An Overview of the United States Turbine Market and the NETL Turbine Research Program

NATIONAL ENERGY TECHNOLOGY LABORATORY

2016 International Gas Turbine Conference

October 12-13, 2016

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

U.S. DEPARTMENT OF ENERGY

Presentation Overview

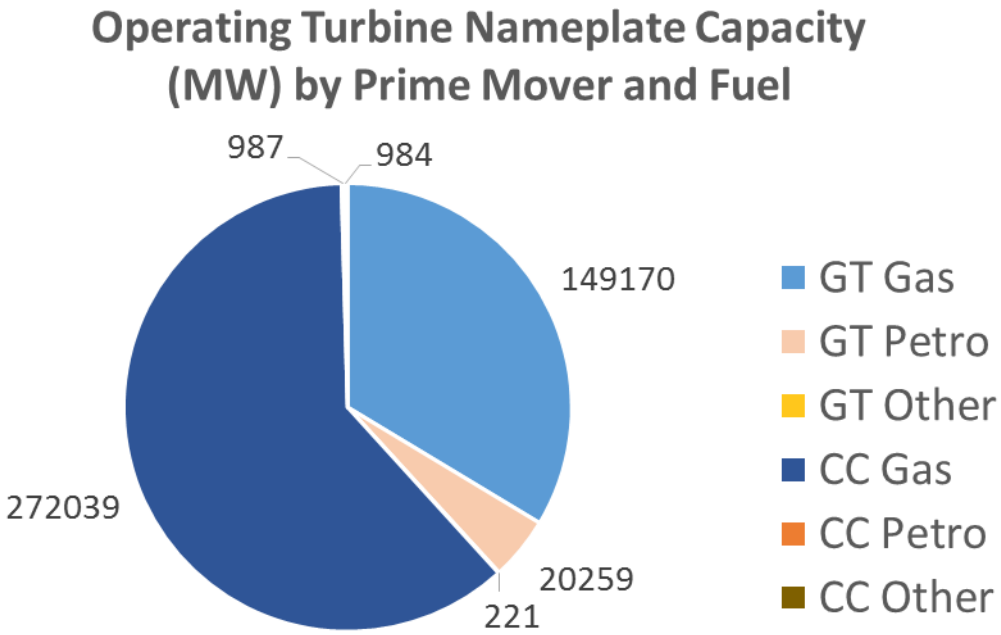
- **Market Analysis of Power Generation**
  - Demographics of Gas Turbine Power Generation
- **Overview of FE Gas Turbine R&D**
  - FE Advanced Turbines Program
  - Crosscutting R&D
- **Overview of DOE's sCO_2 Power Cycle Program**
  - DOE sCO_2 CCI
  - Projects
    - Cycle Analysis
      - Indirect and direct only performance
    - 10 MW sCO_2 Pilot Plant FOA
- **Conclusions**

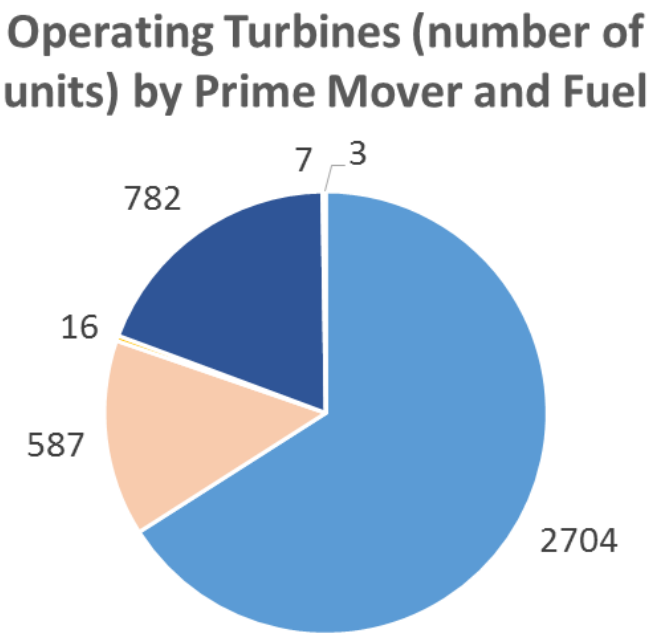
Overview of U.S. Turbines

U.S. 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

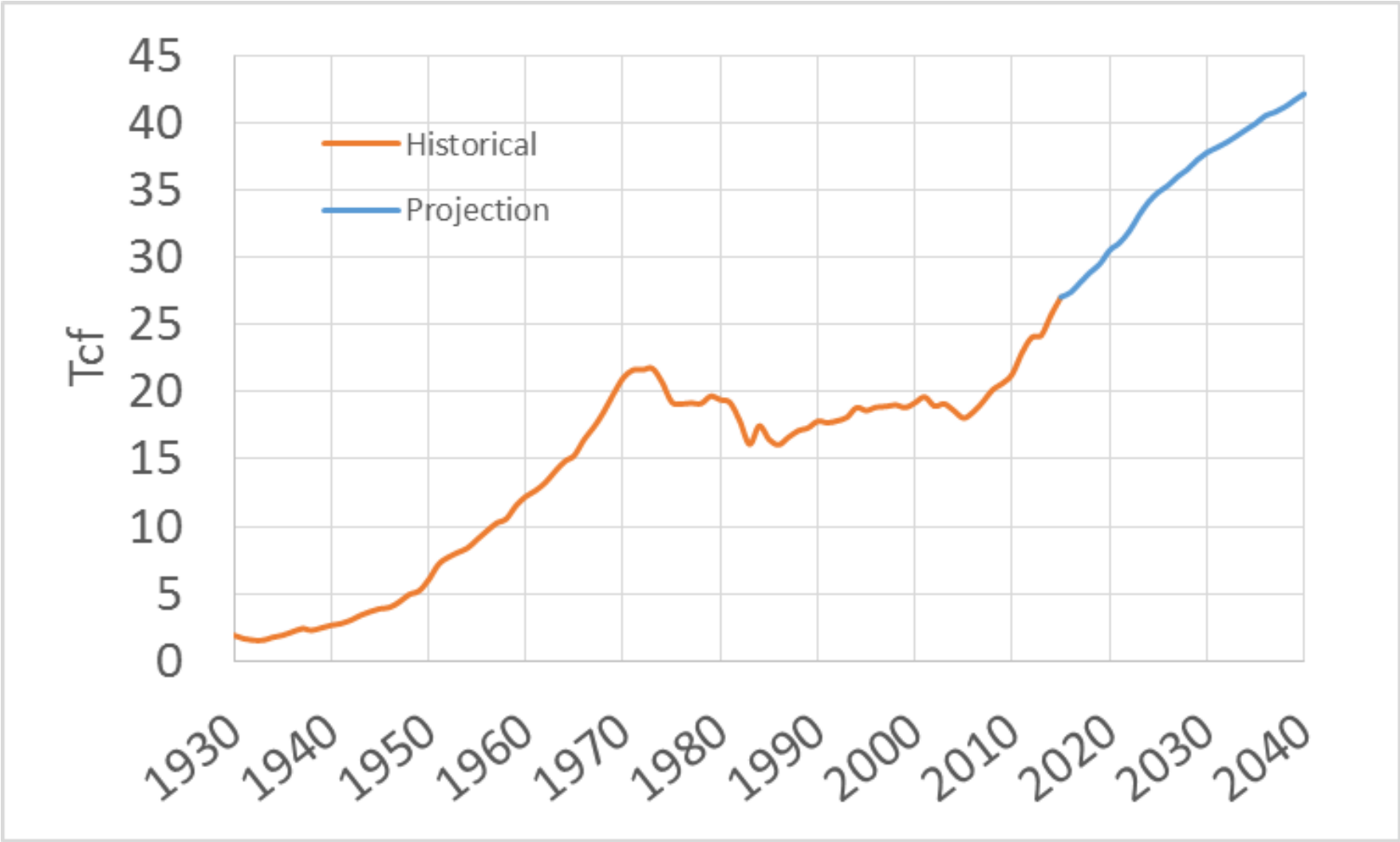
Composition of Combustion Turbine Fleet by Capacity and Number of Units





