DOE FE Advanced Turbines Program

2017 University Turbine Systems Research Project Review Meeting

Rich Dennis
U.S. Department of Energy
National Energy Technology Laboratory

November 1, 2017

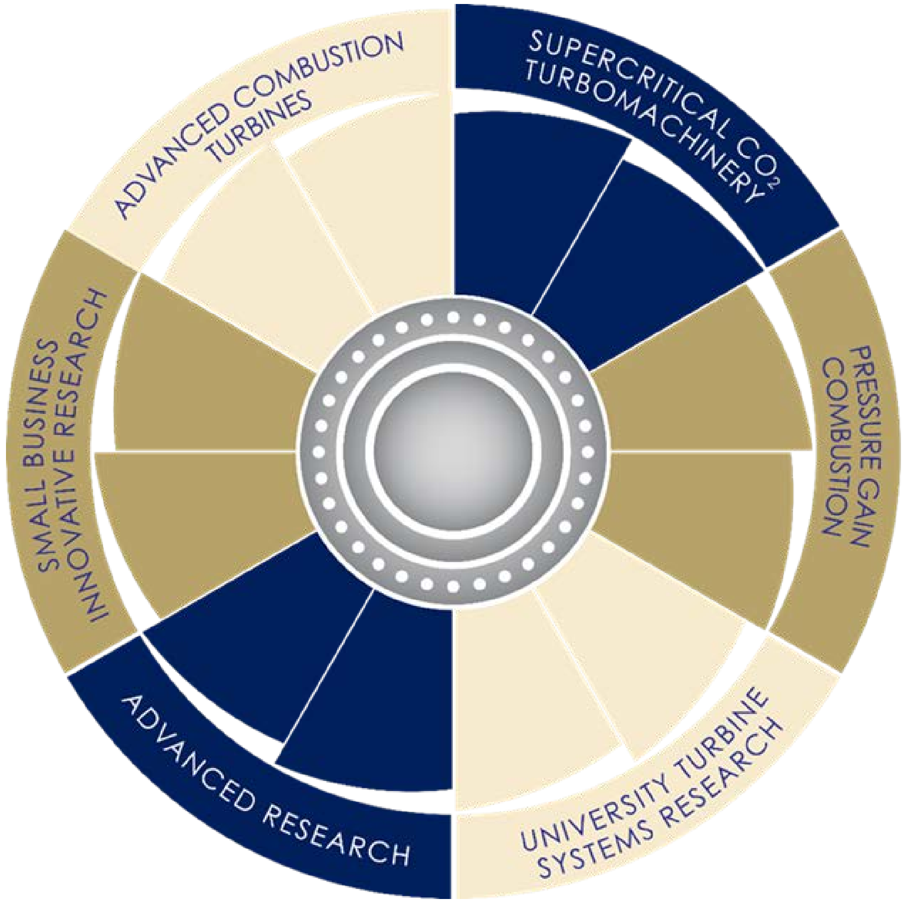
University of Pittsburgh, Pittsburgh, PA

Presentation Overview

2017 University Turbine Systems Research Project Review Meeting

NATIONAL ENERGY TECHNOLOGY LABORATORY

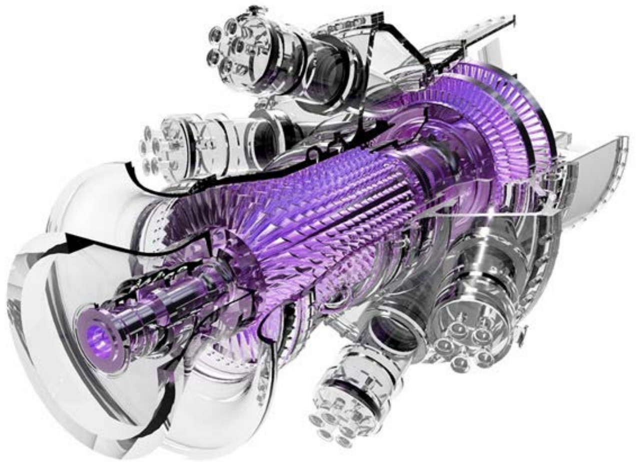
- **Program elements / goals**
- **System studies**
  - H_2 turbine at 3,100°F
  - SCO2 w/ oxy-CFB
  - SCO2 direct (coal gasification based)
- **Program project work**
  - Core projects
  - UTSR projects
  - START rig
  - NETL RIC
- **Next steps**
- **Summary**



