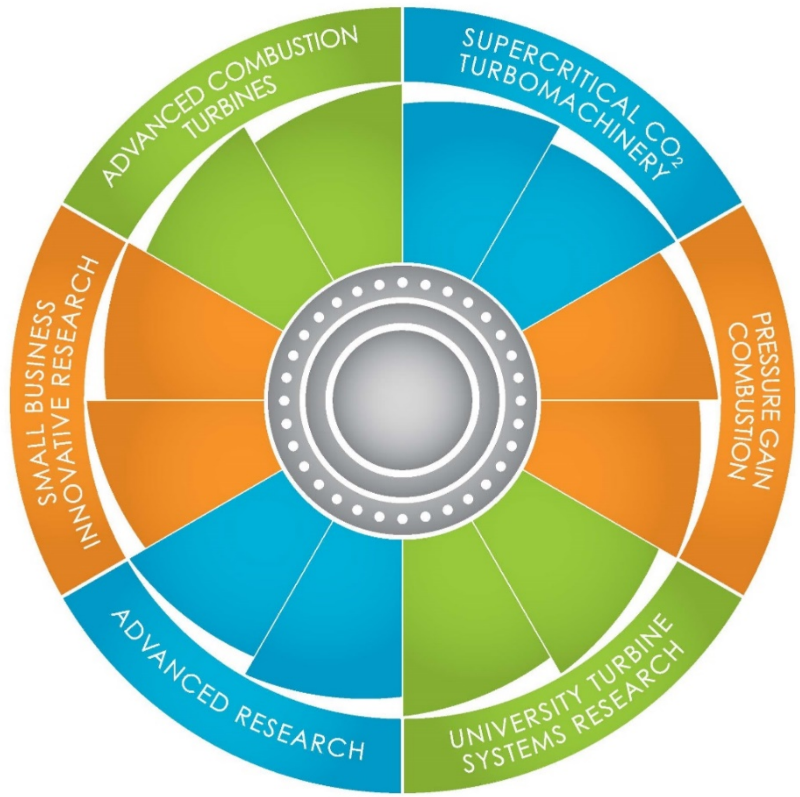
Overview of the US DOE Advanced Turbines Program



2018 UTSR Workshop & Program Overview

DOE, DOD & NASA Synergies in Gas Turbine Technology

Hilton Garden Inn

Dayton Beach, FL

October 30 - November 1, 2018

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**
- **Observations of Gas Turbine Market**
- **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
- **DOE, DOD & NASA Synergies in Gas Turbine Technology**
- **Conclusions & Summary**

Department of Energy

Organizational Structure

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

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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
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Office of the Under Secretary for Science

Under Secretary for Science (S4)

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- Office of Technology Transitions
- Office of the Assistant Secretary for Environmental Management
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Office of the Under Secretary for Energy

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- 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
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- 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