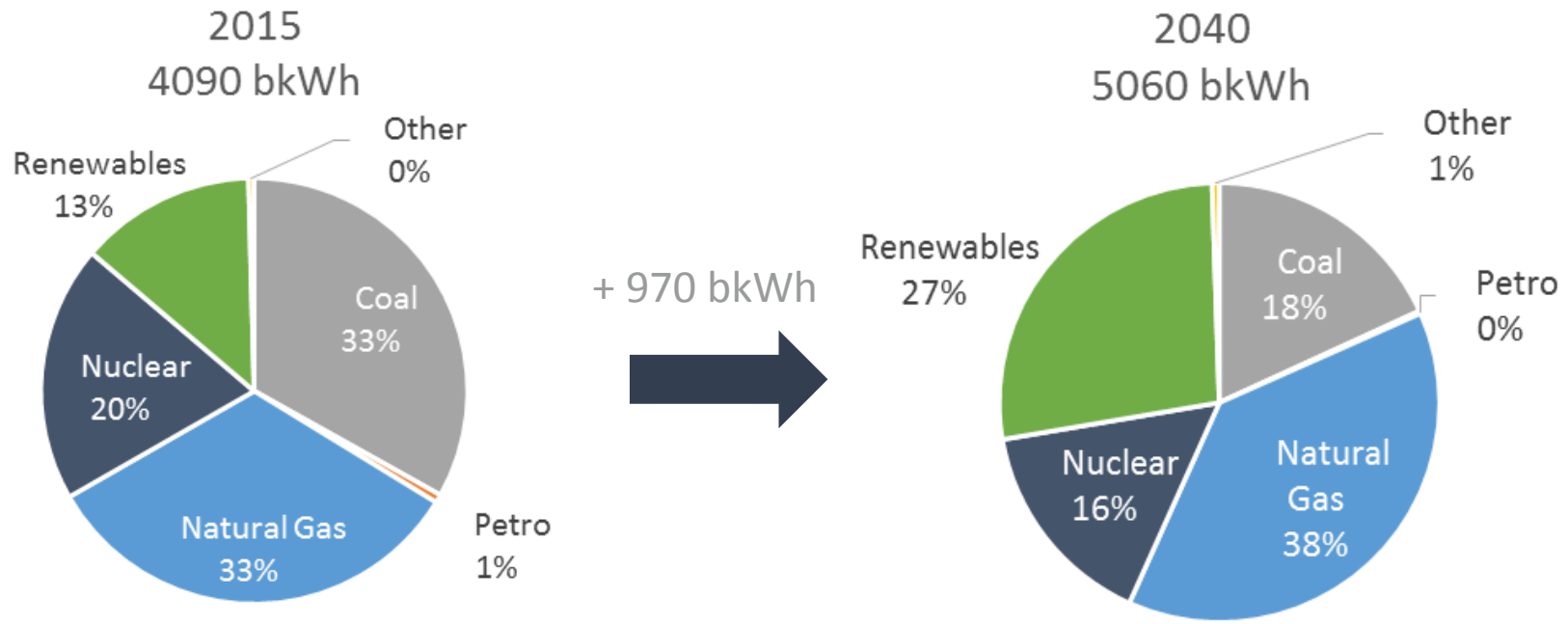
- CC units make up the bulk of capacity
- Combined cycle units are larger than simple cycle units

