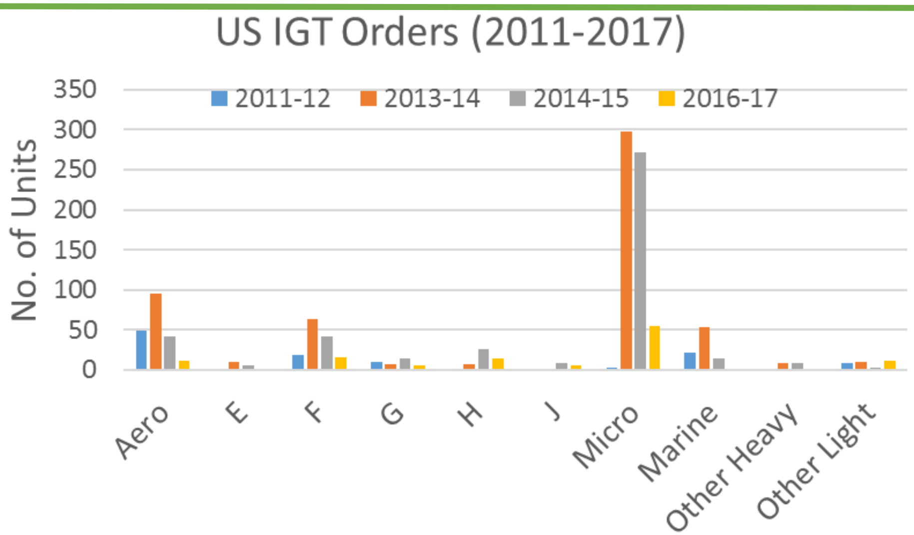
- **2016-2017 Observations:**
  - Data shows decrease in orders to near 2011-12 data
  - SC units dominated by micro turbines
  - CC sizes have continued to increase

US and Worldwide IGT Orders by Class

Noticeable decrease in orders







- Source: GTW Handbook, 2013, 2014-15, 2016-17, 2018

Turbine Market Observations

- **2013 - 15 surge in combustion turbine installations is over**
  - US & Worldwide orders of all sizes of IGTs are down significantly
- **NG price forecasts indicate a slow rise**
  - History shows the projections are not overly accurate
  - NG production will continue to rise through 2050
- **Long term trend in fuel use for electricity is an increase in NG and a reduction in coal**
  - Updated EIA analysis shows a reduced rate of coal decline
- **H-class units are now on par with F-class and aeroderivative units for sales and installed units in the US**

Presentation Overview

NATIONAL ENERGY TECHNOLOGY LABORATORY

Overview of the US DOE Advanced Turbines Program

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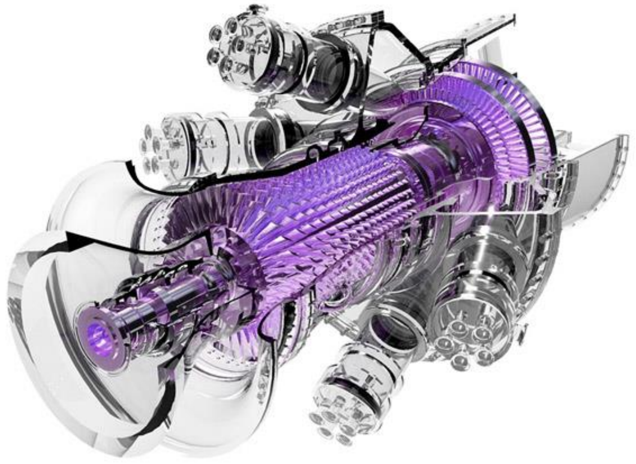
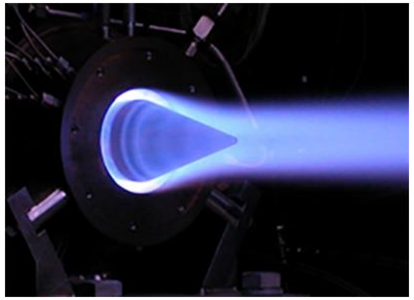
- **Overview of the US DOE Advanced Turbines R&D Program**
    - Advanced combustion turbines for syngas, NG and H_2 fuels
    - Pressure gain combustion for combustion turbines
    - Modular turbine based hybrid heat engines
    - SCO2 turbomachinery
- Conclusions

Advanced Turbines Program for US DOE FE Mission

Focused Research in Four Key Technology Areas

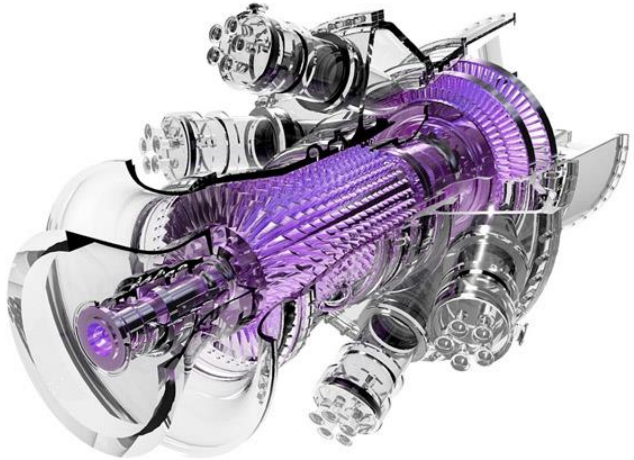
- **Adv. combustion turbines for syngas, NG and H_2 fuels (IGCC, NGCC)**
  - CC eff. ~ 65 % (LHV, NG bench mark), TIT of 3,100 °F
  - Delivers transformational performance benefits by 2025 for coal based IGCC with CCS (ready for full scale demonstration)
    - Delivers another $20/T reduction in CO2 capture cost
- **Pressure Gain Combustion (IGCC, NGCC)**
  - Alternate pathway to high efficiency
  - TRL 2 ~ 3 (risky, long term, high pay back)
- **Modular Turbine Based Hybrid Heat Engines**
  - Supporting modular coal systems and stranded gas assets
- **SCO_2 Turbomachinery (ACS, gasification, NG)**
  - FE's SCO_2 Base Program – Shared with AT, ACS and XC
  - SCO_2 turbines for <u>indirect (ACS, WHR)</u> and <u>direct (gasification, NG)</u> applications
  - Modular
  - Leverage and coordinate with DOE SCO_2 Initiative (STEP)





Advanced Combustion Turbines

Coal based IGCC and natural gas combined cycle applications



- **Objective: Enable CC efficiency of 65%+(LHV, bench mark), TIT of 3,100ºF**
- **Approach**
  - Focus R&D on turbine components
  - Pursue higher TIT, reduce cooling flows, and develop new materials and coatings
    - Increase efficiency and reduce COE
  - Components can be offered in new commercial products or retrofit onto the existing fleet
    - Accelerating TRL increase and deployment

Projects Supporting Advanced Combustion Turbines

Component development for advanced combustion turbines – 65 % CC goal

- **2016 phase II awards nominally $6M ea., 4 yr. projects**
  - Advanced Multi-Tube Mixer Combustion for 65% Efficiency (GE)
  - High Temperature CMC Nozzles for 65% Efficiency (GE)
  - CMC Advanced Transition for 65% Combined Cycle Efficency (SE)

- **2018 phase I awards (18 months), Ph II down select in FY20**
  - Additive Manufactured Metallic 3D OxOx CMC Structures (SE)
  - Low-Weight Ti-AL Airfoils (SE)
  - Low NOx Axial Stage Combustion System (SE)
  - High-Temperature Additive Architectures (GE)
  - High-Temperature, High AN2 Last-Stage Blade (GE)
  - Aero-Thermal Technologies (GE)
  - Hybrid Ceramic-CMC Vane with EBC(UTRC)

Advanced Multi-Tube Mixer Combustion

65% efficiency combined cycle goal

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- Fully develop multi-tube mixer combustion
- Low NOx up to 3100°F TIT supporting load following with an ultra-compact design that minimizes NOx formation and minimizes cooling requirements
- Develop a revolutionary fully Integrated Combustor Nozzle (ICN) in an elegantly yet simple design that includes multi-tube pre-mixer, transition nozzle and CMCs
- g

BENEFITS

- Contributes to DOE goal of 65+% CC efficiency
- Enables robust fuel flexibility

GENERAL ELECTRIC CO.

FE0023965

Partners: GE Power & Water, GE Global Research

1/01/2015 – 8/31/2019

BUDGET		
DOE	*Participant*	*Total*
$6,608,516	$2,832,221	$9,440,737

U.S. DEPARTMENT OF ENERGY

Pressure Gain Combustion

Alternate pathway to 65 % CC goal

- **Objective: Realize 2 – 3 % points improvement in combined cycle efficiency**
- **Approach**
  - Continue investment in fundamental and applied R&D
  - Resolve issues with fuel and air inlet
  - Resolve issues with kinetic energy recovery as a pressure gain
  - Work in a collaborative frame work with US DOD, industry, universities and National Laboratories (NETL)
    - Pursue a fully integrated engine demonstration

Projects Supporting Pressure Gain Combustion

Alternate pathway to 65 % CC goal

- **2016 phase II award nominally $6M, 4 yr. project**
  - RDC for GT and System Synthesis to Exceed 65% Eff. (Aerojet Rocketdyne)

- **Other project activities in PGC**
  - Fuel injection dynamics and composition effects on RDE performance (UTSR - University of Michigan)
  - NETL Modeling and air / fuel inlet conditions
  - NETL and Air Force Research Lab to demonstrate PGC in small engine

Rotating Detonation Combustion for Gas Turbines-Modeling and System Synthesis to Exceed 65% Efficiency Goal

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- Develop & validate RDC system models for CC power plant (PH 1)
- Characterize and optimize the fluid and mechanical interface between the RDC and a turbine cascade.
- Multiple test programs using 10 cm, 21 cm and 31 cm combustors & advanced diagnostics
- CFD models developed and anchored as design tools for maximizing RDC turbine performance.