DOE FE NETL Program Areas

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

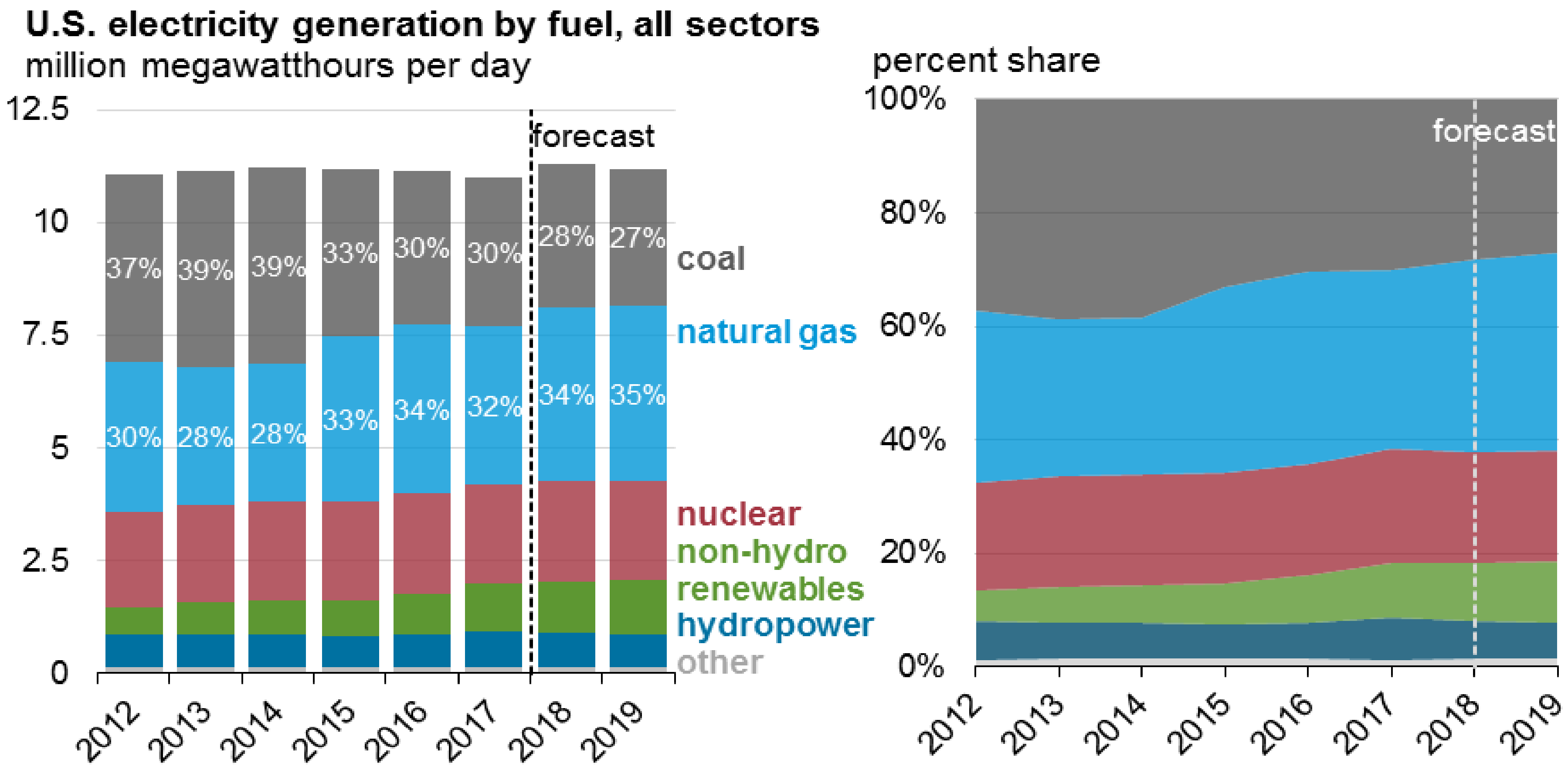
STEP (Supercritical CO_2)

- 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

Electricity Generation Mix (Short Term)



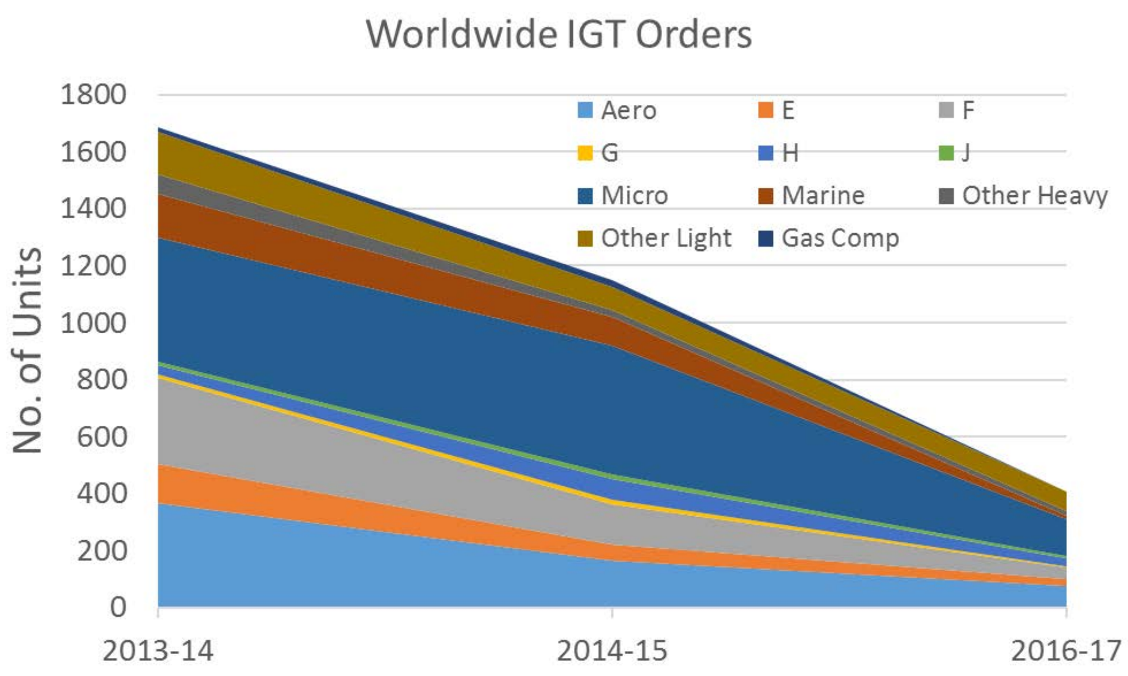
Note: Labels show percentage share of total generation provided by coal and natural gas.