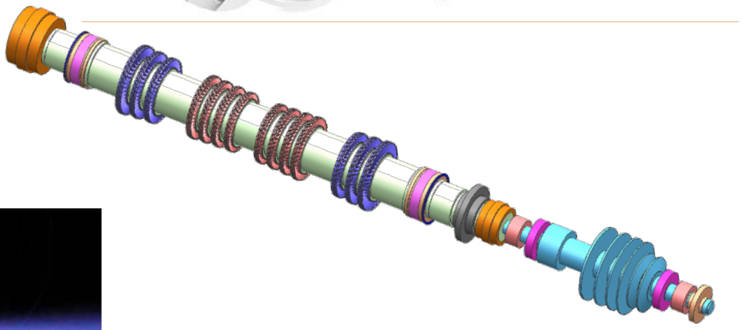
Advanced Turbines Program Elements

Research Focused in Three Key Technology Areas

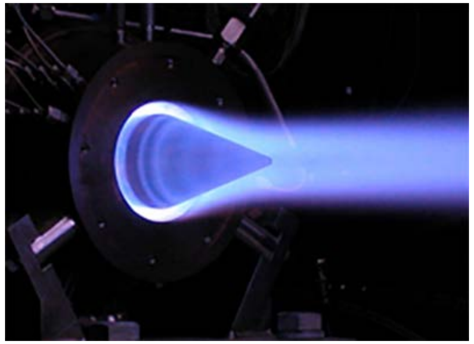
- **Advanced Combustion Turbines**
  - CC eff. ~ 65 % (LHV, NG bench mark), TIT of 3,100 F
  - Delivers transformational performance benefits by 2025



- **SCO2 Turbomachinery**
  - Recompression Brayton Cycles (Indirect) for "boilers"
  - Allam Cycles (Direct) for gasification and NG