US Natural Gas, Dry Gas Production Historical and Projection



Source: EIA

US Electricity Generation by Fuel

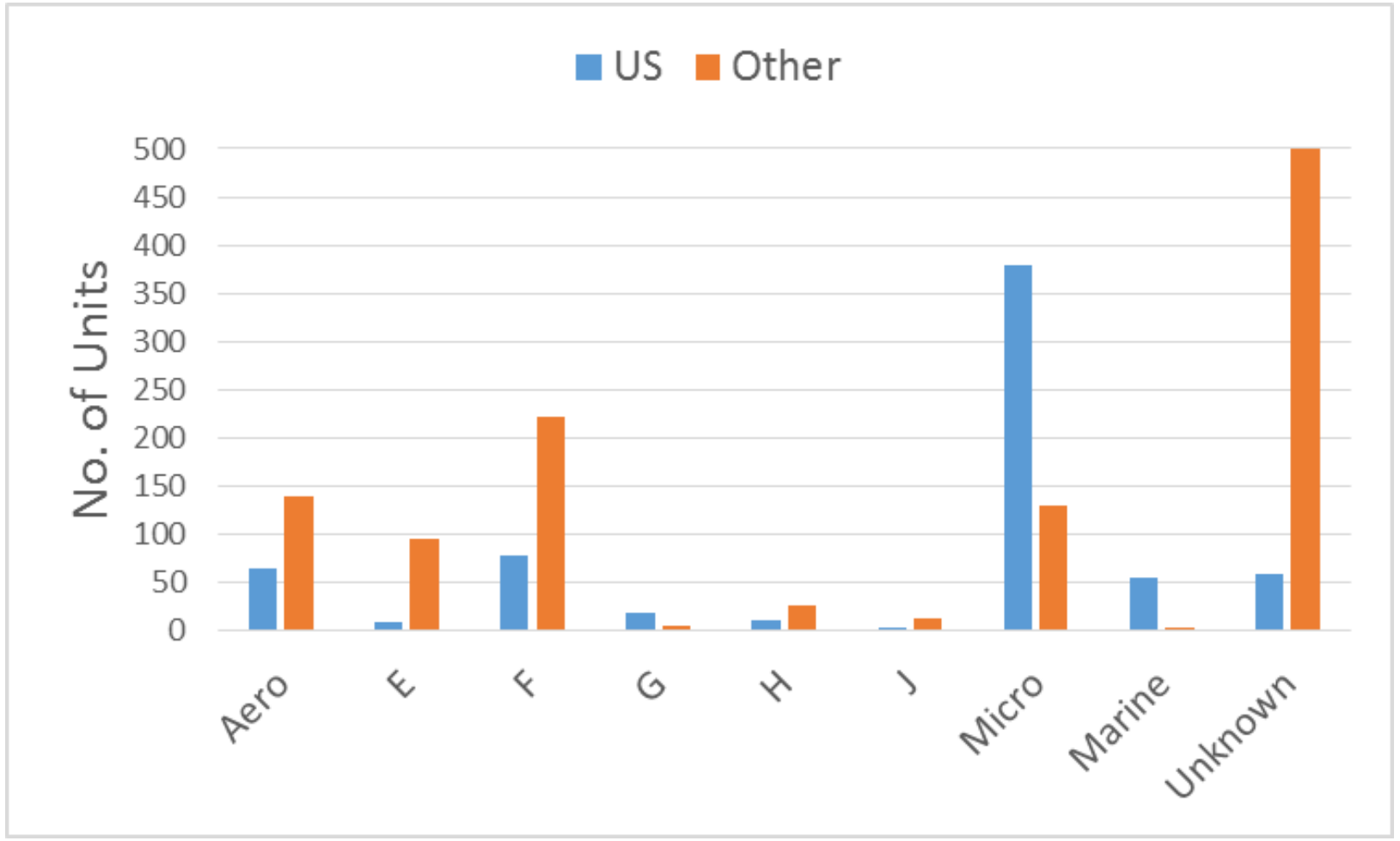


- NG generation increases by 44%
- NG electricity generation experiences the largest growth of 594 bkWh (61.2% of total increase)

- Source: EIA 2016 AEO Reference Case

Combustion Turbine Sales by Class

2014-2015 Data



Source: GTW 2014-2015 Handbook

Number of Planned Combustion Turbines Continues to Grow

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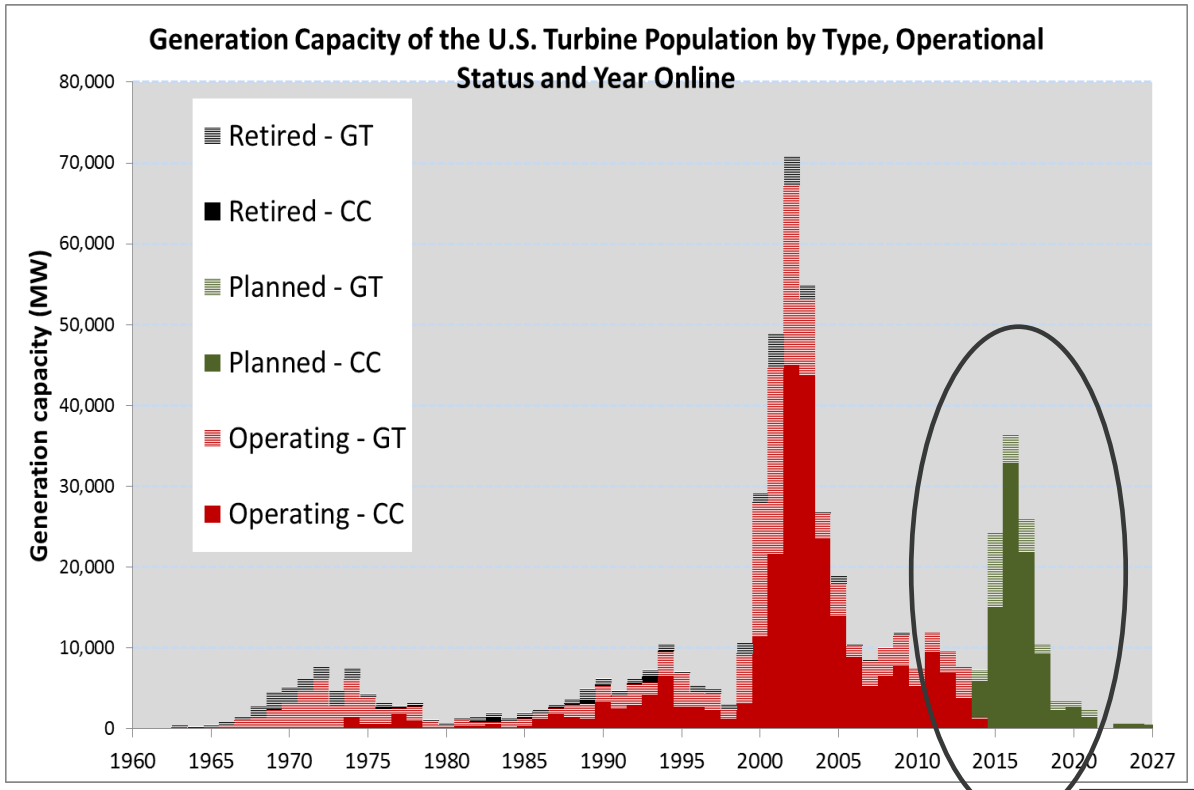
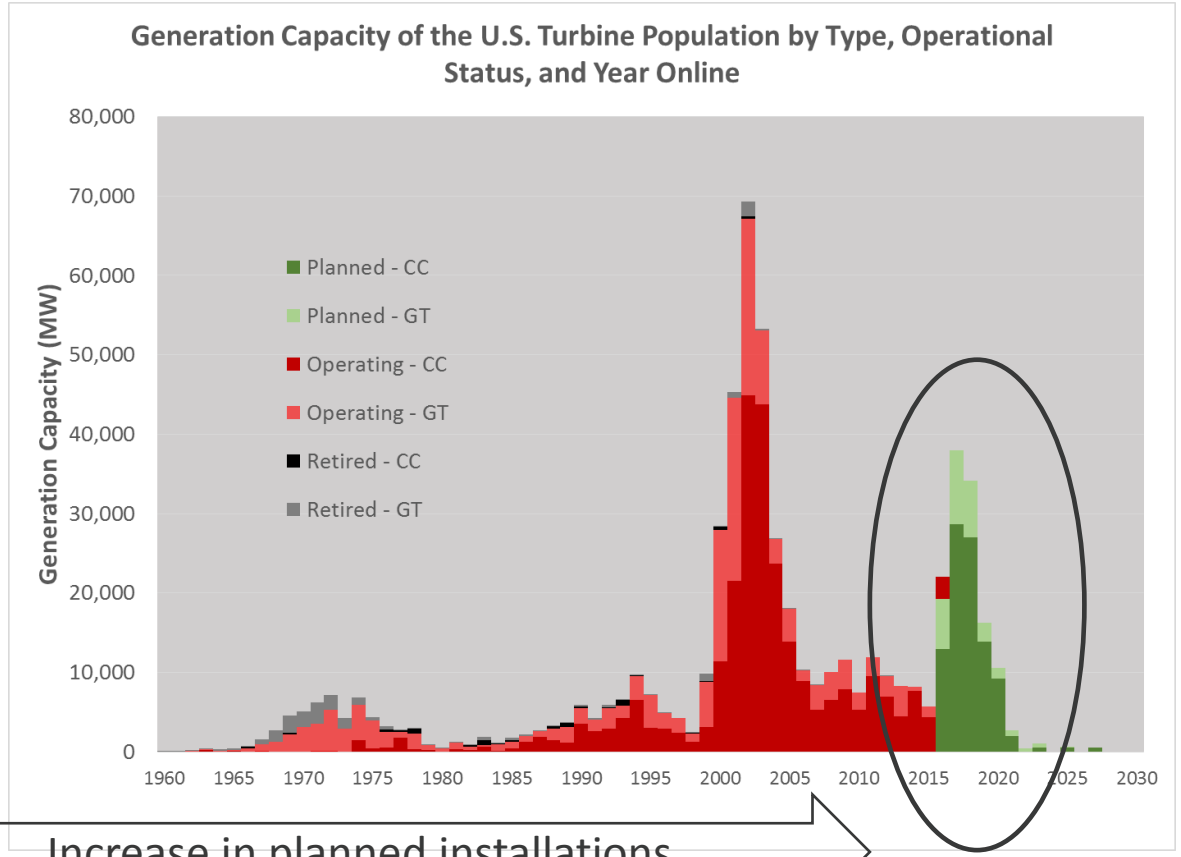
2014 Analysis