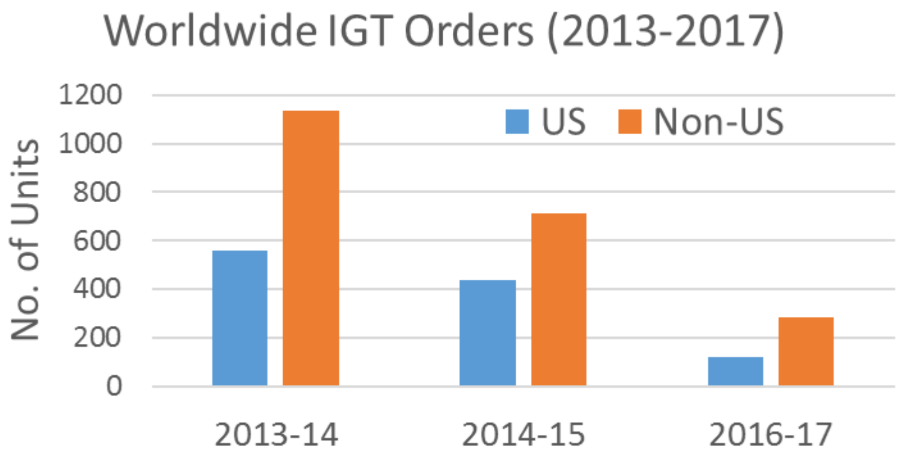
Source: Short-Term Energy Outlook, July 2018