BENEFITS

- Alternative path to DOE 65 % CC goal (2 – 3 % points)

Aerojet Rocketdyne

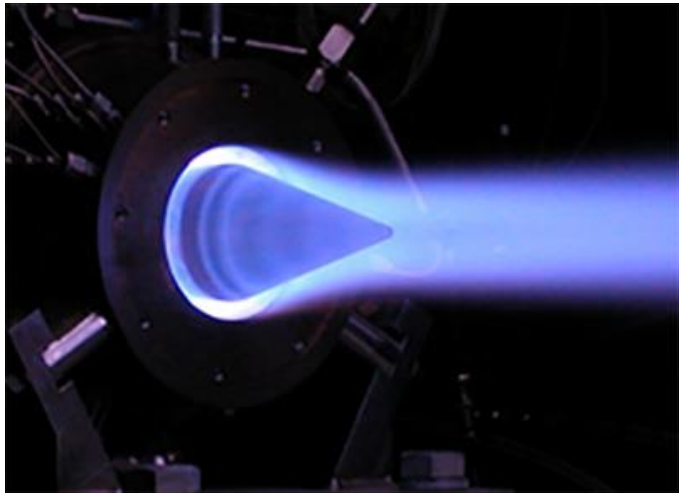
FE0023983

Partners: University of Michigan, University of Alabama, Purdue, SwRI, University of Central Florida, Duke Energy

10/01/2014 – 3/31/2019

BUDGET

DOE	*Participant*	*Total*
$6,054,678	$1,515,449	$7,570,127



Modular Hybrid Heat Engines for FE Applications

Highly efficient and low cost modular heat engines

- **Objective: Develop heat engines for modular coal gasification, stranded gas assets and other DG-like applications (NG compressor stations, etc.)**
- **Approach**
  - System studies to analyze promising configurations and identify benefits, markets, and technology gaps
  - Pursue testing to close technology gaps and develop designs
  - Support development of highly successful technologies

Projects Supporting Hybrid Heat Engines

Modular heat engines for small low cost high efficiency power systems

Six 2018 phase I awards (18 months), Ph II down select in FY20

- Turbo-Compound Reheat GT CC – Bechtel National
- Optimization and Control of a Hybrid GT with sCO_2 Power System – Echogen
- Advanced Modular Sub-Atmospheric Hybrid Heat Engine – GTI
- Modular Heat Engine for the Direct Conversion of NG to H_2 and Power – GTI
- Novel Modular Heat Engines with sCO_2 Bottoming Cycle Utilizing Advanced Oil-Free Turbomachinery – General Electric
- Advanced Gas Turbine and sCO_2 Combined Cycle Power System – SwRI

Advanced Gas Turbine and sCO_2 Combined Cycle Power System

Southwest Research Institute & Solar Turbines

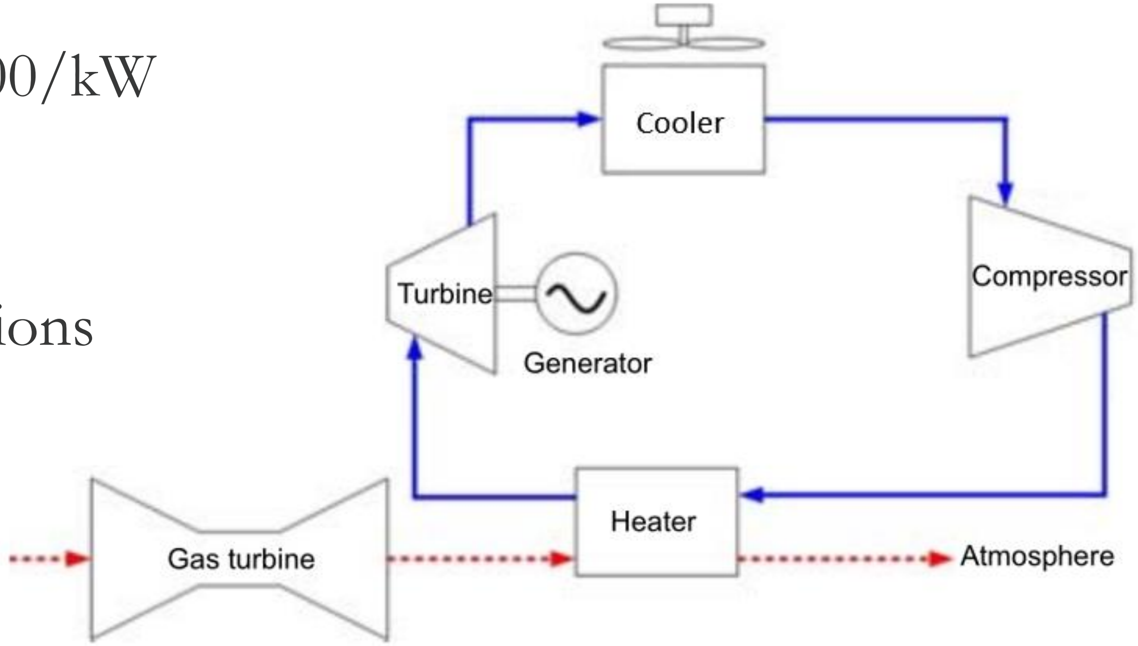
PROJECT NARRATIVE

- CC sCO_2 based waste heat recovery system (WHRS) to the discharge of an existing gas turbine package
- Demonstrate advantage of a sCO_2 bottoming cycle compared to steam based cycle
- Develop commercially competitive WHRS < $1000/kW

BENEFITS

- Increased performance of existing gas turbine installations, including natural gas compressor stations
- Reduced operating costs and footprint
- Cleaner and more efficient operation
- Enhanced load-following capability

Southwest Research Institute		
FE0031619 *Partners: Hanwha Power Systems Americas, Solar Turbines, Williams* *7/9/2018-1/9/2020*		
BUDGET		
DOE	*Participant*	*Total*
$500,000	$125,000	$625,000



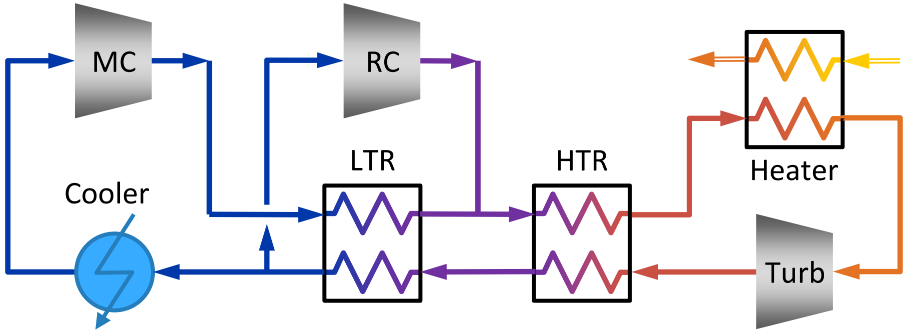
Waste Heat Recovery System

sCO_2 Power Cycles for FE Applications

Two related cycles for advanced combustion and gasification applications

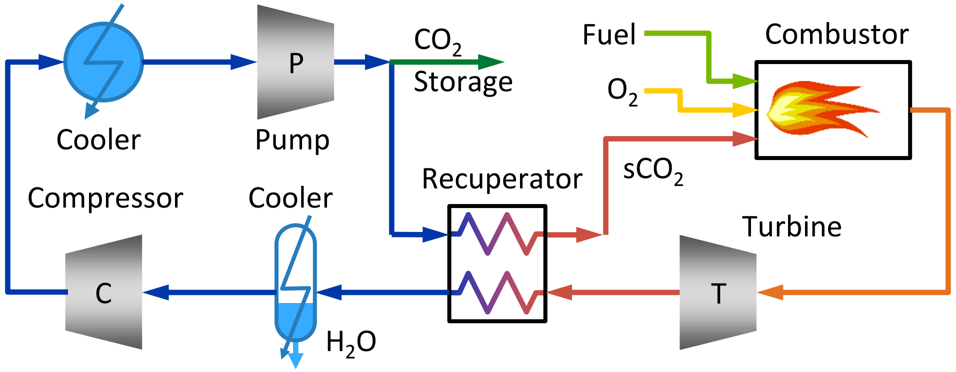
Indirectly-heated cycle (RCBC)

- 10 MWe project (GTI, GE & SwRI)
- Applicable to adv. coal combustion
- Incumbent: USC/AUSC boilers
- >50% cycle efficiency possible
- Compact turbomachinery
- Ideal for constant temp. heat source



Directly-heated cycle (Allam Cycle)

- 25 MWe sCO_2 pilot plant (8 Rivers)
- Applicable to coal syngas &NG
- Incumbent to beat: NGCC and IGCC with CCS
- R&D compatible w/ indirect cycle
- >95% CO_2 capture at pressure
- Net water producer, if dry-cooled



Source: NETL

Projects Supporting sCO_2 Power Cycles

Component development for SCO2 turbomachinery

- **Two Ph. II 2016 awards nominally $6M ea., 4 yr. projects**
  - Low-Leakage Shaft End Seals for Utility-Scale sCO_2 Turbo Expanders (GE)
  - High Inlet Temp. Comb. for Direct Fired Supercritical Oxy-Combustion (SwRI)
- **One Ph 1 award, 18 mo. Ph II down select in FY20**
  - Development of Oxy-fuel Combustion Turbines with CO2 Dilution for Supercritical Carbon Dioxide (SCO2) Based Power Cycles
- **Other sCO_2 Projects**
  - NETL sCO2 techno-economic system studies (NETL)
  - Development of advanced recuperators (Thar Energy)
  - Design, build, and operate 10MWe STEP pilot facility (GTI)
  - sCO2 National Lab R&D Plan (SNL)
  - sCO2 power cycle market deployment study (Deloitte)

Development of Low-Leakage Shaft End Seals for Utility-Scale sCO_2 Turbo Expanders

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- Test expander shaft end seals for utility-scale supercritical CO2 power cycles
- Ph. I evaluation & design of seal concepts and a conceptual design of seal test a facility
- Ph. II will focus on final seal design & test rig construction
- Testing on subscale & full-scale seals

BENEFITS

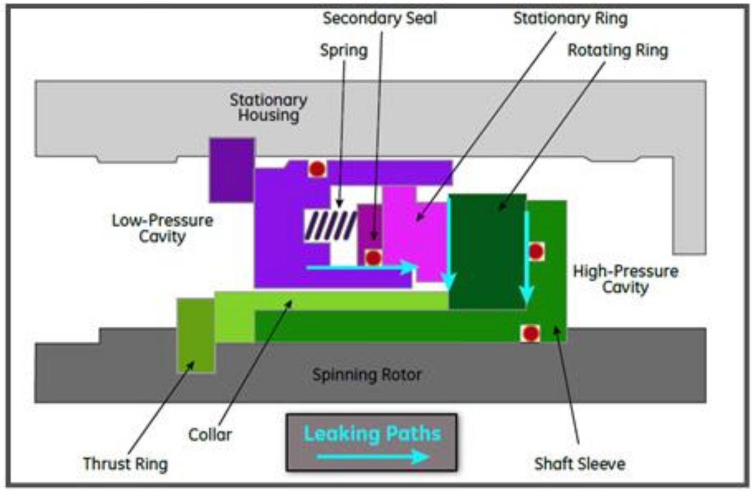
- Enabling cycle efficiencies of 50-52% or greater
- Face seals can enable a 0.55% points benefit over present labyrinth seals technology

GENERAL ELECTRIC CO.