2016 Analysis



Increase in planned installations

Source: EV Database

Conclusions

- **Surge in combustion turbine installations is happening**
  - 2013-14 sales greater than 2011-12 sales
- **NG Price forecasts all indicate a slow rise, but history shows the projections are not overly accurate**
  - New EIA reference case projections include clean power plan
- **NG production will continue to rise through 2040**
- **Long term trend in fuel use for electricity is an increase in NG and a reduction in coal**
  - Short term trend is a small decrease in NG
- **F-class and aero derivative units continue to dominate sales and installed units in the US**
- **Worldwide, E-class units are still selling along with F-class and some H-class**

Advanced Turbine Program

Research Focused in Three Key Technology Areas

- **Adv. combustion turbines for H_2 fuels (IGCC, NGCC)**
  - CC eff. ~ 65 % (LHV, NG bench mark), TIT of 3,100 °F
  - Components Approach TRL ~ 3 --- > TRL 6 - 7
  - Delivers transformational performance benefits by 2025 for coal based IGCC with CCS (ready for full scale demonstration)
    - Delivers another $20/T reduction in CO_2 capture cost
- **sCO2 Turbomachinery (ACS, IGCC, NGCC)**
  - FE's sCO_2 Base Program – Shared with AT, ACS and XC
  - sCO_2 turbines for indirect (ACS) and direct (IGCC, NG) applications
  - Leverage and coordinate with DOE sCO_2 Initiative (STEP)
- **Pressure Gain Combustion (IGCC, NGCC)**
  - Alternate pathway to high efficiency
  - TRL 2 (risky, long term, high pay back)

FY2016 Advanced Turbines FOA

- **11 Projects awarded in FY2014 in 2 topic areas**
  - 7 in advanced combustion turbines in combined cycle applications capable of 65% or greater combined cycle efficiency (LHV)
  - 4 in supercritical carbon dioxide (sCO_2) based power cycles for fossil fuel applications

- **FY2016 Phase II FOA**
  - Applicable only to recipients of Ph. I Awards
  - Phase II awards will be nominally $6M 4 year projects
  - 6 projects selected

High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion

Southwest Research Institute

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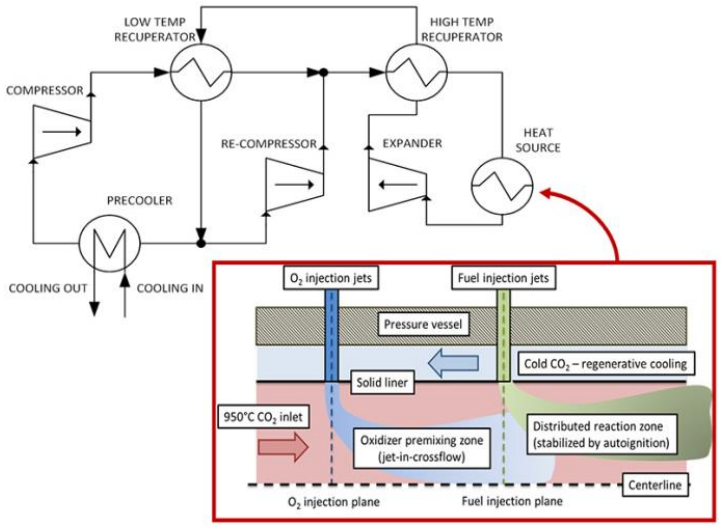
PROJECT NARRATIVE

- The project team will develop a high inlet temperature oxy-combustor suitable for integration into a direct-fired supercritical oxy-combustion power plant for fossil energy applications
- Evaluation of the direct-fired oxy-combustion system using system engineering design and thermodynamic analysis to assess plant efficiencies, verify operating conditions and optimize plant configuration
- Conduction of a technical gap analysis of the proposed plant to identify critical component and technology development needs

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



Autoignition-Stabilized Combustor Concept for Direct Fired Supercritical Oxy-Combustion Cycle

BUDGET

Total Award: $750,000

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

General Electric Co.