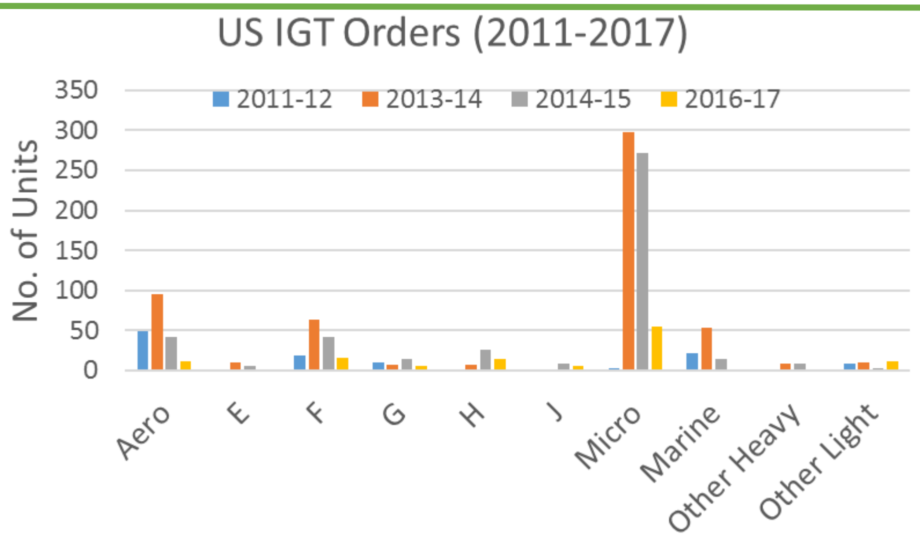
EIA = Energy Information Administration

US and Worldwide IGT Orders by Class

Noticeable decrease in orders

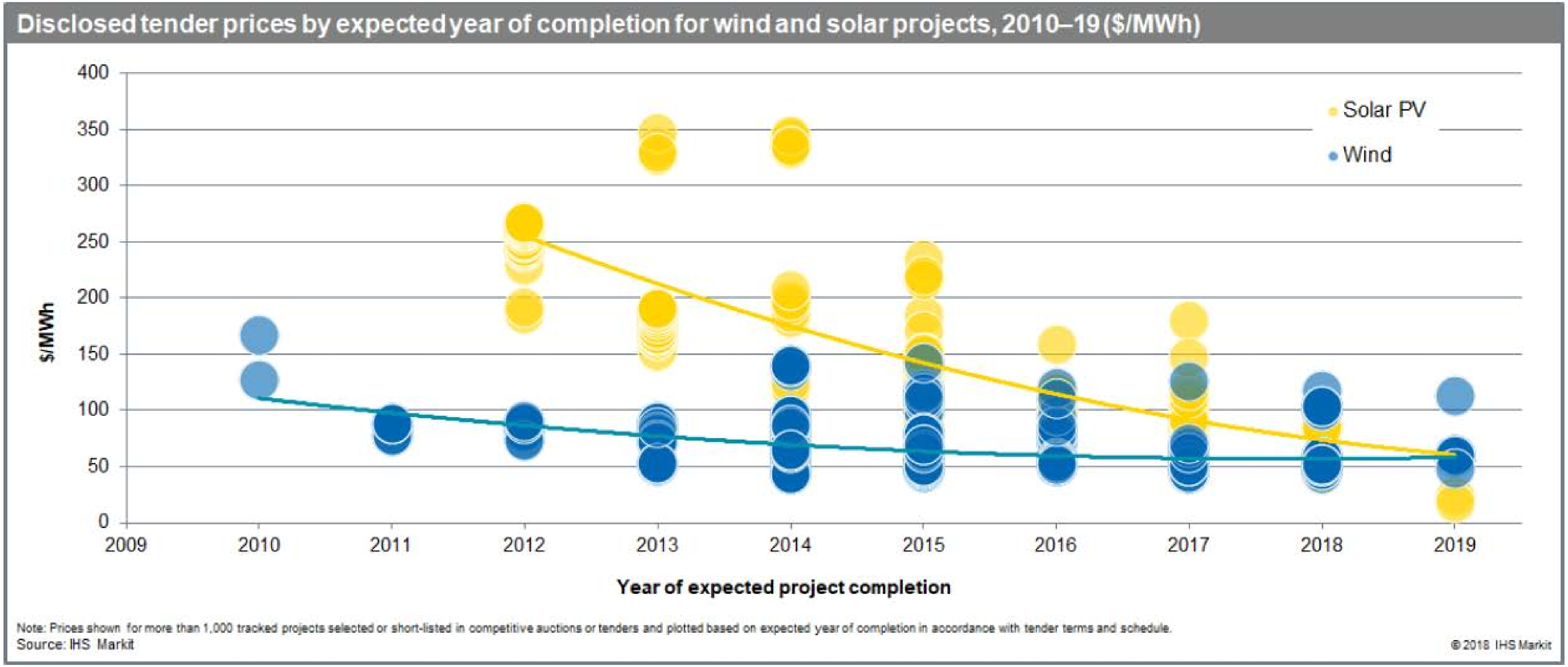






- Source: GTW Handbook, 2013, 2014-15, 2016-17, 2018

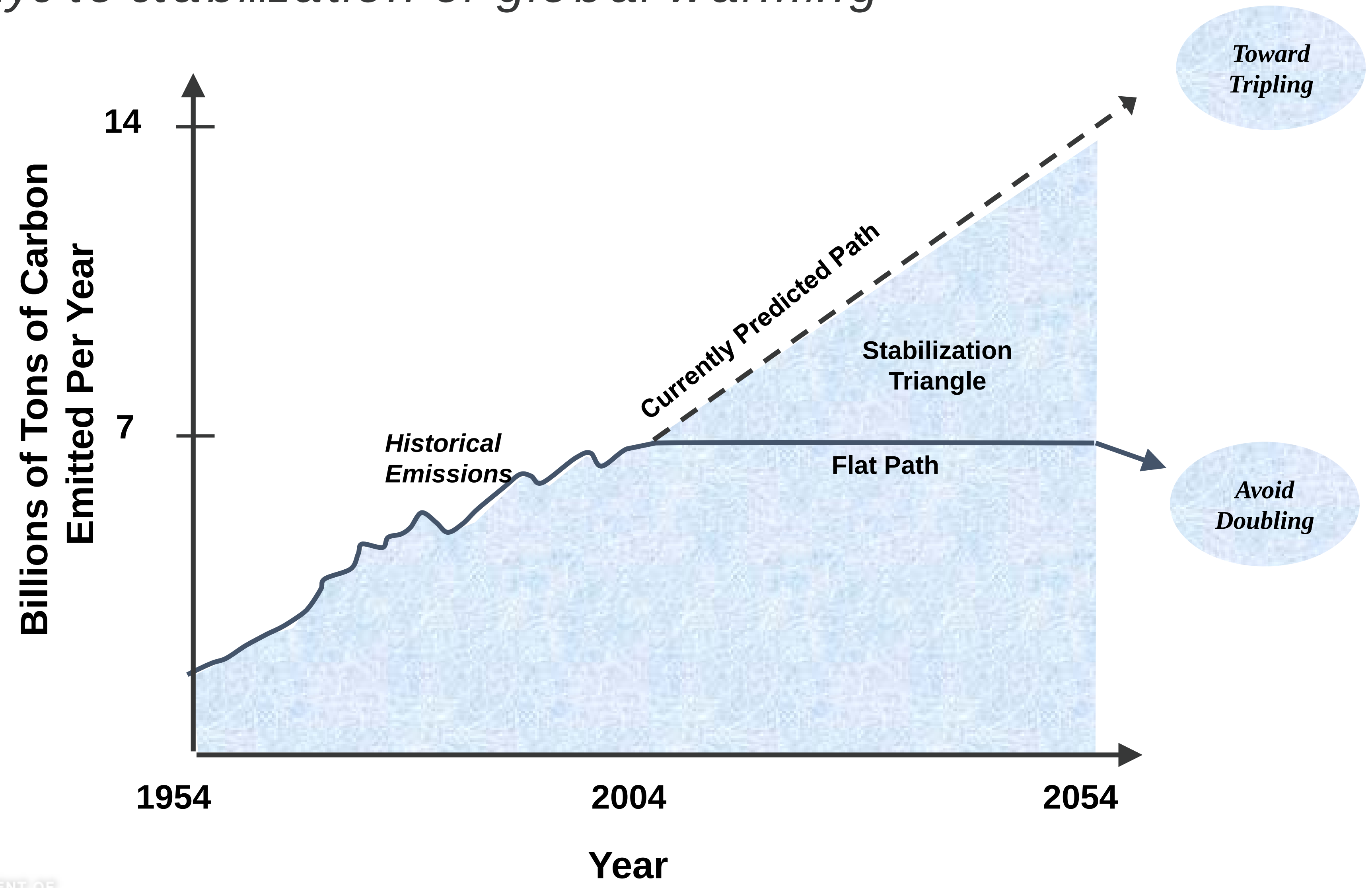
Penetration of low cost renewables