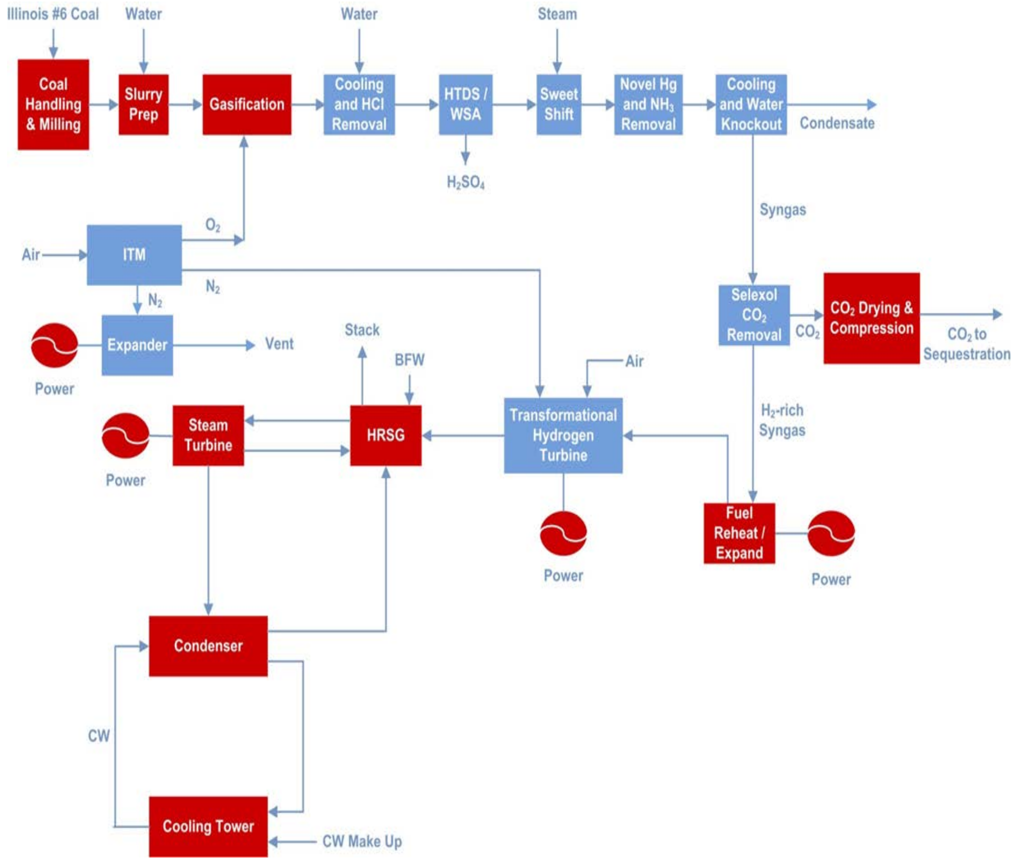


- **Pressure Gain Combustion**
  - Alternate pathway to high efficiency



H_2 Turbines - Performance and Cost Comparisons

Reference, Advanced H2 Turbine, and Transformation H2 Turbine "All-in" Cases



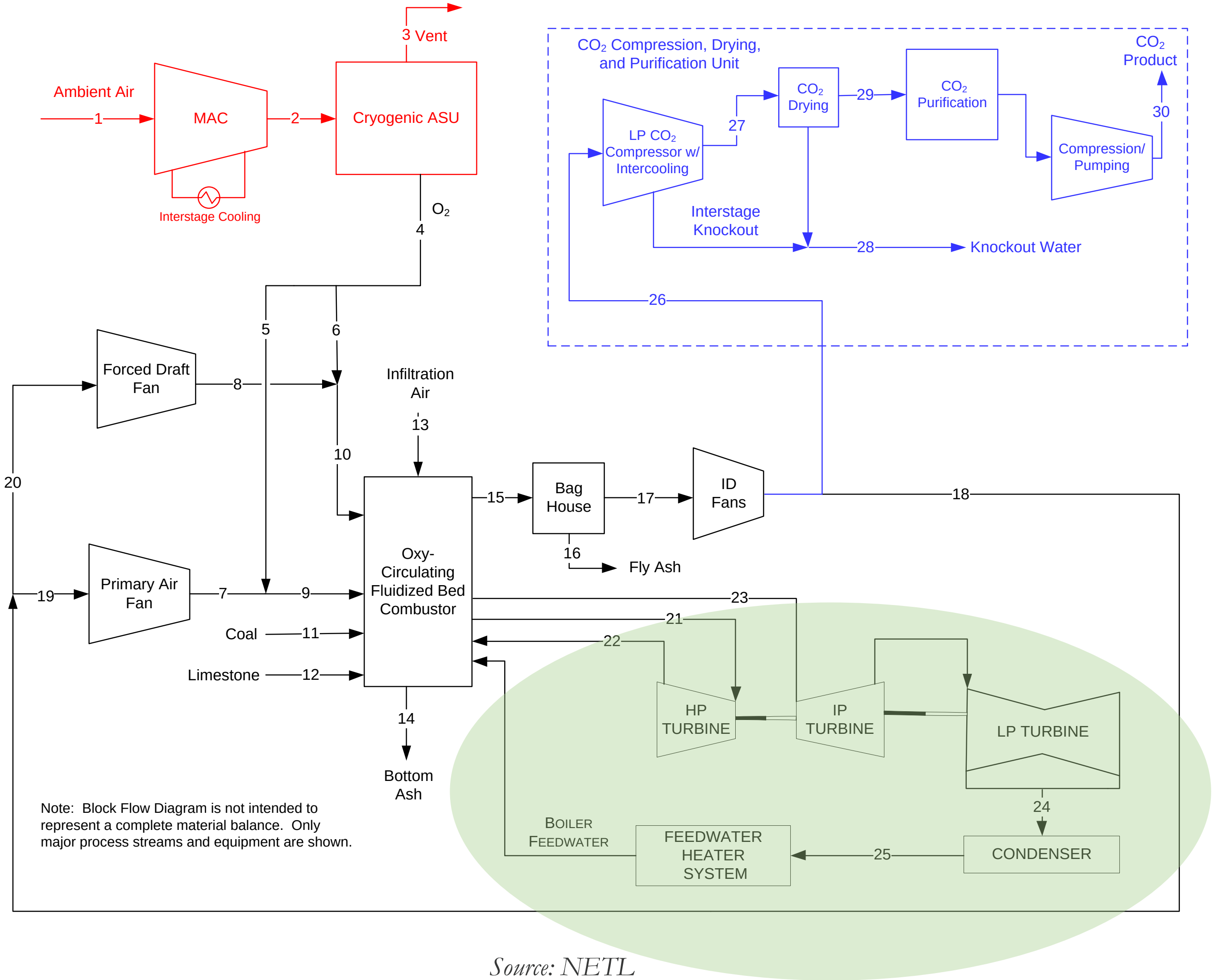
Parameter	"F" Turbine (reference)	AHT (2650 F)	THT (3100 F)
H_2 Turbine (MW)	464	680	940
Fuel Gas Expander (MW)	7	3	7
Air Expander (MW)	n/a	14	39
Steam Turbine (MW)	248	392	485
Gross Power (MW)	719	1,090	1,471
Auxiliary Power (MW)	-186	-262	-338
Net Power (MW)	533	828	1,133
Coal Feed (lb/hr)	481,783	635,089	816,118
Plant Efficiency (%)	32.4	38.1	40.6
COE ($/MWh)*	134.5	104.1	92.7