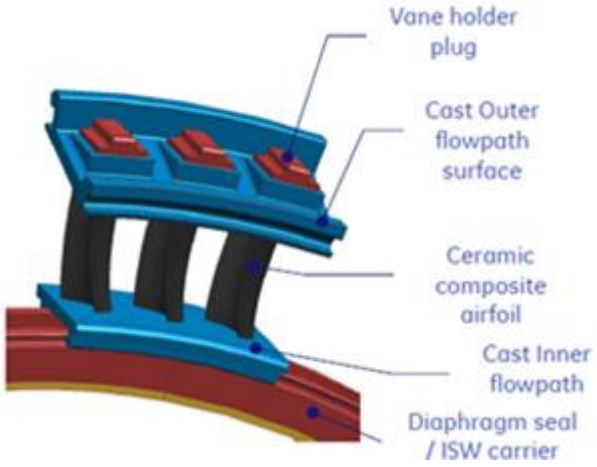
PROJECT NARRATIVE

- GE will develop cooled high-temperature CMC nozzles (non-rotating airfoils)
- Leverages existing knowledge of CMC materials
- Phase I scope includes
  - Design and analysis of attachment configurations
  - Investigation of impingement and film cooling
  - Definition of sealing approaches, design of key sealing features, and analysis of sealing effectiveness
- Limited bench flow testing

BENEFITS

- Contributes to DOE goal of 65% combined cycle efficiency
- Revolutionary component architectures

GE BAYONET NOZZLE ASSEMBLY



BUDGET

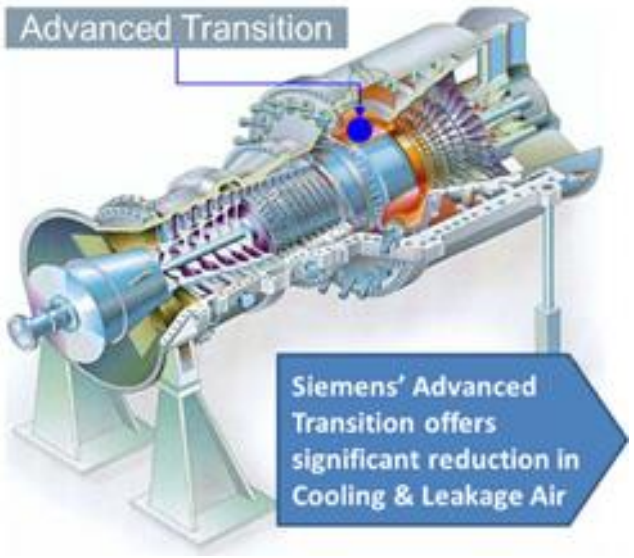
Total Award: $9,537,331

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle

Siemens Energy Inc.

PROJECT NARRATIVE

- Siemens will develop a CMC based design for Siemens's Advanced Transition
- Deliverable is a design concept ready for fabrication and test in a Phase II project
- Will utilize Siemen's patented Hybrid Oxide CMC system



BENEFITS

- Reduced cooling requirements enabling higher turbine inlet temperatures
- Contributes to DOE goal of 65% combined cycle efficiency

BUDGET

Total Award: $8,118,348

Advanced Multi-Tube Mixer Combustion for 65% Efficiency

General Electric Co.

PROJECT NARRATIVE

- GE will develop and synthesize their multi-tube mixer combustion technology
- Goal of low NOx emissions up to 3100F while supporting load following grid needs
- Ultra-compact design that minimizes NOx formation and minimizes surface area to be cooled
- In-depth engineering analysis and design with minimal laboratory testing

GE FULL SCALE EARLY COMBUSTION HARDWARE

BENEFITS

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

BUDGET

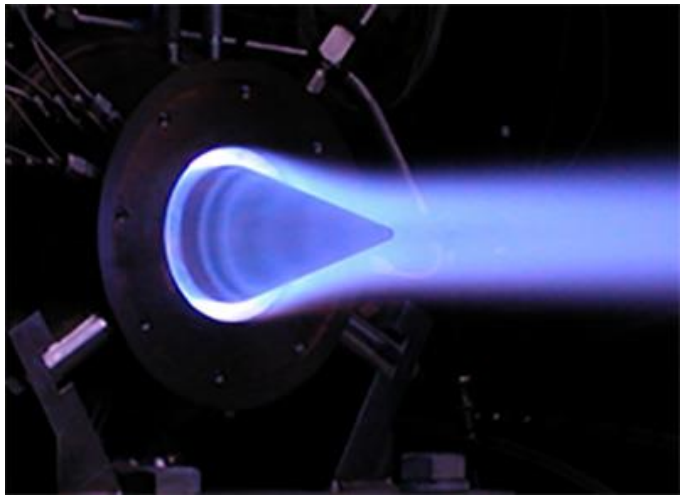
Total Award: $970,988

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

Aerojet Rocketdyne (now GTI)

PROJECT NARRATIVE

- Aerojet Rocketdyne, Inc. will develop, validate, and integrate a systems model for a rotating detonation combustor in a power plant systems model
- Initially creates a system simulation tool for integration
- Results of simulation will be integrated into systems model to define the path to configurations that exceed 65% efficiency



BENEFITS

- Contributes to DOE goal of 65% combined cycle efficiency
- Advances technology for combustion turbines for combined cycle applications

BUDGET

Total Award: $747,643

Crosscutting R&D
Novel Temperature Sensors and Wireless Telemetry for Active Condition Monitoring of Advanced Gas Turbines

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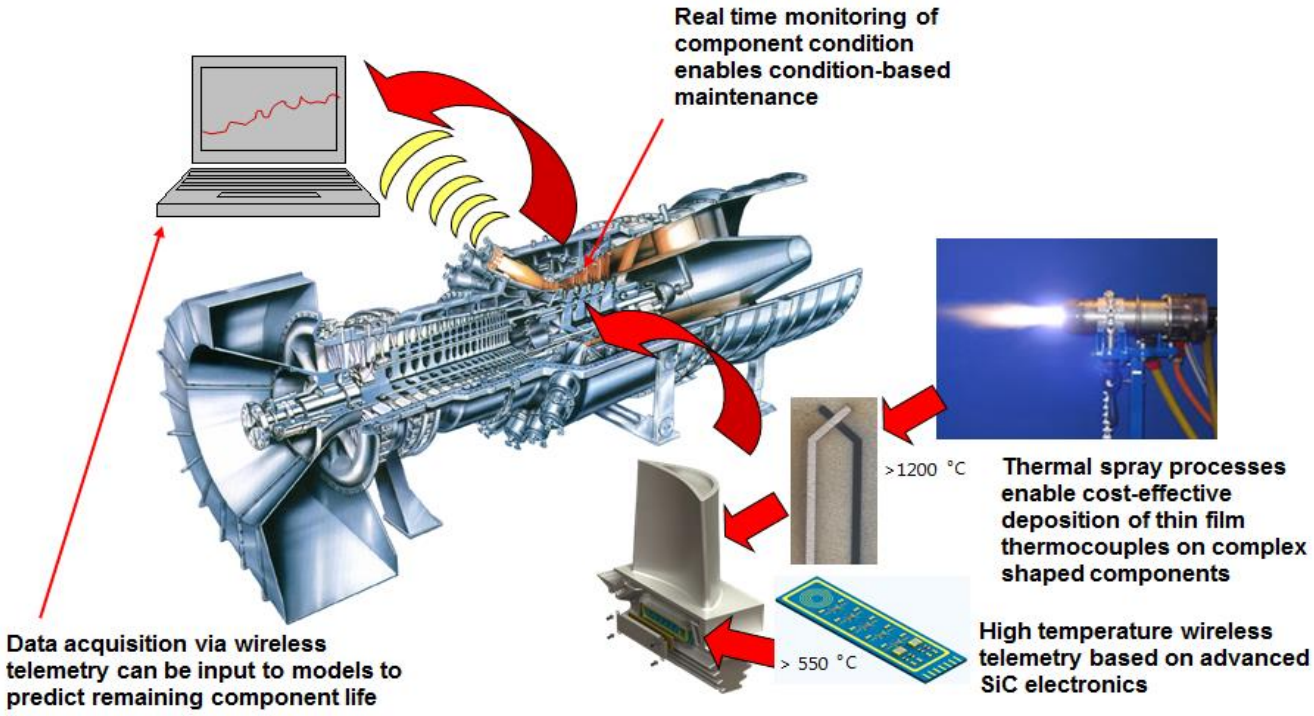
Project Objective & Scope