Ref: From Strategic Horizons, Renewables Costs: A Global Comparison of Wind and Solar, October 24, 2018 after IHS Markit Power, Gas, Coal & Renewables

Historical CO_2 Emissions - Potential Pathways

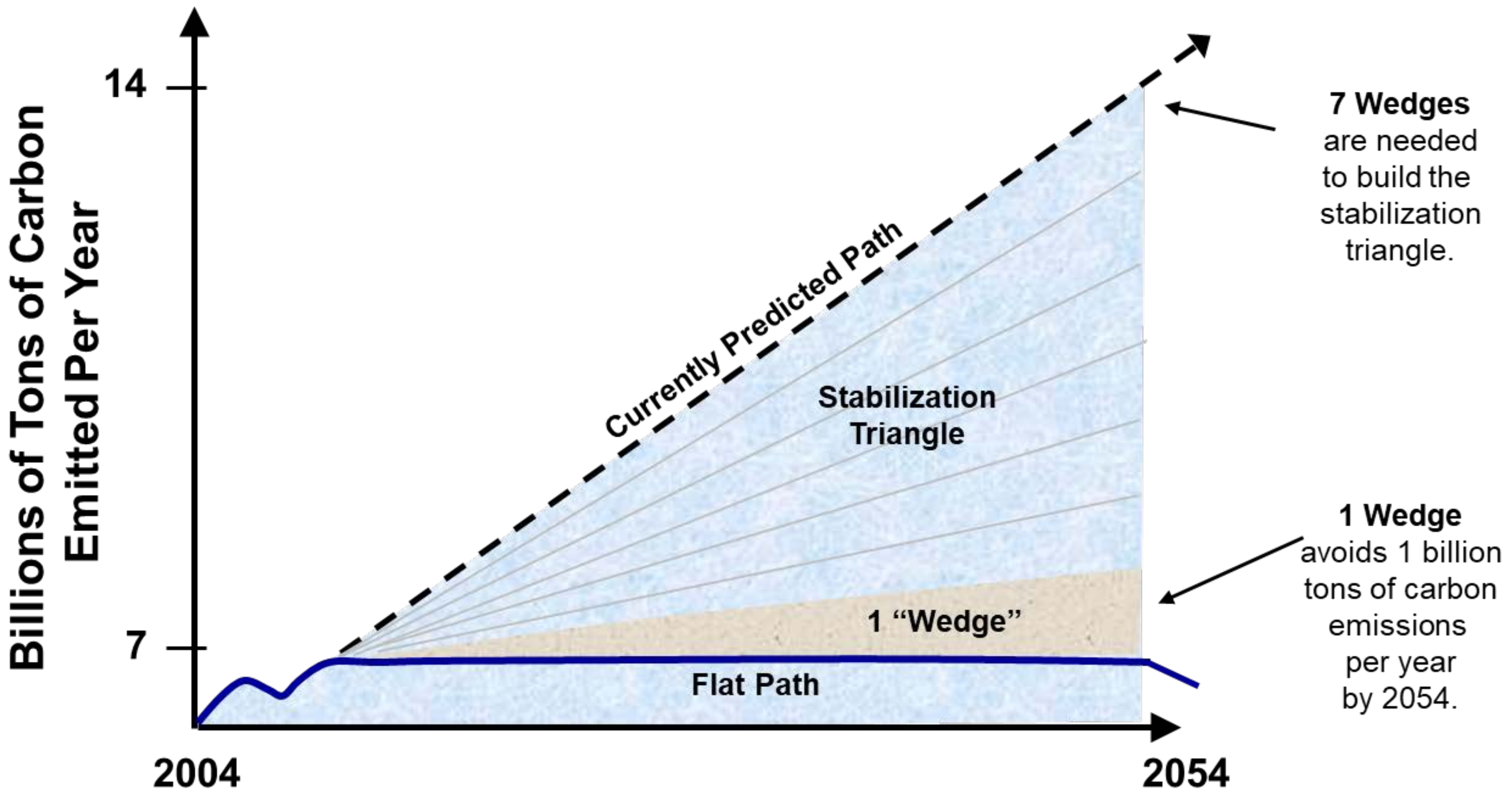
Pathways to stabilization or global warming



Source: R. Socollow, R. Hotinski, J.B. Greenblatt, and S. Pacala.