FE0024007
Partners: SwRI
10/1/2014 – 8/31/2019

BUDGET

DOE	Participant	Total
$6,824,098	$1,793,304	$8,617,402



Dry Gas Sealing Technology

Conclusions & Summary

Overview of the US DOE Advanced Turbines Program

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Natural gas prices remain low**
- **Gas turbine deployments are declining**
  - Why? Demand is low: energy efficiency and renewables filling the gap?
  - Historically a cyclic process
- **DOE FE is supporting a robust program in four areas**
  - Large scale combined cycle machines
  - Pressure gain combustion
  - Modular hybrid heat engines
  - Supercritical CO_2 based power cycles

Mark Your Calendars!

March 19 & 20, 2019; Berlin, Germany

Visit the symposium website to submit an abstract:

www.asme.org/events/amrgt

Back-up Slides

FY 2018 Advanced Turbines FOA

$7 million, 14 awards, 18 mo. Phase I projects, Ph II downselect in FY20

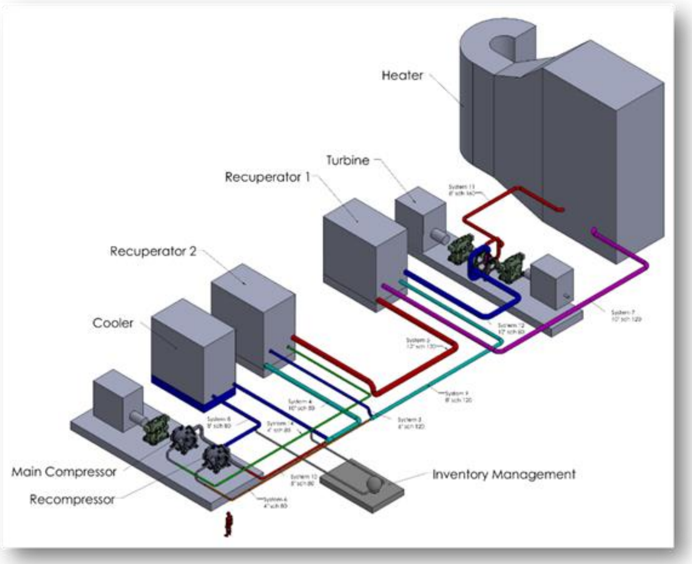
1. **Advanced Combustion Turbines for Combined Cycle Applications**
   - *High-Temperature Additive Architectures for 65 Percent Efficiency* – **General Electric**
   - *High-Temperature, High AN2 Last-Stage Blade for 65 Percent Combined Cycle Efficiency* – **General Electric**
   - *Turbine Aero-Thermal Technologies for 65 Percent Combined Cycle Efficiency* – **General Electric**
   - *Additive Manufactured Metallic-3D Ox-Ox CMC Integrated Structures for 65 Percent Combined Cycle Efficient Gas Turbine Components* – **Siemens Energy**
   - *Design and Development of Low-Weight, Titanium Aluminide Airfoils for High-Performance Industrial Gas Turbines Meeting 65 Percent Combined Cycle Efficiency* – **Siemens Energy**
   - *Extension of Operating Envelope for an Extremely Low NOx Axial Stage Combustion System* – **Siemens Energy**
   - *Hybrid Ceramic-CMC Vane with EBC for Future Coal-Derived Syngas-Fired Highly Efficient Turbine Combined Cycle* – **United Technologies Research Center**
2. **Development of Oxy-fuel Combustion Turbines with CO2 Dilution for Supercritical Carbon Dioxide (SCO2) Based Power Cycles**
   - *Development of Oxy-Fuel Combustion Turbines with CO_2 Dilution for sCO_2-Based Power Cycles* – **Southwest Research Institute**
3. **Turbine-based Modular Hybrid Heat Engines for FE Applications**
   - *Turbo-Compound Reheat Gas Turbine Combined Cycle* – **Bechtel National**
   - *Integrated Optimization and Control of a Hybrid Gas Turbine/sCO_2 Power System* – **Echogen Power Systems**
   - *Advanced Modular Sub-Atmospheric Hybrid Heat Engine* – **Gas Technology Institute (GTI)**
   - *A Modular Heat Engine for the Direct Conversion of Natural Gas to Hydrogen and Power Using Hydrogen Turbines* – **Gas Technology Institute**
   - *Novel Modular Heat Engines with sCO_2 Bottoming Cycle Utilizing Advanced Oil-Free Turbomachinery* – **General Electric**
   - *Advanced Gas Turbine and sCO_2 Combined Cycle Power System* – **Southwest Research Institute**

Supercritical Carbon Dioxide 10 MWe Pilot Plant Test Facility

Gas Technology Institute

- **Objectives**
  - Plan, design, build, and operate a 10 MWe sCO_2 Pilot Plant Test Facility
  - Demonstrate the operability of the sCO_2 power cycle
  - Verify performance of components (turbomachinery, recuperators, compressors, etc.)
  - Evaluate system and component performance capabilities
    - Steady state, transient, load following, limited endurance operation
  - Demonstrate potential for producing a lower COE and thermodynamic efficiency greater than 50%
- **STEP Facility Configuration**
  - Located at SwRI's San Antonio, TX campus
  - 10 MWe Recompression closed Brayton cycle (RCBC)
  - 700°C turbine inlet temperature

Gas Technology Institute		
Partners: SwRI, GE Global Research *10/1/2016 – 9/30/2022*		
BUDGET		
DOE	*Participant*	*Total*
$79,999,226	$33,279,408	$113,278,634



Conceptual Layout

Project Activities in sCO_2 Based Power Cycles

NATIONAL ENERGY TECHNOLOGY LABORATORY

Turbomachinery for Indirect and Direct sCO_2 Power Cycles
- Low-leakage shaft end seals for sCO_2 turbomachinery (**GE**)
- Adv. turbomachinery for sCO_2 cycles (**Aerojet Rocketdyne**)

Modular Hybrid Heat Engines
- Integrated optimization and control of a hybrid gas turbine/sCO_2 power system (**Echogen Power Systems**)
- Novel modular heat engines with sCO_2 bottoming cycle utilizing advanced oil-free turbomachinery (**GE**)
- Advanced gas turbine and sCO_2 combined power cycle power system (**SwRI**)

Oxy-Fuel Combustion for Direct sCO_2 Power Cycles
- Development of oxy-fuel combustion turbines with CO_2 dilution for sCO_2-based power cycles (**SwRI)**
- HT combustor for direct fired supercritical oxy-combustion (**SwRI**)
- Oxy fuel combustion (**NETL**)
- Autoignition and combustion stability of high pressure sCO_2 oxy-combustion (**GA Tech**)
- Chemical kinetic modeling and experiments for direct fired sCO_2 Combustor (**UCF**)
- Coal syngas comb. for HP oxy-fuel sCO_2 cycle (**8 Rivers Capital**)

Recuperators for sCO_2 Power Cycles
- Microchannel HX (**Oregon State U**)
- Low-cost recuperative HX (**Altex Tech. Corp**)
- Mfg. process for low-cost HX applications (**Brayton Energy**)
- HT HX for systems with large pressure differentials (**Thar Energy**)
- Thin film primary surface HX (**SwRI**)

Materials, Fundamentals and Systems
- R&D materials & systems analyses (**NETL**)
- Oxidation/corrosion performance of alloys in sCO_2 (**EPRI**)
- Advanced materials for supercritical carbon dioxide (**ORNL**)
- Replacement of the reference EOS for CO_2 thermodynamic props (**NIST**)
- Thermophysical properties of sCO_2 (**NIST**)

Systems Integration & Optimization
- Novel indirect sCO_2 power cycle for integration with the power block (**SwRI**)
- Thermal integration of closed sCO_2 power cycles with oxy-fired heaters (**EPRI**)

Large Pilot Scale Projects
- Scale-up of coal-based supercritical CO_2 cycle technology (**U. of N. Dakota**)
- Supercritical carbon dioxide primary power large-scale pilot plant (**Echogen**)

STEP
- Development of advanced recuperators (**Thar Energy**)
- Design, build, and operate 10MWe STEP pilot facility (**GTI)**
- sCO_2 National Lab R&D Plan (**Sandia National Laboratories**)

U.S. DEPARTMENT OF ENERGY

NETL Major sCO_2 Systems Analyses

- Techno-economic Evaluation of Utility-Scale Power Plants Based on the Indirect sCO_2 Brayton Cycle
- Performance of an Integrated Gasification Direct-Fired Supercritical CO_2 Power Cycle
- Development of a dynamic sCO_2 plant model to assess control mechanisms and transient/part load performance of the 10 MWe STEP demo sCO_2 plant
  - Preliminary analyses complete, model refinements ongoing
- Analysis of Natural Gas Direct-Fired sCO_2 Power Cycle

NETL Major sCO2 Systems Analyses

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Techno-economic Evaluation of Utility-Scale Power Plants Based on the Indirect sCO_2 Brayton Cycle[1]**
  - Examined the cost and performance of power plants with carbon capture based on:
    - Coal-fired oxy-CFB heat source with the indirect recompression sCO2 Brayton cycle
  - 4 Cycle Configurations Examined - Base, Reheat sCO2 turbine, Intercooled 2-stage main sCO2 compressor, Reheat and Intercooling
  - Oxy-CFB indirect sCO2 power plants shown to improve efficiency 1–4% points at comparable COE relative to steam
  - Improvements identified to further reduce sCO2 plant COE relative to an air-fired, supercritical PC coal plant with CCS
- **Performance of an Integrated Gasification Direct-Fired Supercritical CO_2 Power Cycle[2]**
  - sCO2 cases deliver higher efficiency than IGCC cases with a gas turbine and steam combined cycle power island
  - sCO2 plant design (with thermal integration) offers very high efficiency (40.6%) and low COE ($122.7/MWh) for a coal plant with CCS
- **Analysis of Natural Gas Direct-Fired sCO_2 Power Cycle[3]**
  - sCO2 plant achieves greater HHV efficiency compared to NGCC, 48.2% vs. 45.7%, due to cycle efficiency differences
  - sCO2 plant captures more carbon (98.2%) than the NGCC plant and consumes 17% less water
- **Development of a dynamic sCO_2 plant model to assess control mechanisms and transient/part load performance of the 10 MWe STEP demo sCO_2 plant[4,5]**
- **sCO2 Cycle as an Efficiency Improvement Opportunity for Air-Fired Coal Combustion (non-CCS case)[6]**
  - Preliminary examination of the potential benefits of the indirect sCO2 power cycle for improving the efficiency and cost of non-capture coal-fired power plants
  - Results have shown that the sCO2 power cycle can achieve higher efficiencies than SOA PC/Rankine systems with no increase in COE
  - Full-load, steady-state CO2 emissions of 1353 lbs CO2/MWh gross nominally meets the current EPA's 1400 lbs CO2/MWh gross for new coal plants
    - However, the EPA's standard is based on average annual emissions – additional analyses are required to assess system performance under realistic annual operating profiles, including part-load
  - Shows that plants based on the sCO2 power cycle have significantly lower (22-33%) water consumption than comparable reference Rankine cycle plants