* w/o T&S

Oxy-CFB Coal-fired Rankine Cycle Power Plant

Steam Rankine Comparison Cases

- **LP Cryogenic ASU**
  - 99.5% O_2
  - 3.1% excess O_2 to CFB
- **Atmospheric oxy-CFB**
  - Bituminous coal
  - 99% carbon conversion
  - In-bed sulfur capture (94%), 140% excess $CaCO_3$
  - Infiltration air 2% of air to ASU MAC
- **Operating conditions for Rankine plants**
  - Supercritical (SC) Rankine cycle
    (Case B22F: 24.2 MPa/ 600 °C/ 600 °C)
  - Advanced ultra-supercritical (AUSC) Rankine cycle
    (Case B24F: 24.2 MPa/ 760 °C / 760 °C)
- **No low temperature flue gas heat recovery**
- **45% flue gas recycle to CFB**
- **CO_2 purification unit**
  - ~100% CO_2 purity
  - 96% carbon recovery

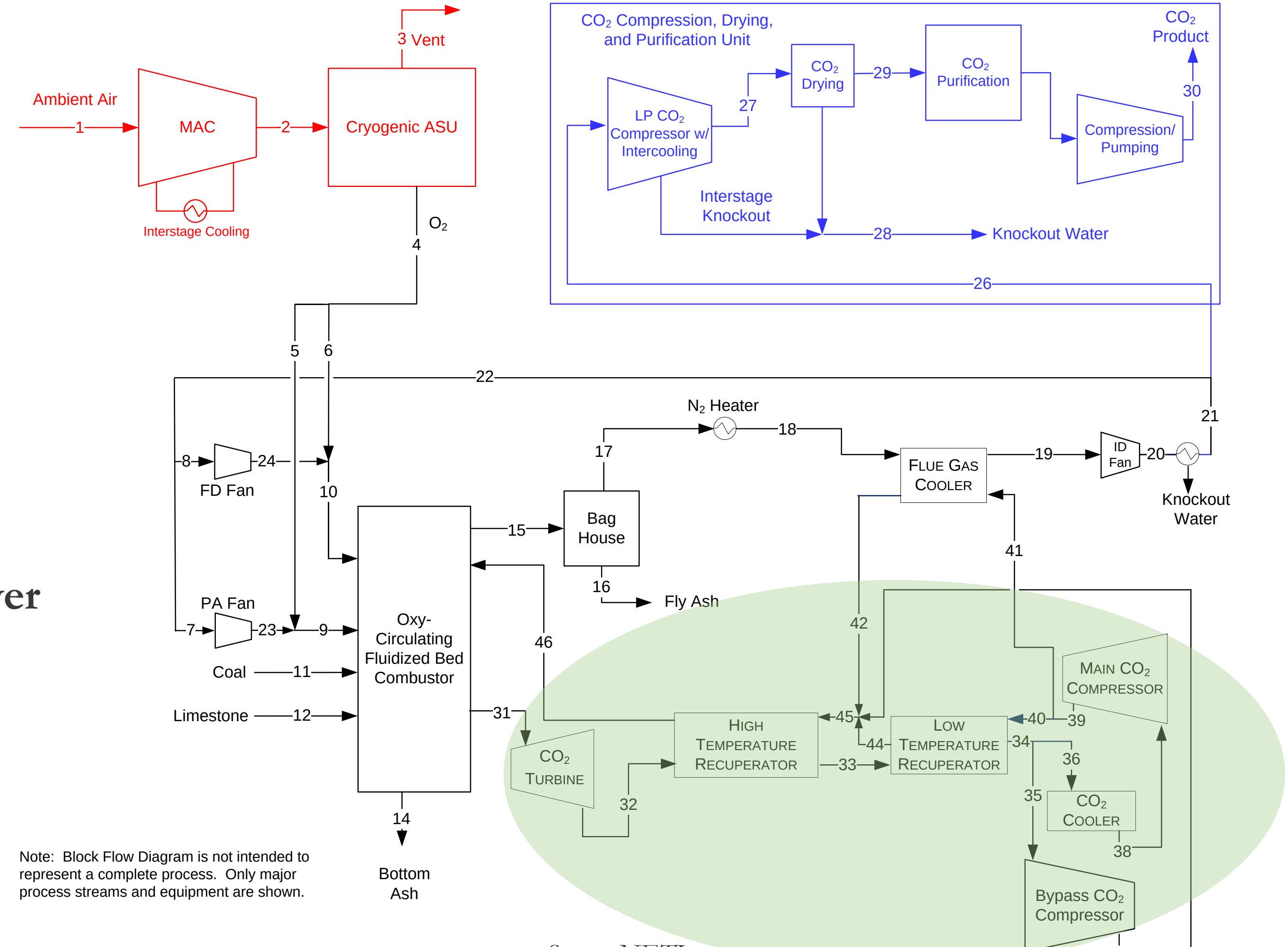


Source: NETL

Oxy-CFB Coal-fired Indirect sCO_2 Power Plant

Baseline sCO_2 process

- **LP Cryogenic ASU**
  - 99.5% O_2
  - 3.1% excess O_2 to CFB
- **Atmospheric oxy-CFB**
  - Bituminous coal
  - 99% carbon conversion
  - In-bed sulfur capture (94%), 140% excess $CaCO_3$
  - Infiltration air 2% of air to ASU MAC
- **Recompression sCO_2 Brayton cycle**
  - Turbine inlet temperature 620 °C and
  - Turbine inlet temperature 760 °C
- **Low temperature flue gas heat recovery in sCO_2 power cycle**
- **45% flue gas recycle to CFB**
- **CO_2 purification unit**
  - ~100% CO_2 purity
  - 96% carbon recovery