- Develop an innovative, real-time sensor integrated component monitoring concept (Smart Turbine Component) that will consist of integrated embedded sensors with wireless telemetry that will be operational in the harsh environments of gas turbine.

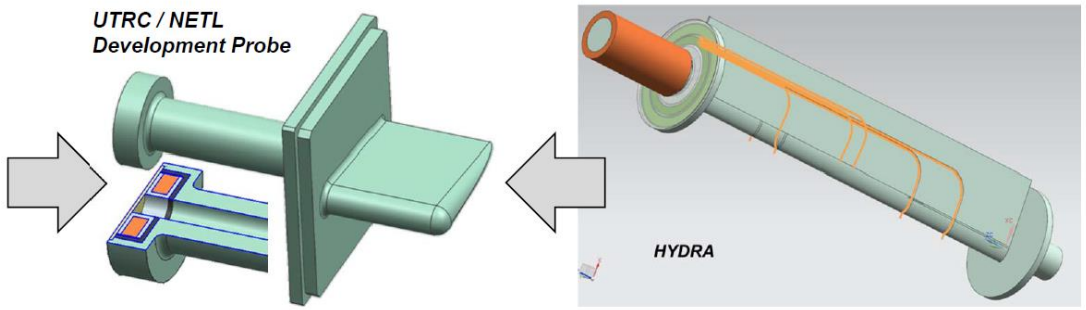


The Smart Turbine Component, consisting of integrated embedded sensors with wireless telemetry, operational in the harsh environments of the gas turbine

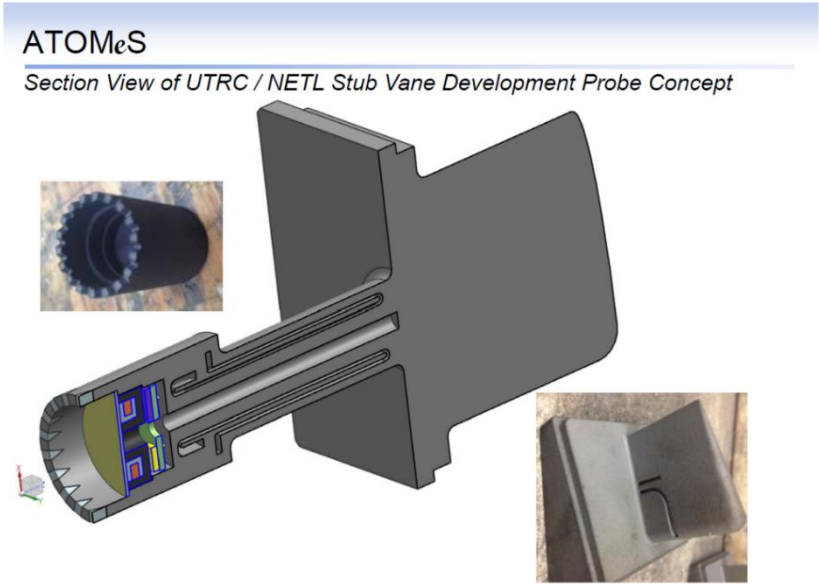
Crosscutting R&D
United Technologies Research Center

Additive Topology Optimized Manufacturing with Embedded Sensing

- Holistic approach to tailoring sensor embedding process for industrial gas turbine airfoils
- Physics-based, structural, and electromagnetics modelling
- Real-time diagnostics via health-utilization-monitoring system (HUMS)
- Additive manufacturing processes include high velocity metal powder cold spray deposition combined with direct metal laser sintering (DMLS)
- Sensing elements protected from harsh environments without compromising functionality or part life



Integrated Inlet Guide Vane with Embedded Sensing

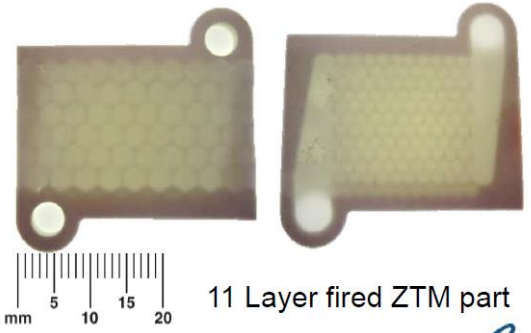


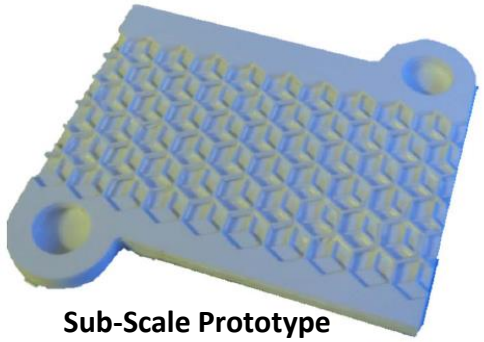
Source: 1) P. Attridge, S. Bajekal, T. El-Wardany, et. al, "ATOMeS: Additive Topology Optimized Manufacturing & Embedded Sensing," 2014 DOE/NETL Crosscutting Research Annual Review Meeting, Pittsburgh, PA, May 19 – 23, 2014. 2) [Images] P. Atteridge, S. Bajekal, M. Klecka, et. al., "Additive Manufacturing Enabled Ubiquitous Sensing in Integrated Aerospace and Ground Based Turbine Systems," 2015 DOE/NETL Crosscutting Research Annual Review Meeting, Pittsburgh, PA, April 27 – May 1, 2015.