FY17 UTSR FOA

FY 2017 University Turbines Systems Research FOA (shared with AT, AC and CCR&D)

FOA Awards (3 yr. projects, nominal value $700 – 800 k)

- High Frequency Transverse Combustion Instabilities in Low-NOx Gas Turbines (GA Tech)
- Improving NOx Entitlement with Axial Staging (Embry-Riddle Aeronautical University)
- Integrated Transpiration and Lattice Cooling Systems developed by Additive Manufacturing with Oxide-Dispersion-Strengthened (ODS) Alloys (U of Pitt)
- Discrete Element Roughness Modeling for Design Optimization of Additively and Conventionally Manufactured Internal Turbine Cooling Passages (PSU)
- Development of High performance Ni-base Alloys for Gas Turbine Wheels using a Coprecipitation Approach (OSU)
- Integrated TBC/EBC for SiC Fiber Reinforced SiC Matrix Composites for Next Generation Gas Turbines (Clemson)
- Real-Time Health Monitoring for Gas Turbine Components using Online Learning and High Dimensional Data (GA Tech)
- In-situ Optical Monitoring of Operating Gas Turbine Blade Coatings under Extreme Environments (UCF)
- Fuel injection dynamics and composition effects on RDE performance (UM)

High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion

Southwest Research Institute

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- The project team seeks to develop a high inlet temperature oxy-combustor suitable for integration with direct-fired supercritical CO_2 power cycles for fossil energy applications
- R&D evaluation of direct-fired sCO_2 oxy-combustor has involved system engineering design and thermodynamic analysis to assess plant efficiencies, verify operating conditions and optimize plant configuration in conjunction with technical gap analysis
- The Phase II effort seeks to build a 'first-of-a-kind' 1 MW test facility in order to evaluate the sCO_2 oxy-combustor technology in an integrated system (which enables both component- and system-level testing) to address/reduce technical uncertainties
- The Phase II R&D testing seeks to increase the TRL of key components (such as the oxy-combustor and related equipment) and reduce uncertainties associated with chemical kinetics, thermal management, water separation, flue gas cleanup, materials, and corrosion.

BENEFITS

- Efficient power generation with integrated carbon capture at up to 99 % of generated CO_2
- Advances state-of-the-art in high pressure, high temperature combustor design

SOUTHWEST RESEARCH INSTITUTE

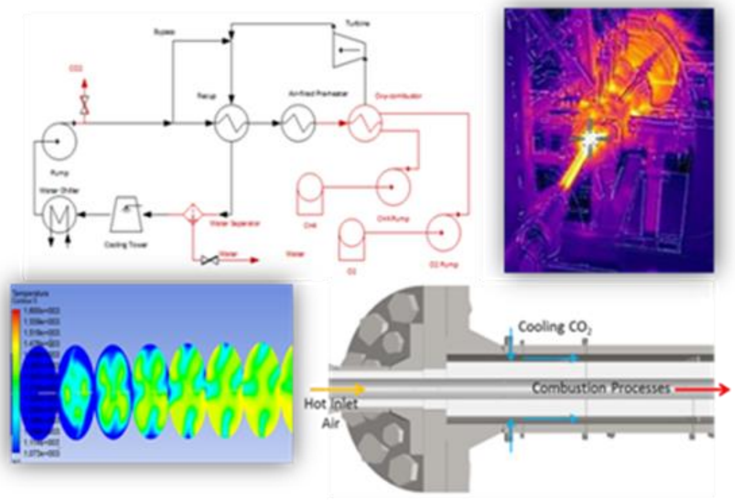
FE0024041

Partners: Thar Energy, GE Global Research, U. of Central Florida, Georgia Tech

10/1/2014 - 3/31/2020

BUDGET

DOE	*Participant*	*Total*
$3,793,540	$948,404	$4,741,944



Direct Fired Supercritical CO_2 Oxy-Combustion: Bench Scale Testing and 1MW Scale Concept

Development of Low-Leakage Shaft End Seals for Utility-Scale sCO_2 Turbo Expanders

General Electric Co.

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- GE and SwRI will develop and test expander shaft end seals for utility-scale supercritical CO2 power cycles
- Phase I included an evaluation of seal concepts, a thermodynamic optimization and turbomachinery preliminary design of a conceptual utility-scale sCO2 plant to evaluate the effectiveness of the seal design, and a conceptual design of a rig/facility to test the seals
- Phase II will focus on finalizing the design of the face seals and designing and constructing a rig to test the final seal design
- The testing will consist of subscale and full-scale testing of seals in a graded approach to proving the technology.

BENEFITS

- Enabling technology for thermodynamic cycle efficiencies of 50-52% or greater
- Face seals can enable a 0.55% points benefit over present labyrinth seals technology

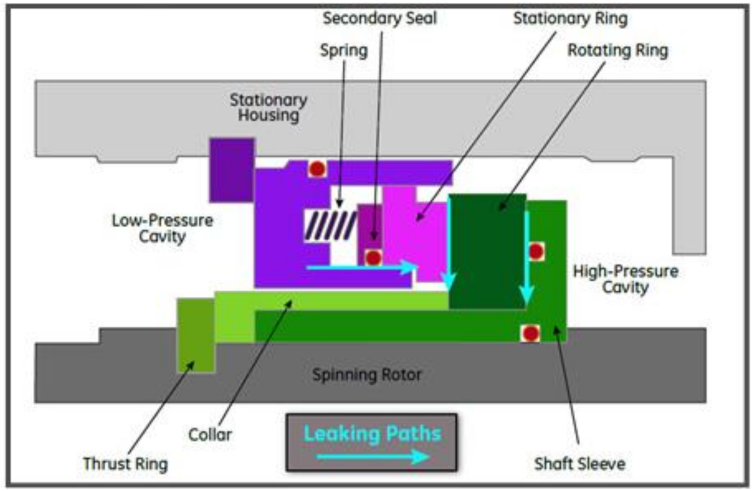
GENERAL ELECTRIC CO.

FE0024007

Partners: SwRI

10/1/2014 – 8/31/2019

BUDGET		
DOE	*Participant*	*Total*
$6,824,098	$1,793,304	$8,617,402



Dry Gas Sealing Technology

High Temperature Ceramic Matrix Composite (CMC) Nozzles for 65% Efficiency

General Electric Co.

NATIONAL ENERGY TECHNOLOGY LABORATORY

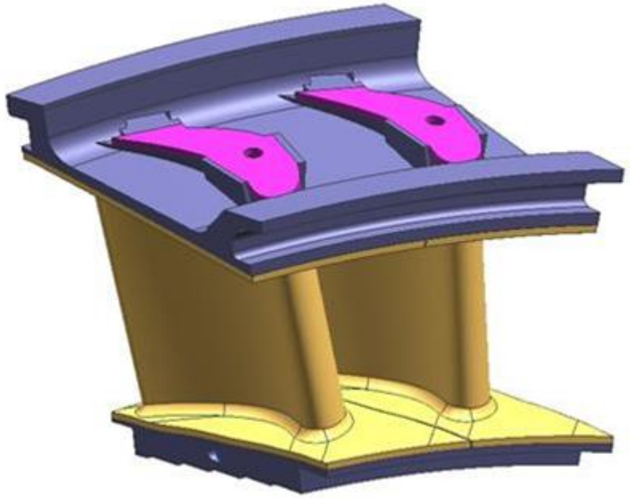
PROJECT NARRATIVE

- GE will develop cooled high-temperature CMC nozzles (non-rotating airfoils) leverages existing knowledge of CMC materials and previous DOE investment
- Phase I included design and analysis of attachment configurations, definition of sealing approaches, design of key sealing features, analysis of sealing effectiveness, and down-selection of an assembly that features metal support structure with CMC carrying the thermal load
- Phase II plan is to complete the CMC nozzle design, design a high temperature test rig, fabricate the nozzles and the rig and then conduct full scale high temperature tests
- Final result will be ready for commercial deployment beyond 2020

BENEFITS

- Contributes to DOE goal of 65% combined cycle efficiency, allows higher turbine inlet temperatures (~3100°F)
- Leverage advanced manufacturing process

GENERAL ELECTRIC CO.		
FE0024006 *10/1/2014 – 8/31/2019*		
BUDGET		
DOE	*Participant*	*Total*
$6,564,478	$2,972,853	$9,537,331



Downselected nozzle geometry

Advanced Multi-Tube Mixer Combustion for 65% Efficiency

General Electric Co.

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- GE will develop and synthesize their multi-tube mixer combustion technology
- Goal of low NOx emissions up to 3100°F while supporting load following grid needs, with an ultra-compact design that minimizes NOx formation and minimizes surface area to be cooled
- Under Phase II, GE will develop a revolutionary fully Integrated Combustor Nozzle (ICN) in a bold yet elegantly simple design that builds on successful DOE/GE programs including the Advanced Hydrogen Turbine program that advanced several technologies, including the Multi-Tube Pre-mixer, Transition Nozzle and Ceramic Matrix Composites (CMCs)

BENEFITS

- Contributes to DOE goal of 65+% combined cycle energy efficiency
- Enables robust fuel flexibility

GENERAL ELECTRIC CO.

FE0023965

Partners: GE Power & Water, GE Global Research

1/01/2015 – 8/31/2019

BUDGET

DOE	*Participant*	*Total*
$6,608,516	$2,832,221	$9,440,737

Rotating Detonation Combustion for Gas Turbines-Modeling and System Synthesis to Exceed 65% Efficiency Goal

Aerojet Rocketdyne

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- Aerojet Rocketdyne, Inc. will develop, validate, and integrate a systems model for a rotating detonation combustor in a power plant systems model
- Under Phase I, Aerojet Rocketdyne assessed the potential of incorporating a rotating detonation engine into a Natural Gas Combined Cycle power plant.
- Under Phase II, a multi-faceted team of researchers will systematically characterize and optimize the fluid and mechanical interface between the RDE and a turbine cascade.
- Multiple test programs will be undertaken using 10 cm, 21 cm and 31 cm combustors using advanced diagnostics
- CFD models will be developed and anchored as design tools for maximizing RDE and unsteady turbine performance.