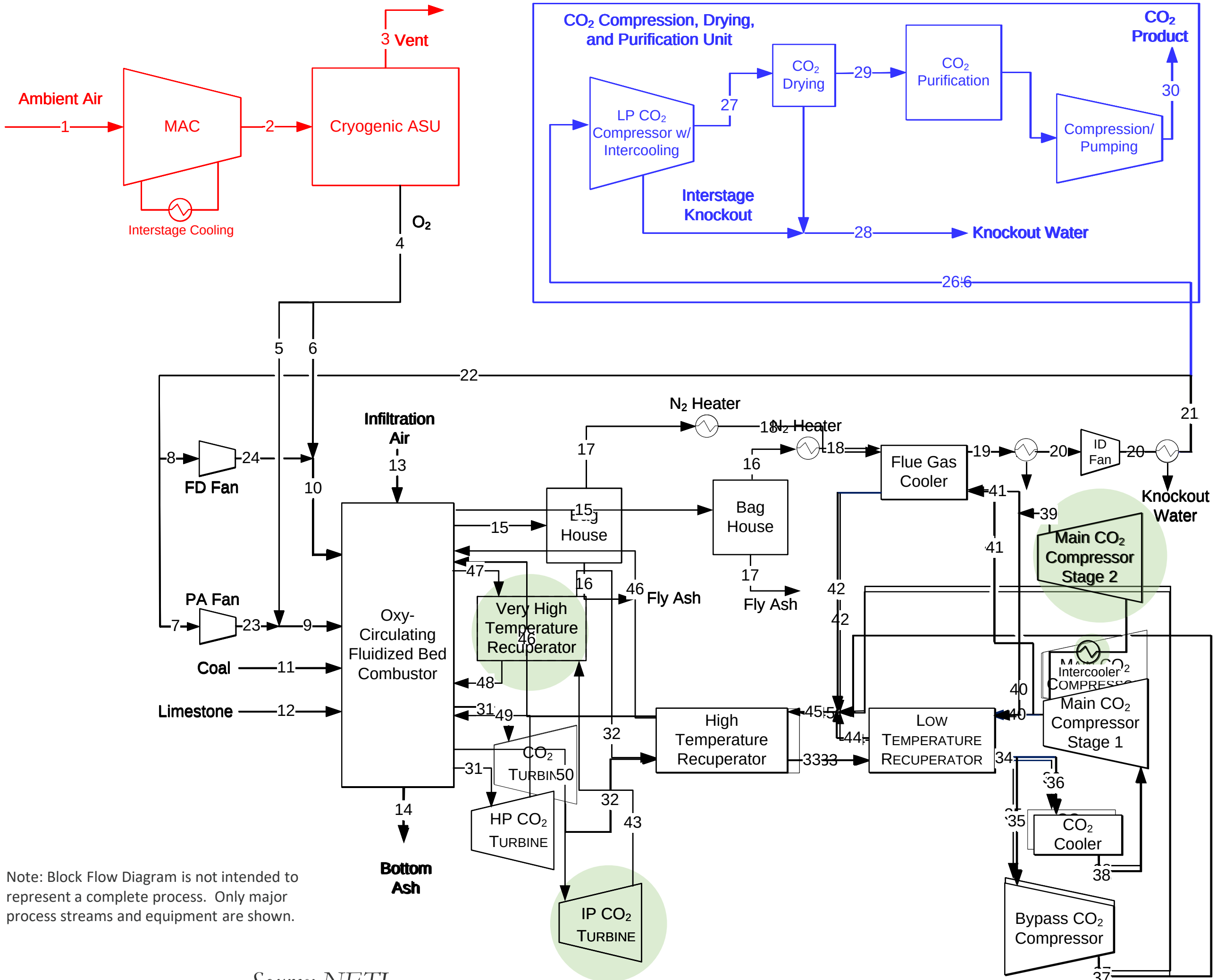


Source: NETL

Oxy-CFB Coal-fired Indirect sCO_2 Power Plant

Four sCO_2 cycle configurations analyzed

- Baseline configuration
- Reheat sCO_2 turbine
- Intercooled 2-stage main sCO_2 compressor
- Reheat sCO_2 turbine and Intercooled main sCO_2 compressor

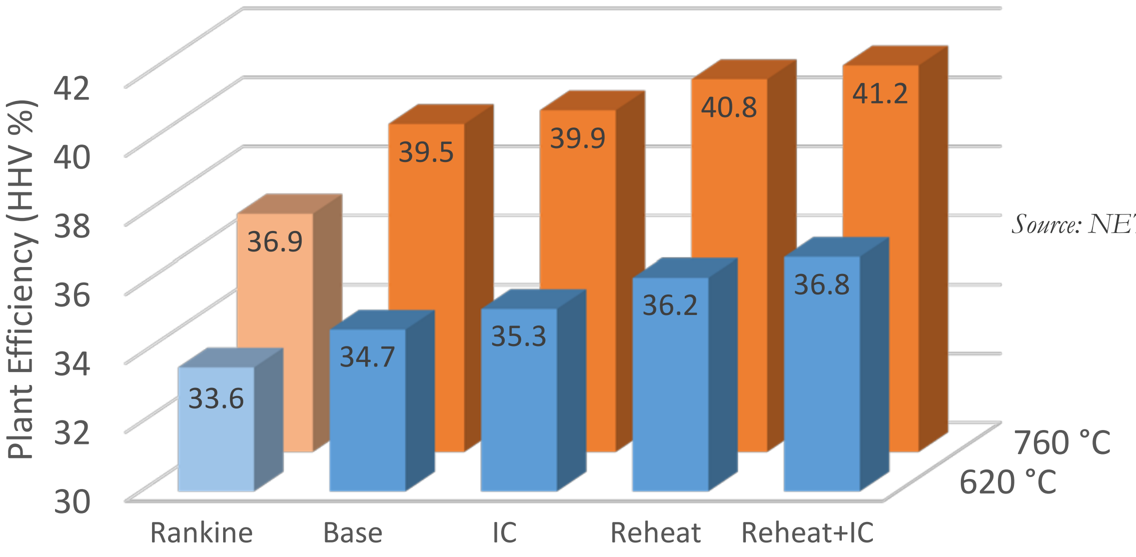


Note: Block Flow Diagram is not intended to represent a complete process. Only major process streams and equipment are shown.