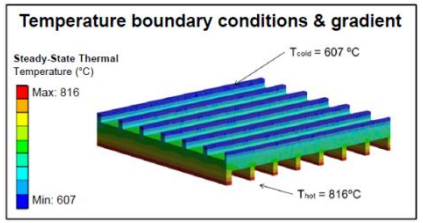
Crosscutting R&D
Ceralink, Inc.

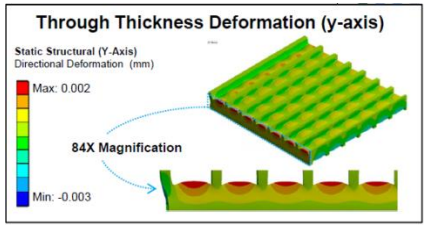
Additive Manufacturing for Cost Efficient Production of Compact Heat Exchangers and Recuperators

- Design and build a prototype compact high-temperature ceramic heat exchanger (HEX) as a key component for high efficiency advanced power generation systems
- Laminated object manufacturing (LOM)
- Functionally graded 3D geometries that transition candidate material (ex: aluminum nitride, ALN) to another (ex: zirconia toughened mullite, ZTM) to enable property match for sealing to metals (ex: stainless steel)
- Target: 60% weight to volume reduction compared to metal HEX; 25% microturbine thermal cycle efficiency improvement; scalable design
- Temperature >1500°F (816°C)
- Research effort includes HEX modeling & optimization (thermal-fluid modeling, thermal stress analysis), materials selection, sub-scale + full-scale prototype development, and testing.
- Research Collaborator: United Technologies Research Center




Sub-Scale Prototype featuring honeycomb design





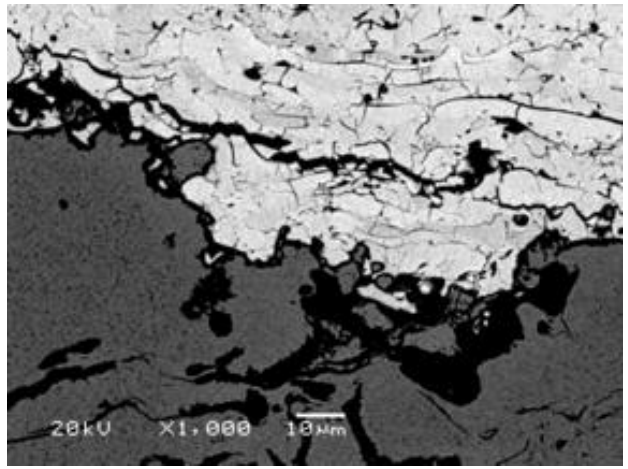
Source: N. Ross, H. Shulman, and S. Allan, "Additive manufacturing for cost efficient production of compact ceramic heat exchangers and recuperators," 2015 DOE/NETL Crosscutting Research Annual Review Meeting, Pittsburgh, PA, April 27-30, 2015.

NETL Crosscutting Technology Program

Turbine Materials Research

- **SCO_2 Turbines**
  - Corrosion testing of H282 in sCO_2 at 3000 psi and 730 °C
  - Fatigue crack growth tests on H282 after exposure to sCO_2

- **Gas Turbines**
  - New Turbine Wheel Alloy for 65% combined cycle turbine
  - Advanced Thermal Barrier Coatings (TBC)
    - Functional graded La2Zr2O7 based TBC
    - Novel Multi Layer TBC – Graded Bond Coat plus YSZ/pyrochlore coating
  - Additive Manufacturing of Fuel Injectors



#6 $La_2Zr_2O_7$ and bond coat interface

FE Supercritical Carbon Dioxide Technology Program

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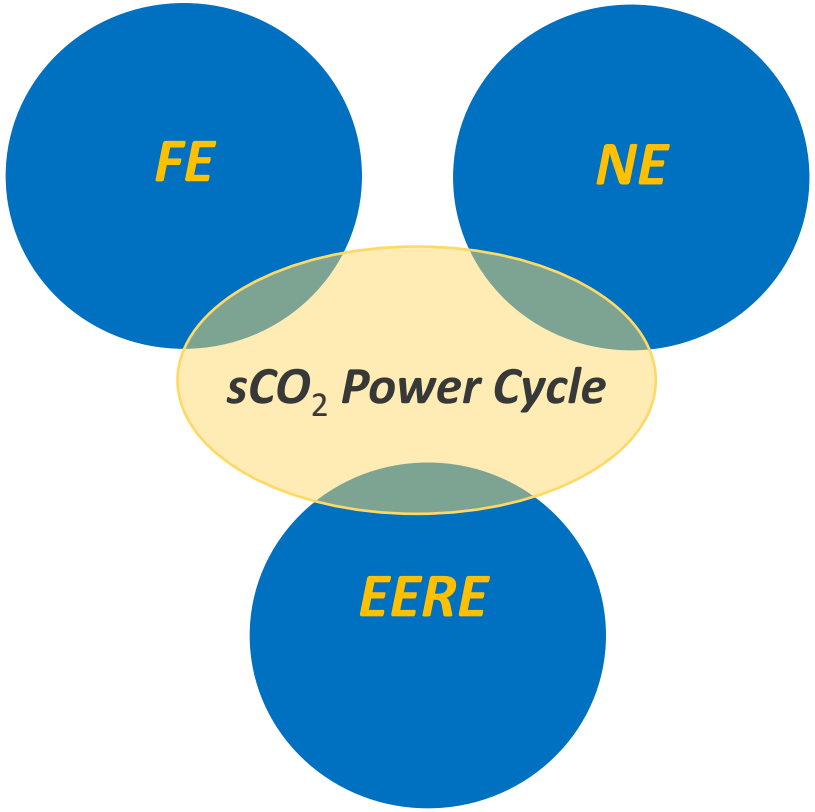
Summary

- **Benefits of Supercritical CO_2 (sCO_2) Based Power Cycles**
  - Higher efficiency – Lower emissions per MWhr and positively affects COE calculation
    - Indirect (STEP): ~ 3 % pts greater than steam at the same temperature
    - Direct: Still doing analysis but others have shown it has a considerably lower cost relative to NGCC w/CCS.
  - Fuel/energy source flexibility
  - Water producer direct fire configuration
- **DOE sCO_2 Crosscut Initiative (STEP)**
  - Collaboration between DOE Offices (FE, NE, and EERE – CSP & Geothermal)
  - Mission: Address technical issues, reduce risks, and mature technology
  - Objective / goal: Design, build, and test 10 MWe pilot facility (STEP)
  - Major Crosscut procurement actions:
    - Advanced recuperator development (FE FOA: $ 10 M in FY 2015)
    - Cost and technical approach for STEP (NE RFP: $ 5 M ~ 3 awards by 12/2015)
    - Design, build & operate STEP facility (FE FOA: $ 15 M (FY16 enacted), ~ $ 80 M total DOE 80/20 cost share