BENEFITS

- Alternative path to DOE goal of 65% combined cycle efficiency (2-3% point)
- Advances technology for combustion turbines for combined cycle applications

Aerojet Rocketdyne

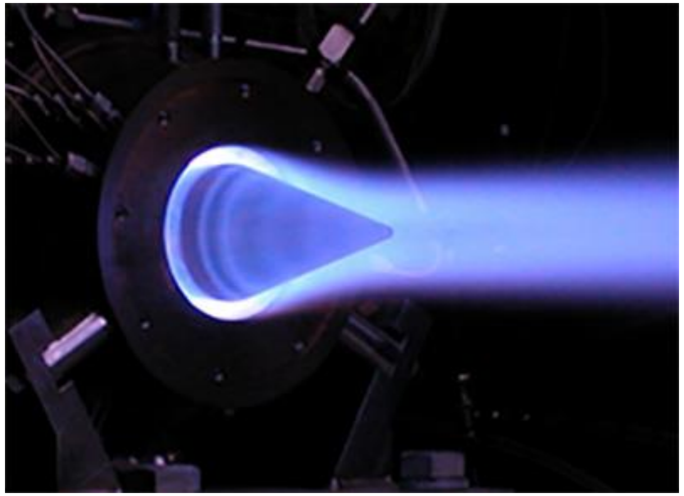
FE0023983

Partners: University of Michigan, University of Alabama, Purdue, SwRI, University of Central Florida, Duke Energy

10/01/2014 – 3/31/2019

BUDGET

DOE	*Participant*	*Total*
$6,054,678	$1,515,449	$7,570,127



Novel Modular Heat Engines with sCO_2 Bottoming Cycle Utilizing Advanced Oil-Free Turbomachinery

General Electric

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- Develop a conceptual design of a novel, hermetically sealed oil-free sCO_2 drivetrain for a bottoming cycle for a natural gas combustion turbine used for pipeline compression
- A conceptual design for a 10MW sCO_2 bottoming cycle and associated machinery will be developed and include an integrated approach between different disciplines such as thermodynamic cycles, aero design, rotordynamics, bearing design, and electric machine sizing
- Commercial assessment and viability of the concept

BENEFITS

- sCO_2 lubricated bearing system allows hermetically sealed drivetrain – preventing loss of efficiency due to CO_2 leakage
- Enable heat engine cycle efficiencies >50% by demonstrating the feasibility of a novel two-machine oil-free drivetrain consisting of a high-speed sCO_2 turbo-compressor with a direct drive starter-generator aerodynamically coupled to an sCO_2 turbo-generator
- Higher efficiency and lower cost system

General Electric		
FE0031617 *Partners: SwRI* *7/9/2018-1/9/2020*		
BUDGET		
DOE	*Participant*	*Total*
$499,757	$125,000	$624,757

General Electric Radial sCO_2 Bearing (L) and Thrust sCO_2 Bearing (R) Technologies

A Modular Heat Engine for the Direct Conversion of Natural Gas to Hydrogen and Power Using Hydrogen Turbines

Gas Technology Institute

PROJECT NARRATIVE

- GTI will design, test, and demonstrate a modular heat engine system for clean and efficient conversion of natural gas to power, hydrogen, and carbon dioxide (CO_2).
- The concept centers on clean power generation using hydrogen produced from GTI's compact hydrogen generator (CHG), combined with an existing gas turbine modified for hydrogen combustion or with an advanced hydrogen turbine.
- During Phase I, detailed thermodynamic cycle analyses will be performed using commercially available modeling tools; trade studies will be conducted at the component and subsystem levels to define an optimized modular system that may be demonstrated to produce power with load-following capability; and technology gaps will be identified through consultations with system end-users and turbine OEMs.

BENEFITS

- Using the CHG technology, GTI predicts a greater than 15 percent reduction in hydrogen cost.

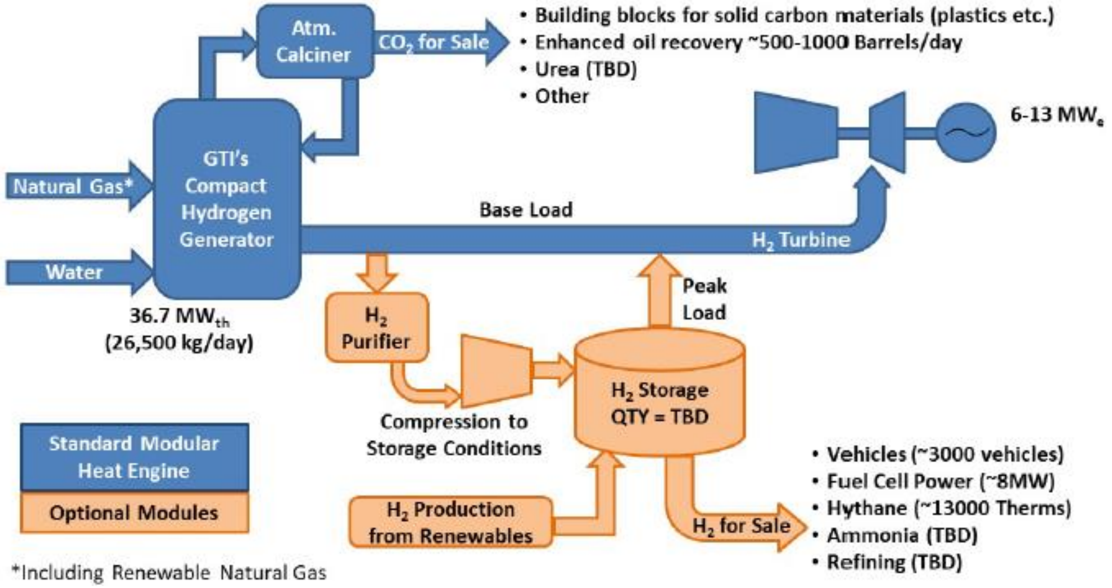
Gas Technology Institute

FE0031615

07/09/2018-01/09/2020

BUDGET

DOE	*Participant*	*Total*
$500,000	$125,000	$625,00



Integrated Optimization and Control of a Hybrid Gas Turbine/sCO2 Power System

Echogen Power Systems (DE), Inc.

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- Echogen will define a hybrid gas turbine sCO2 power cycle design to achieve improved steady-state and transient performance relative to a baseline gas turbine/sCO2 combined cycle plant.
- The cycle optimization code will be extended to include the gas turbine system. With this approach, an integrated optimization process can be used to obtain higher thermodynamic efficiency for the overall plant.
- Transient models of the hybrid system will be updated and converted into functional mockup units for co-simulation using the open-source FMI standard. The individual transient models will be combined into an overall power system and grid model that will be used to create an integrated control system model and control strategy.

BENEFITS

- The commercialization of this system will benefit microgrid and remote power installations by improving their efficiency and load-following characteristics. This reduces the need for short-term battery storage to accommodate rapid shifts in power supply due to intermittency of renewable generation sources and in power demand due to changing customer loads.

Echogen Power Systems

FE0031621

Project Partners: Dresser-Rand/Siemens

07/09/2018-01/08/2020

BUDGET		
DOE	*Participant*	*Total*
$500,000	$125,000	$625,000

U.S. DEPARTMENT OF ENERGY

Turbo-Compound Reheat Gas Turbine Combined Cycle

Bechtel National, Inc.

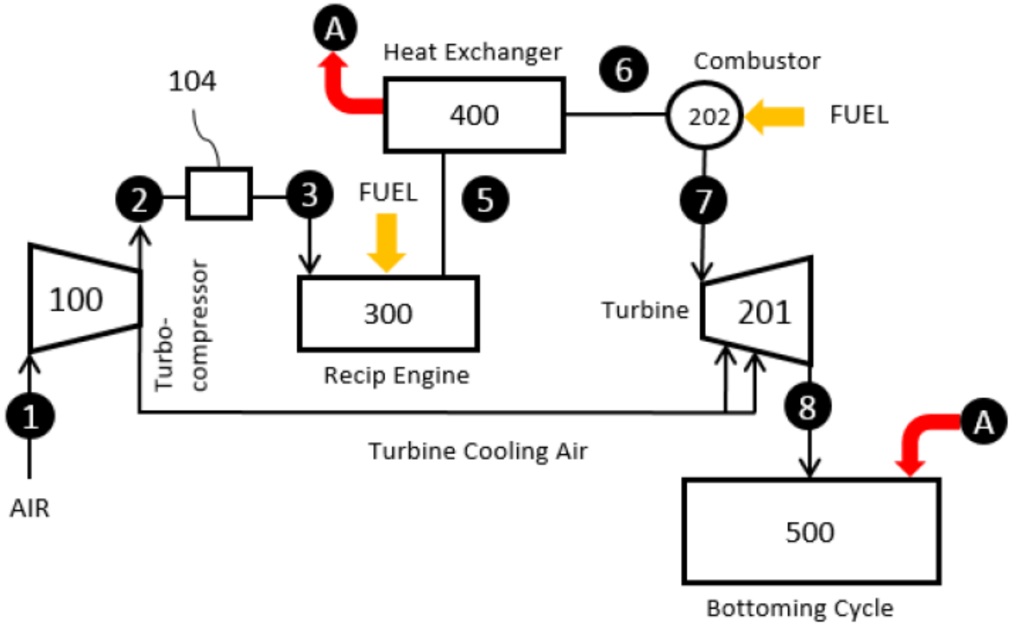
PROJECT NARRATIVE

- Bechtel will develop the Turbo-Compound Reheat Gas Turbine Combined Cycle to a stage of readiness for a small-scale demonstration to prove successful integration of the key components, operability, and multi-fuel compatibility.
- This cycle is based on a combination of technologies to enable thermodynamic cycle performance, including constant volume combustion, reheat, and waste recovery.
- Goals of this project include the development of detailed heat and mass balances using engineering software tools; modules for flexible integration of the components that comprise the power system; and conceptual design of variations of the original patented technology with different fuels including syngas.

BENEFITS

- The system is modular, scalable, fuel-flexible, highly efficient, and amenable to distributed generation and cogeneration.