Source: NETL

Summary of Overall Plant HHV Efficiencies

- **Relative to the steam Rankine cycles:**
  - At 620 °C, sCO_2 cycles are 1.1 – 3.2 percentage points higher in efficiency
  - At 760 °C, sCO_2 cycles are 2.6 – 4.3 percentage points higher
- **The addition of reheat improves sCO_2 cycle efficiency by 1.3 – 1.5 percentage points**
- **The addition of main compressor intercooling improves efficiency by 0.4 – 0.6 percentage points**
  - Main compressor intercooling reduces compressor power requirements for *both* the main and bypass compressors



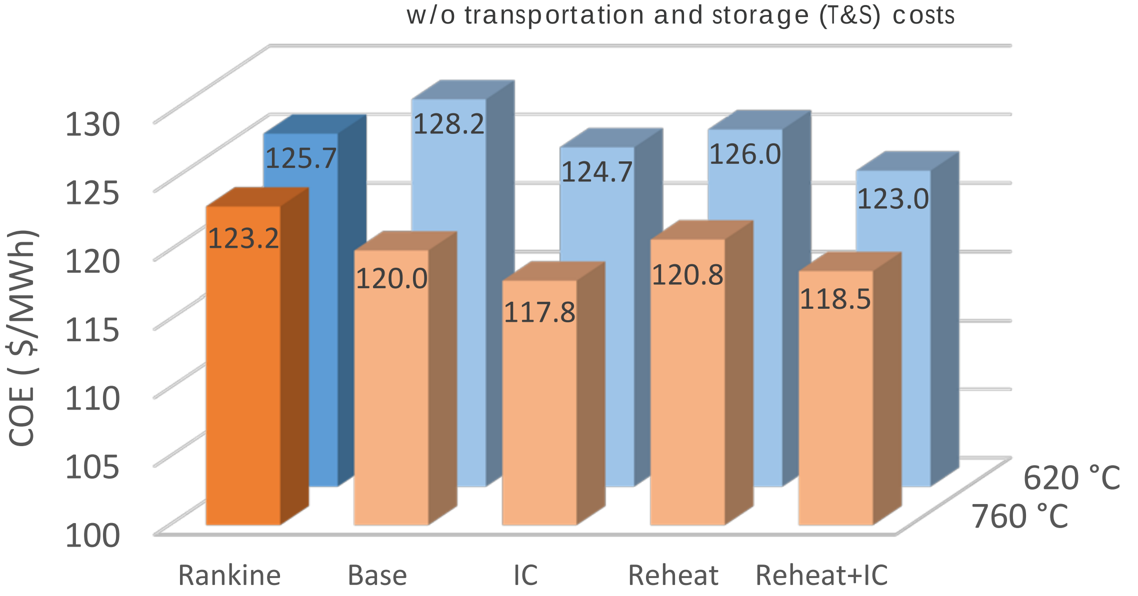
Source: NETL

Power Summary (MW)	B22F	Base	IC	Reheat	Reheat+IC
Coal Thermal Input	1,635	1,586	1,557	1,519	1,494
sCO_2 Turbine Power	721	1,006	933	980	913
CO_2 Main Compressor		160	154	148	142
CO_2 Bypass Compressor		124	60	117	58
Net sCO_2 Cycle Power	721	711	708	704	702
Air Separation Unit	85	83	81	79	78
Carbon Purification Unit	60	56	55	54	53
Total Auxiliaries, MWe	171	161	158	154	152
Net Power, MWe	550	550	550	550	550

Summary of COE

Steam Rankine vs. sCO_2 Cases

- **Note that there is significant uncertainty in the CFB and sCO_2 component capital costs (-15% to +50%)**
- **Large capital cost uncertainties being addressed in projects funded by NETL, EPRI and OEM(s):**
  - sCO_2 turbine (GE, Doosan, Siemens)
  - Recuperators (Thar Energy, Brayton Energy, Altex)
  - Primary heat exchanger (B&W, GE)
- **sCO_2 cases have comparable COE to steam Rankine plant at 620 °C, and lower COE for 760 °C cases**