Stabilization Wedges

How big and or significant is a wedge?



Potential Stabilization Wedges

Options to reduce carbon emissions by 25 GtC over 50 yrs.(1)

Potential Wedge Option		Level of Effort
• Efficient vehicles	→	• Increase MPG from 30 to 60 for 2 billion cars
• Efficient buildings	→	• Reduce emissions by ¼ in all buildings / appliances by 2054
• Efficient base load coal plants	→	• Produce twice today's coal power at 60% vs. 40% efficiency (32 % today's average)
• Base load coal w/CCS	→	• Introduce CCS at 800 GW of coal plants (compared to 1060 GW existing coal)
• Wind power for coal	→	• Add 2 M 1-MW peak windmills (50 times current capacity)
• PV power for coal	→	• Add 2000 GW peak (700 times current capacity)

Ref (1):Pacala and Socolow, Science, Vol. 305, August 13, 2004

Summary of Observations

- **2013 - 15 surge in combustion turbine installations is over**
- **NG price forecasts indicate a slow rise**
- **Long term trend for electricity is an increase in NG and a reduction in coal**
- **Renewables continue to deploy creating new requirements for FE power systems**
  - Highly efficient modular coal plants
  - Dynamic and efficient gas turbines
  - Will energy storage be required and who will own it
- **FE AT provides technological solutions to CO_2 emission by addressing stabilization wedges**
  - Highly efficient gas turbines for coal based IGCC
  - SCO2 power systems for coal combustion
  - All compatible with FE's CO_2 capture & storage programs

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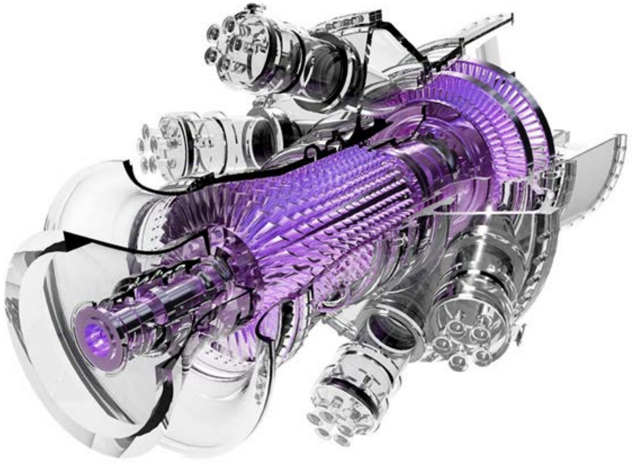
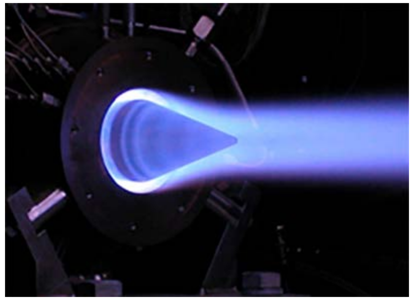
Advanced Turbines Program for US DOE FE Mission

Focused Research in Four Key Technology Areas

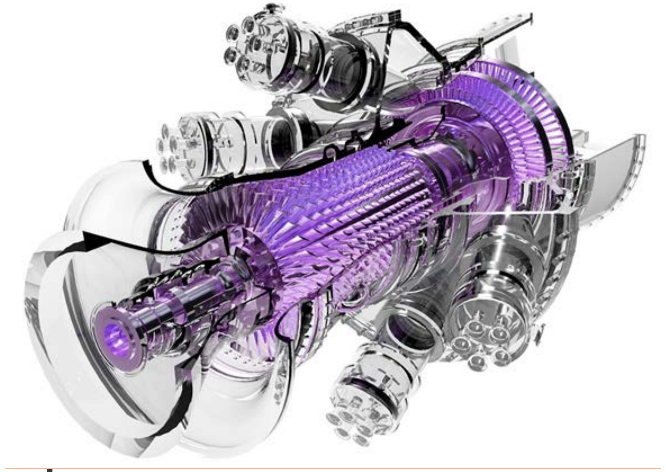
- **Adv. combustion turbines for syngas, NG and H_2 fuels (IGCC, NGCC)**
  - CC eff. ~ 65 % (LHV, NG bench mark), TIT of 3,100 ^{o}F
  - Transformational performance benefits by 2025 for coal based IGCC w/ CCS (ready for full scale demo); another $20/T reduction in CO2 capture cost
- **Pressure Gain 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</u> and <u>direct</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 Efficiency (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