Bechtel National, Inc.		
FE0031618 *07/09/2018 – 01/09/2020*		
BUDGET		
DOE	*Participant*	*Total*
$499,823	$124,956	$624,779



Turbo-Compound Reheat GT Combined Cycle

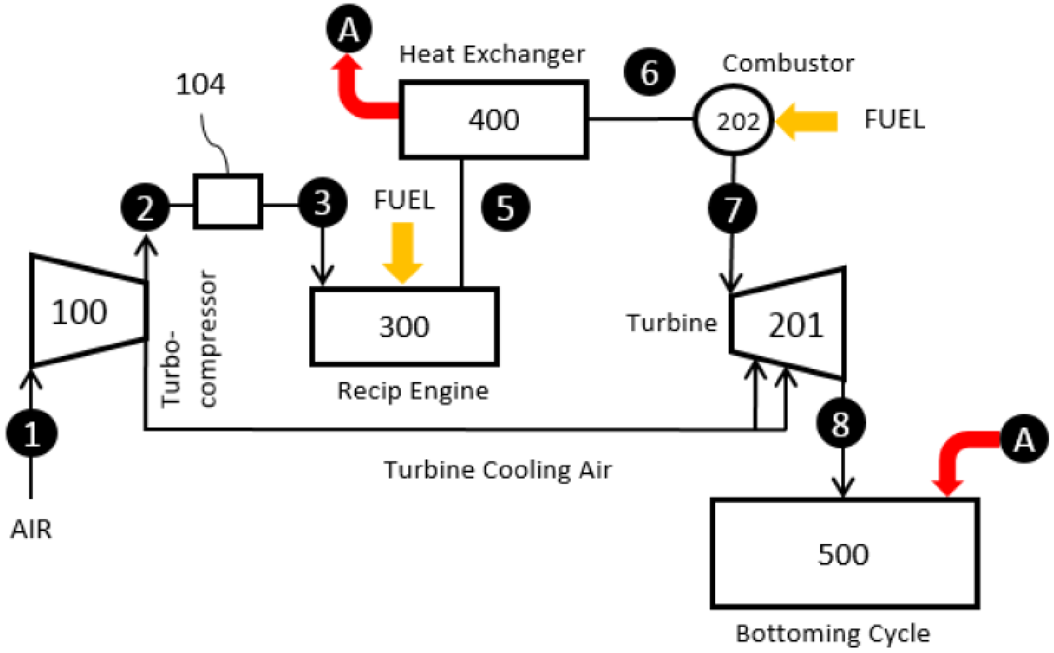
PROJECT NARRATIVE

- Develop the Turbo-Compound Reheat GT CC for a small-scale demo to prove integration of key components, operability, & multi-fuel compatibility.
- Cycle is based on a combination of technologies to enable constant volume combustion, reheat, and waste recovery for improved performance.
- Goals include detailed mass & energy balances, demonstrate flexibilty & use of coal derived syngas.

BENEFITS

- Modular, scalable, fuel-flexible, highly efficient, and amenable to distributed generation and cogeneration.

Bechtel National, Inc.		
FE0031618 *07/09/2018 – 01/09/2020*		
BUDGET		
DOE	*Participant*	*Total*
$499,823	$124,956	$624,779



Advanced Modular Sub-Atmospheric Hybrid Heat Engine

Gas Technology Institute

PROJECT NARRATIVE

- GTI will develop a turbine-based advanced modular sub-atmospheric hybrid heat engine for fossil energy applications to produce electric or mechanical power.
- The engine will be developed as a modular unit that can be used with modular coal or biomass gasifiers, distributed power generation systems, large power plants composed of multiple generating units, and with natural gas compression stations.
- The objectives of this project are to develop a conceptual design of the turbine-based modular sub-atmospheric hybrid heat engine, including thermodynamic cycle analysis; define the nominal engine component boundary conditions; identify technology gaps; and develop a detailed test plan to address these gaps through bench-scale testing in a Phase 2 project.

BENEFITS

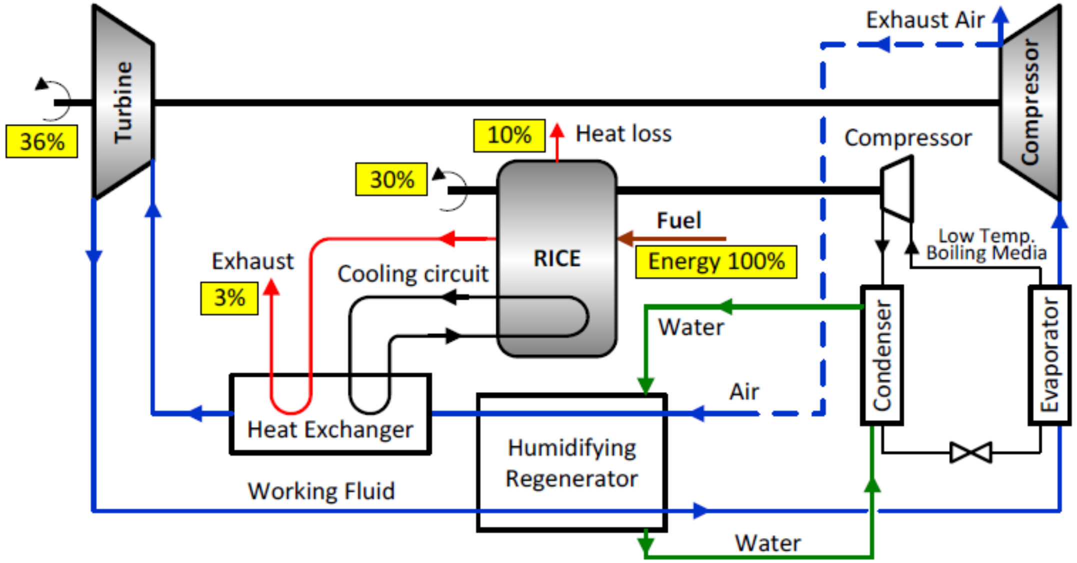
- This hybrid heat engine can achieve greater than 65 percent net electrical or mechanical power-conversion efficiency based on lower heating value of the fuel and provide ultra-low pollutant emissions at a competitive cost.

Gas Technology Institute

FE0031614
Project Partners: SoftInWay
07/09/2018-01/09/2020

BUDGET

DOE	Participant	Total
$499,997	$127,230	$627,227



Scale-Up of Coal-Based Supercritical CO2 Cycle Technology

University of North Dakota Energy and Environmental Research Center (UNDEERC)

PROJECT NARRATIVE

- UNDEERC will design, build, and operate a direct-fired, supercritical CO_2 cycle pilot plant that uses a variety of domestic coal reserves as the primary feedstock.
- In Phase I, the team will evaluate the appropriate scale and candidate host sites for a large coal-based Allam Cycle pilot plant; develop a preliminary design, cost, and schedule for the pilot; secure commitments for Phase II; and complete an Environmental Information Volume.
- UNDEERC will ensure that key aspects of the coal-based Allam cycle are addressed, including syngas combustion and the impact of impurities
- Design starting point is a 5-50MW system.

BENEFITS

- The pilots supported by DOE will be used to assess the scalability and commercial potential of transformational coal technologies, helping mitigate risk and aiding in commercial adoption.

University of North Dakota Energy and Environmental Research Center

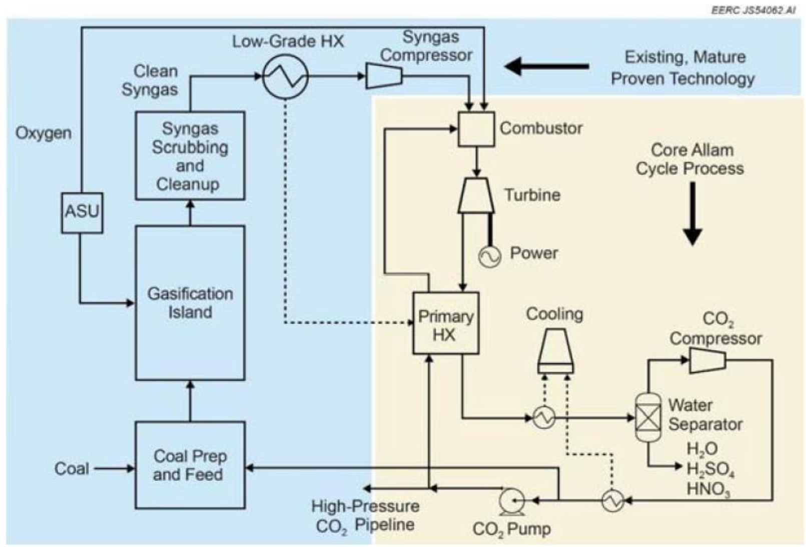
FE0031584

04/01/2018 – 07/31/2019

BUDGET

DOE	*Participant*	*Total*
$700,000	$175,000	$875,000

COAL-BASED ALLAM CYCLE



Supercritical Carbon Dioxide Primary Power Large - Scale Pilot Plant

Echogen Power Systems, LLC

PROJECT NARRATIVE

- Echogen will design, construct, and operate a 10MWe coal-fired supercritical carbon dioxide (sCO2) large-scale pilot.
- In Phase I, Echogen will complete and refine the pilot conceptual system and key component designs, perform a series of pilot site evaluations to decide primary and alternate host site locations, develop the Phase II team for a front-end engineering design (FEED) study, and identify potential sources of cost share for the Phase II and Phase III activities.

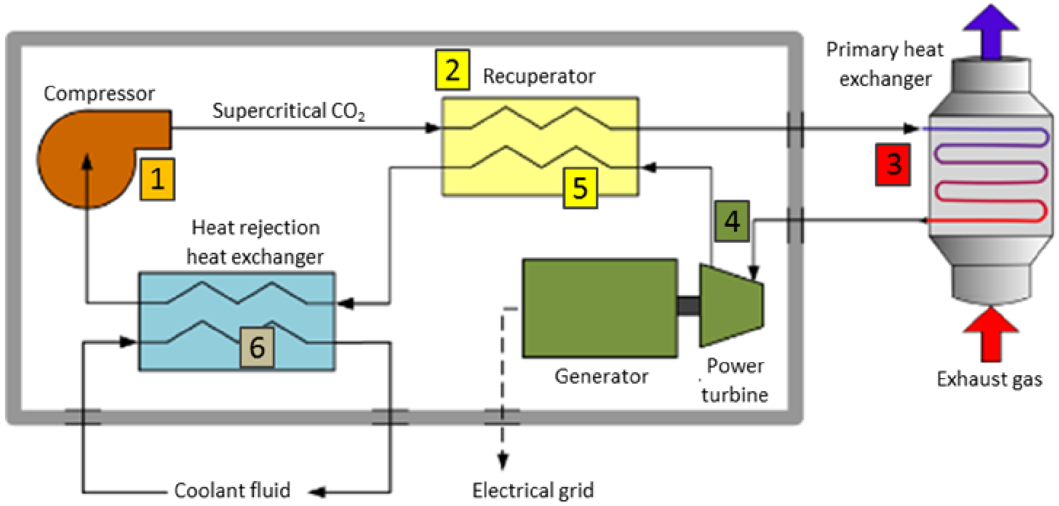
Echogen Power Systems

FE0031585

Project Partners: Siemens, Louis Perry Group, EPRI, Paul Weitzel Technical Consulting