FE Supercritical Carbon Dioxide Technology

Program DOE sCO_2 Crosscut Initiative

- **Nuclear Energy (NE), Fossil Energy (FE) and Energy Efficiency and Renewable Energy (EERE) collaborate on sCO_2 power cycles**
  - Coordinate efforts to solve common challenges to the applications
- **Mission:** Address technical issues, mature technology, reduce risks towards commercialization of the sCO_2 power cycle
- **Design, build, and operate 10 MWe STEP (Supercritical Transformational Electric Power) indirect-fired sCO_2 power cycle pilot-scale facility to demonstrate**
  - Component performance
  - Cycle operability
  - Progress towards a lower cost of electricity
- **Base R&D portfolios within the three offices continue to address application specific development needs**



Design, Build, and Operate Supercritical Transformational Energy Program (STEP) Facility

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FE 2016 FOA: Award and Objective

Award

- FOA issued March 2016
- Cooperative agreement awarded September 2016
- Cost—DOE: $79,999,226/Non-DOE: $33,279,408/Total Funding: $113,278,634

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%

Contact Information

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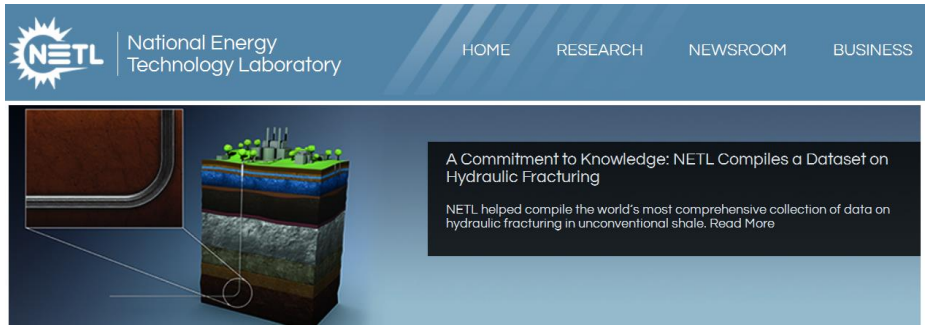

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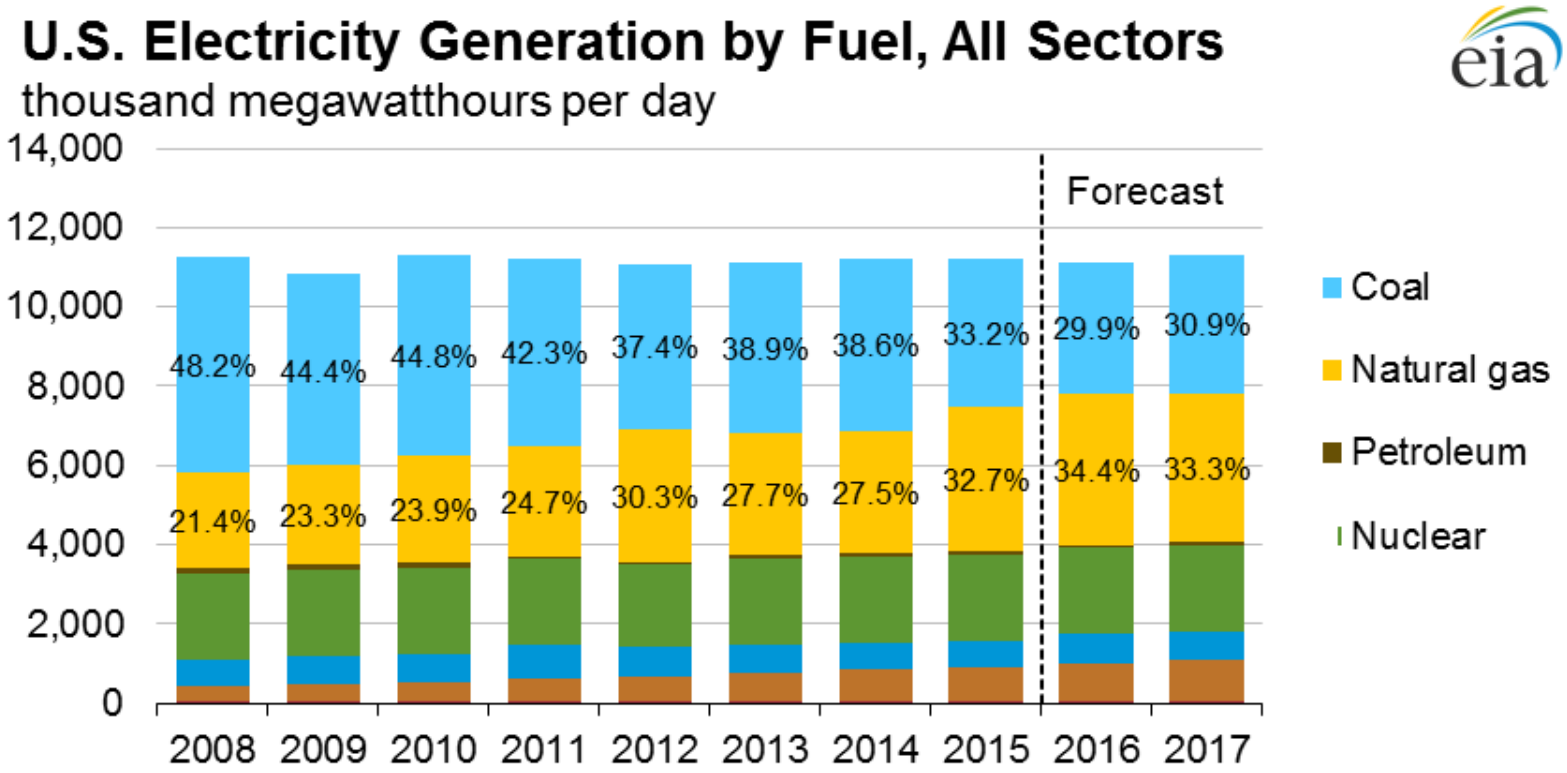
Backup Slides

Short Term Look at Electricity Generation Mix



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

Source: Short-Term Energy Outlook, June 2016.