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

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

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

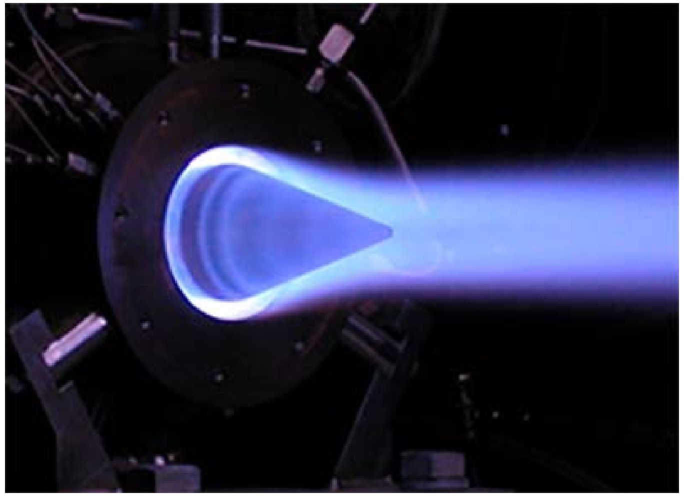
FE0023983

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

NATIONAL ENERGY TECHNOLOGY LABORATORY

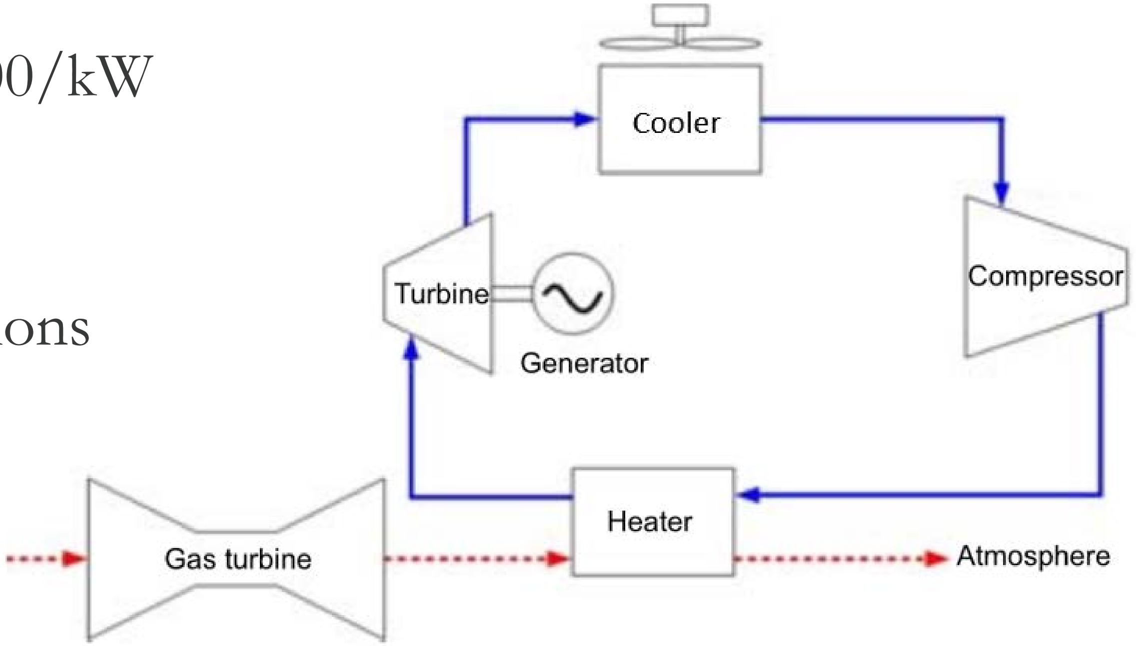
PROJECT NARRATIVE

- 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



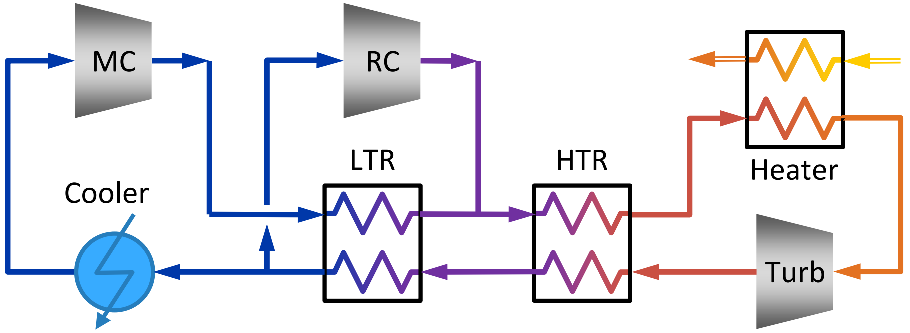
Waste Heat Recovery System

sCO_2 Power Cycles for FE Applications

Two related cycles for advanced combustion and gasification applications

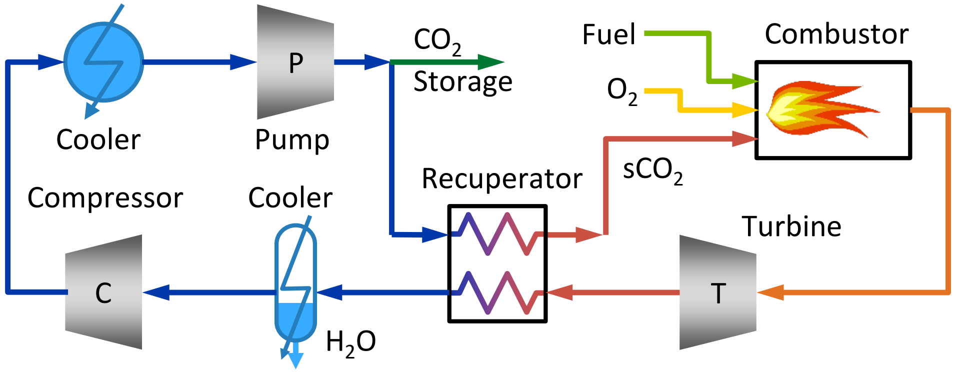
Indirectly-heated cycle (RCBC)

- 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



Projects Supporting sCO_2 Power Cycles

Component development for SCO2 turbomachinery

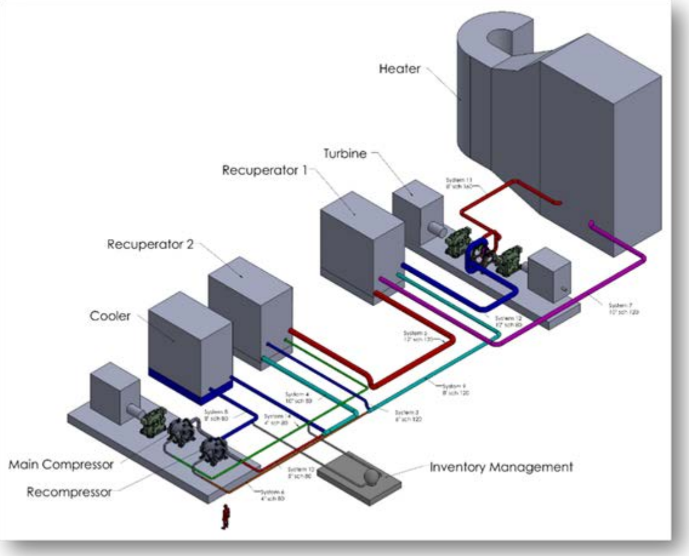
- **Two Ph. II 2016 awards nominally $6M ea., 4 yr. projects**
  - Low-Leakage Shaft End Seals for Utility-Scale sCO_2 Turbo Expanders (GE)
  - High Inlet Temp. Comb. for Direct Fired Supercritical Oxy-Combustion (SwRI)
- **One Ph 1 award, 18 mo. Ph II down select in FY20**
  - Development of Oxy-fuel 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)

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 operability of the sCO_2 power cycle
  - Verify performance of components
  - Evaluate system / component 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