04/01/2018 – 07/31/2019

BUDGET		
DOE	*Participant*	*Total*
$745,744	$186,436	$932,180



BENEFITS

- The proposed 10 MWe coal-fired sCO2 pilot power plant will reduce the technical and economic risk of this transformational technology; therefore, increasing the potential for commercial deployment.

sCO2 Market Deployment Strategy

MESA-Deloitte and KeyLogic

- **The Deloitte/KeyLogic team will produce a market deployment strategy focused on describing cost, performance, schedule, and obstacles/barriers of how sCO_2 technology will penetrate/deploy across the U.S. electrical market.**
- **The strategy will consider:**
  - Characteristics unique to sCO_2
  - Market applications-gas, nuclear, solar, waste heat recovery, and marine
  - Future energy scenarios for geographical areas where sCO_2 can penetrate
  - Prioritization of markets/applications base on sCO_2 cost, efficiency, and schedule
- **Workshops to engage sCO_2 stakeholders**

NETL sCO2 Systems Analyses References

NATIONAL ENERGY TECHNOLOGY LABORATORY

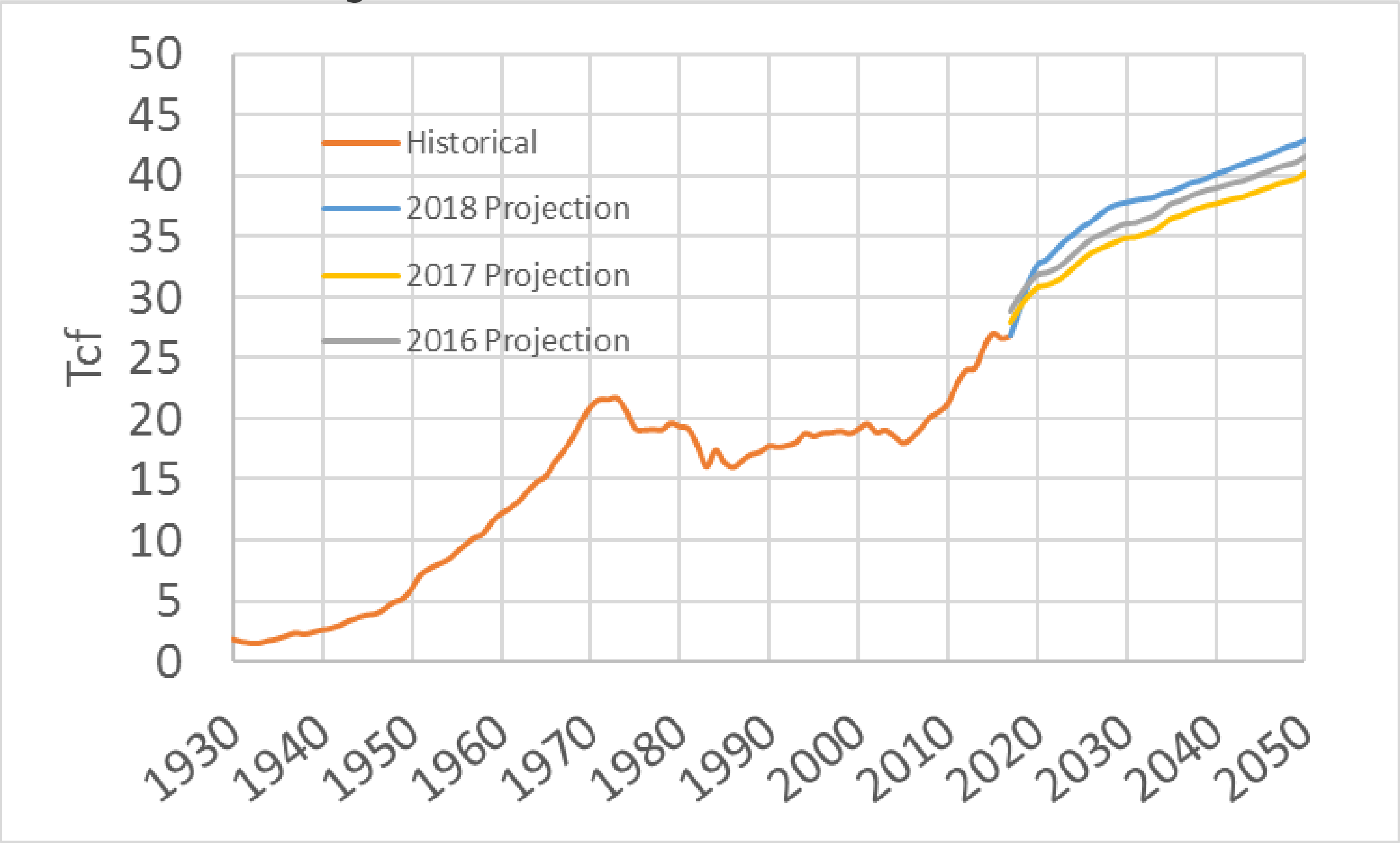
- [1]National Energy Technology Laboratory (NETL), "Techno-economic Evaluation of Utility-Scale Power Plants Based on the Indirect sCO2 Brayton Cycle," DOE/NETL- 2017/1836, Pittsburgh, PA, September 2017
- [2]Nathan T. Weiland, Charles W. White, "Techno-economic Analysis of an Integrated Gasification Direct-Fired Supercritical CO2 Power Cycle," 8th International Conference on Clean Coal Technologies, May 8-12, 2017
- [3]Charles W. White, Nathan T. Weiland, "Preliminary Cost and Performance Results for a Natural Gas-fired Direct sCO2 Power Plant," 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, PA, Mar 27–29, 2018
  - Reference baseline NGCC plant: National Energy Technology Laboratory (NETL), "Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3," NETL, Pittsburgh, July 2015.
- [4]Stephen E. Zitney and Eric A. Liese, "Dynamic Modeling and Simulation of a 10 MWe Supercritical CO2 Recompression Closed Brayton Power Cycle for Off-Design, Part-Load, and Control Analysis," 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, PA, March 27–29, 2018
- [5]P. Mahapatra, J.T. Albright, S.E. Zitney, and E.A. Liese, "Advanced Regulatory Control of a 10 MWe Supercritical CO2 Recompression Brayton Cycle towards Improving Power Ramp Rates," 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, PA, Mar 27–29, 2018
- [6]Charles W. White, Walter W. Shelton, Nathan T. Weiland, Travis R. Shultz, "sCO2 Cycle as an Efficiency Improvement Opportunity for Air-Fired Coal Combustion," 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, PA, March 27–29, 2018

Overview of US Turbine Population

Prime Mover/ Fuel Type	Nameplate Capacity	Average Capacity	Number of Units	Average Age	Average Heat Rate	Average Efficiency
Combined Cycle	274,011.0	346.0	792.0	16.0	8,624.7	41.0
Gas	272,039.0	347.9	782.0	16.0	8,617.1	41.0
Petro	987.0	141.0	7.0	14.1	9,091.3	38.0
Other	984.0	328.1	3.0	7.7	9,820.0	35.0
Gas Turbines	169,650.0	51.3	3,307.0	23.8	15,616.1	24.2
Gas	149,170.0	55.2	2,704.0	20.7	14,763.9	25.2
Petro	20,259.0	34.5	587.0	38.1	19,003.4	20.1
Other	221.0	13.8	16.0	23.2	17,070.0	20.0
Steam Turbine	420,518.0	152.0	2,759.0	40.2	12,896.8	28.4
Gas	84,106.0	130.6	644.0	47.9	14,414.9	25.6
Petro	21,084.0	163.4	129.0	46.0	14,861.8	26.7
Coal	298,183.0	226.2	1,318.0	40.8	11,358.3	31.0
Other	17,145.0	25.4	668.0	30.3	16,843.2	21.7

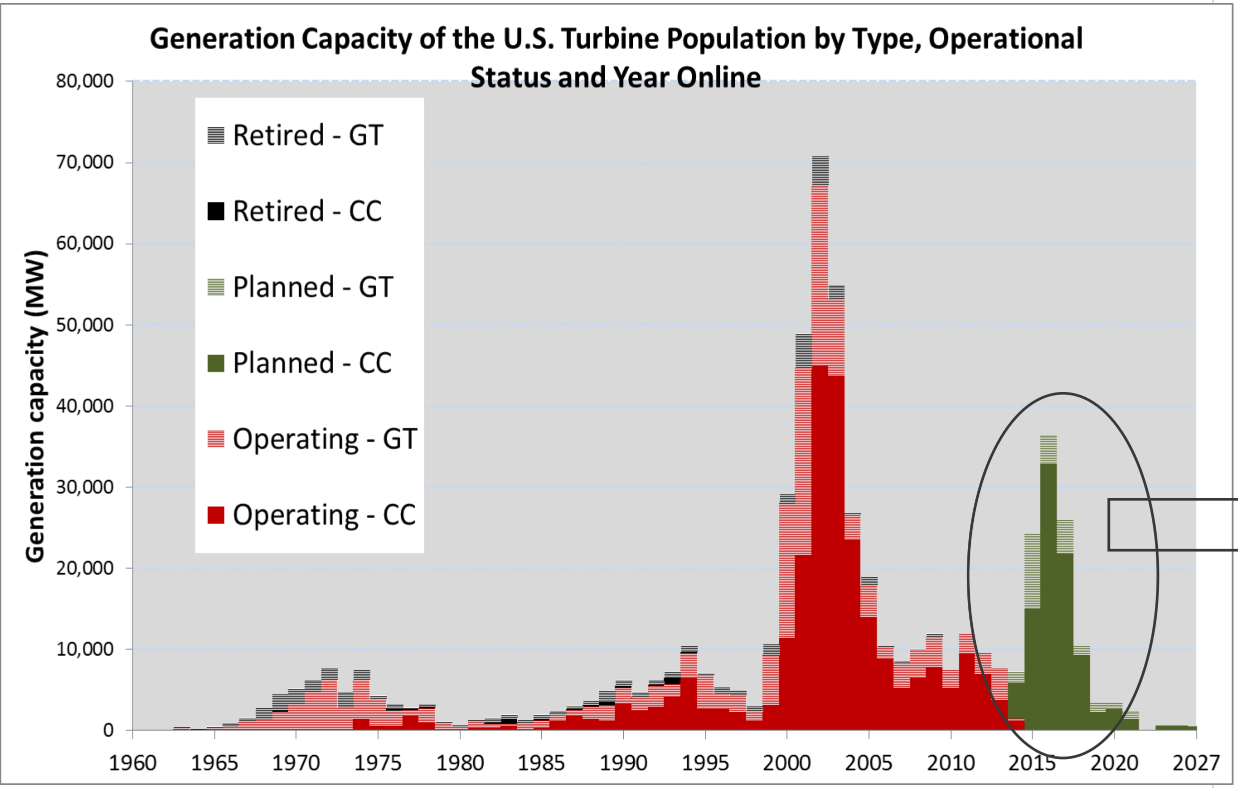
Source: EV Database

US Natural Gas, Dry Gas Production Historical and Projection

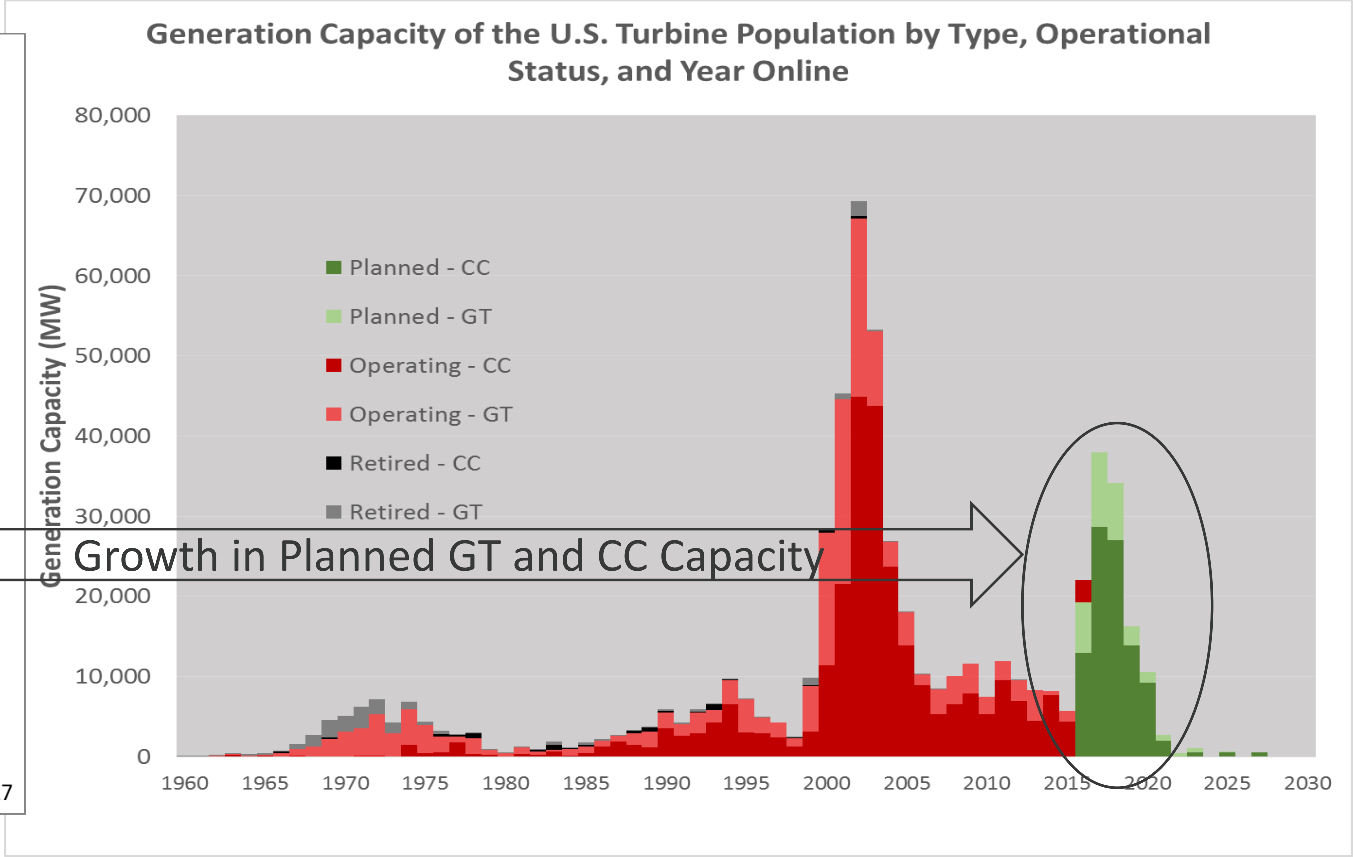


Growth has peaked, now into decline period as predicted

NATIONAL ENERGY TECHNOLOGY LABORATORY



2014 Analysis

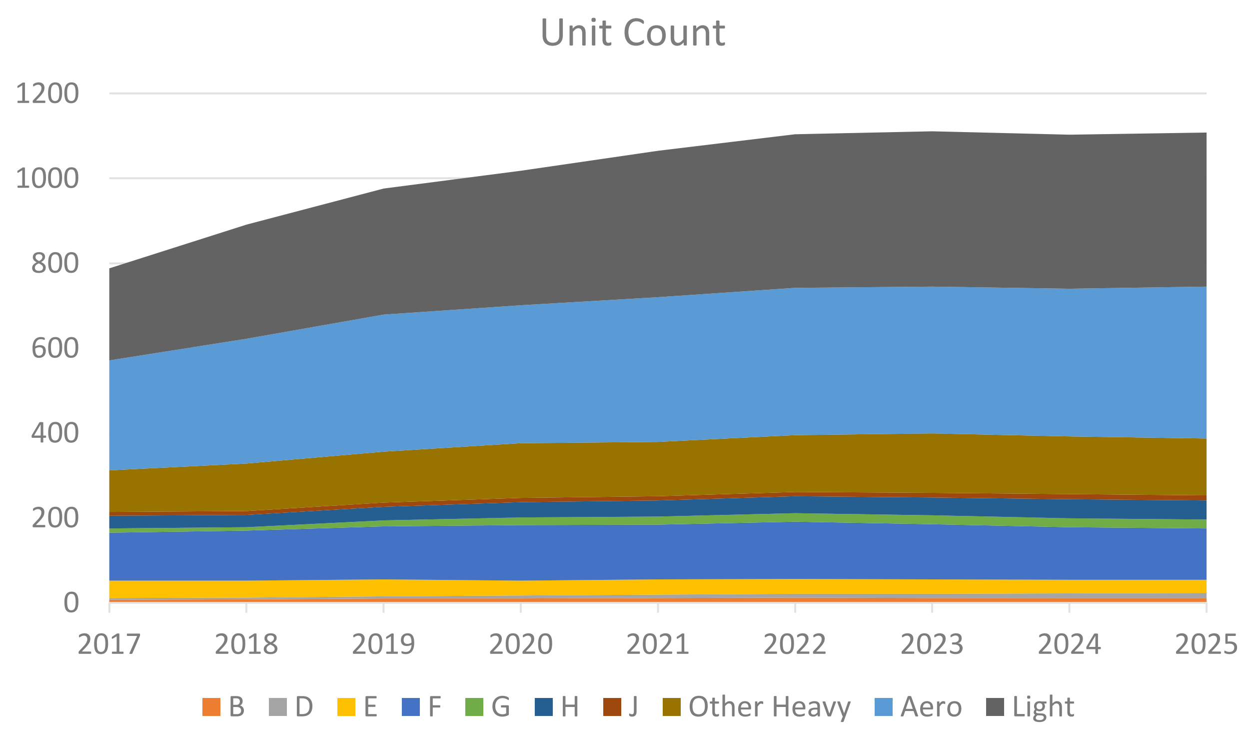


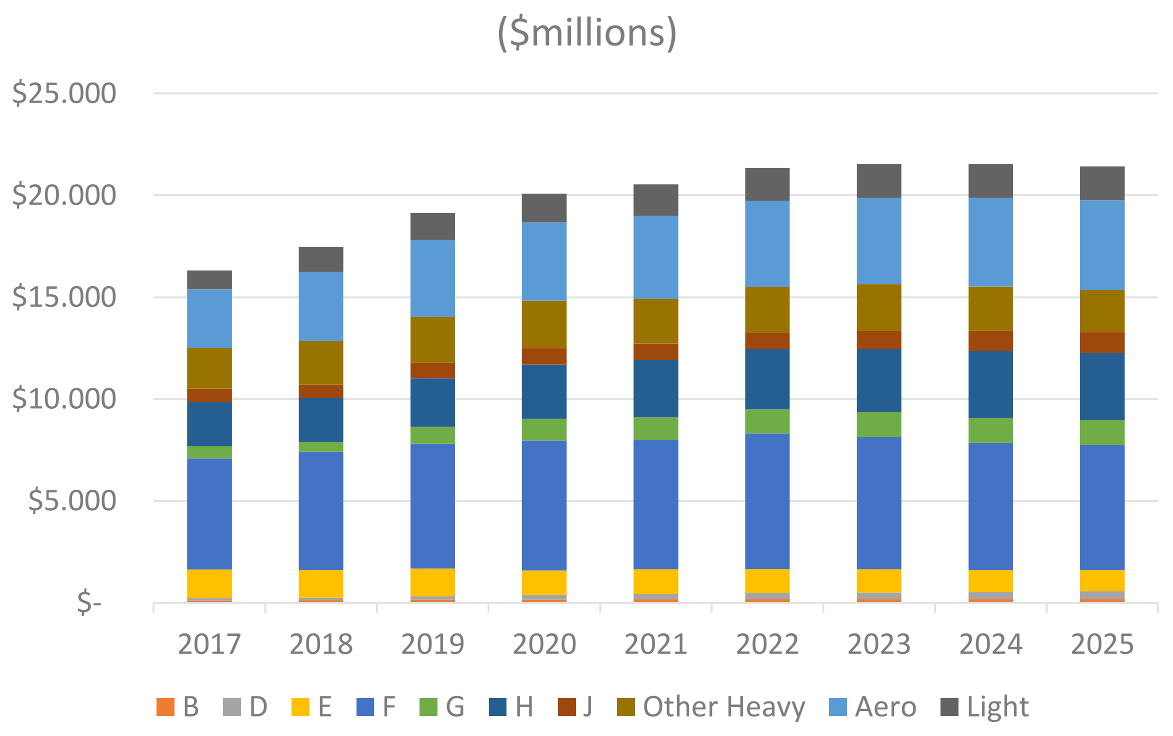
2016 Analysis

Worldwide IGT Turbine Forecast by Class

Predictions not matching actual sales

NATIONAL ENERGY TECHNOLOGY LABORATORY





Source: GTW IGT Forecast, 2016