  - 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

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DOE, DOD & NASA Synergies

Many synergies driven by extreme performance requirements

- **Materials**
  - CMC
  - SX
- **Advanced manufacturing**
  - New parts
  - MRO
- **Cooling requirements**
  - Facilitating high temperature
- **Power density**
  - Modular hybrid heat engines
  - Mission driven
- **Advanced designs**
  - SCO2 Power Cycles
- **Combustion**
  - PGC

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Five technical topic areas:**
  - Pressure Gain Combustion
  - Adv. Materials Develop. for Hot Gas Path Turbine Components
  - Adv. Mfg Development for Hot Gas Path Turbine Components
  - Fundamental Research for sCO2 Power Cycle Development
  - Fossil Fuel-Based Power Generation w/Large-Scale Energy Storage

- **Read the full NOI at Grants.Gov (http://www.grants.gov) or FedConnect (http://www.fedconnect.net/FedConnect).**

Conclusions & Summary

Overview of the US DOE Advanced Turbines Program

- Gas turbine deployments are declining
- Natural gas prices remain low
- Renewables affecting GT performance requirements
- AT well positioned to deal with CO2 emissions thru efficiency improvements and making CCS affordable
- DOE FE is supporting a robust program in four areas and finding synergies with DOD and NASA R&D
- New work planned in FY2019 UTSR FOA

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

- Provided on request