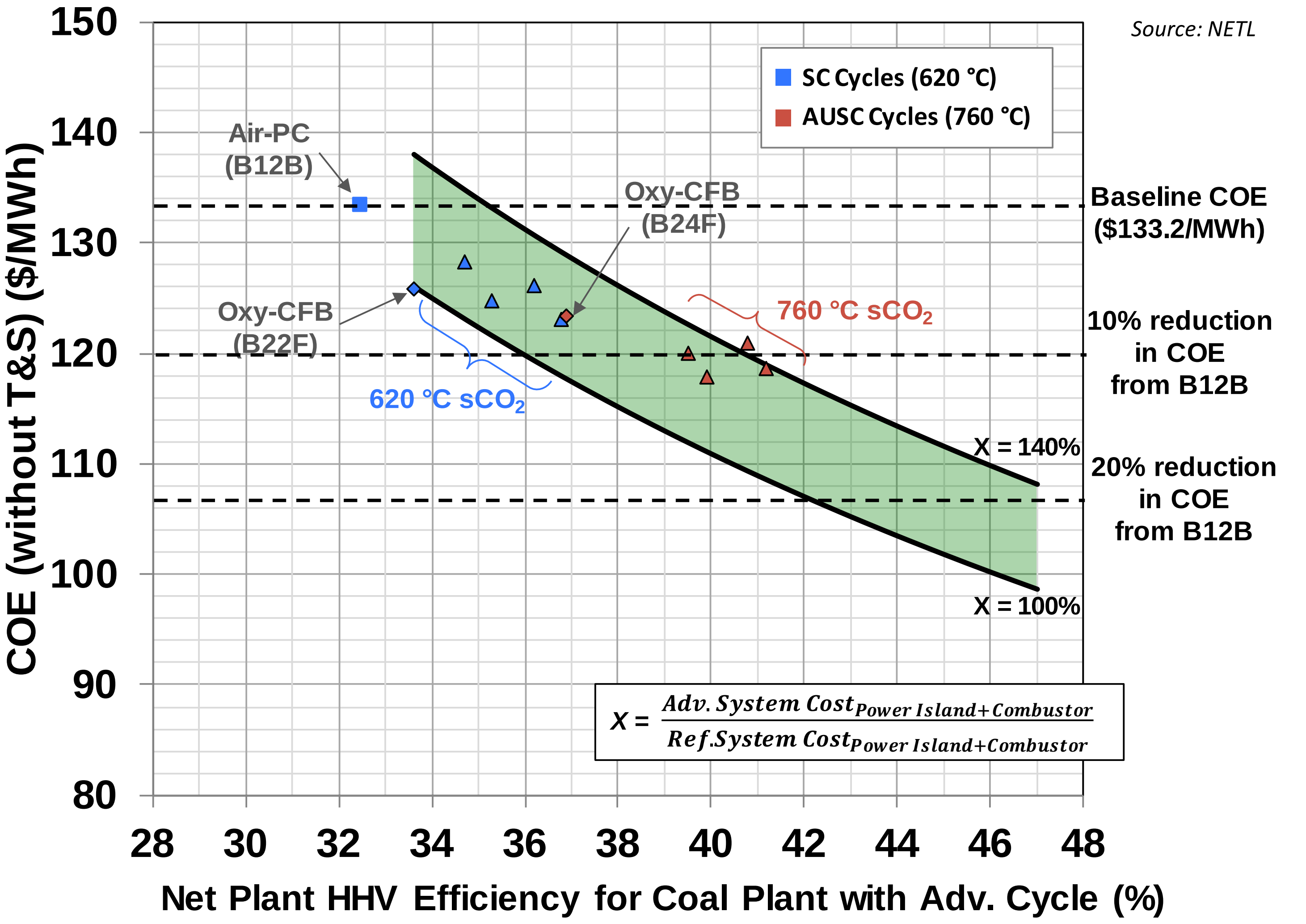
Source: NETL

- **Main compressor intercooling improves COE 2.2 – 3.5 $/MWh**
  - Low cost means of reducing sCO_2 cycle mass flow
- **Reheat reduces the COE for the 620 °C cases, but increases COE for turbine inlet temperatures of 760 °C**
  - Due to the high cost of materials for the reheat portions of the cycle in 760 °C cases

Comparison of sCO_2 versus Rankine Cases

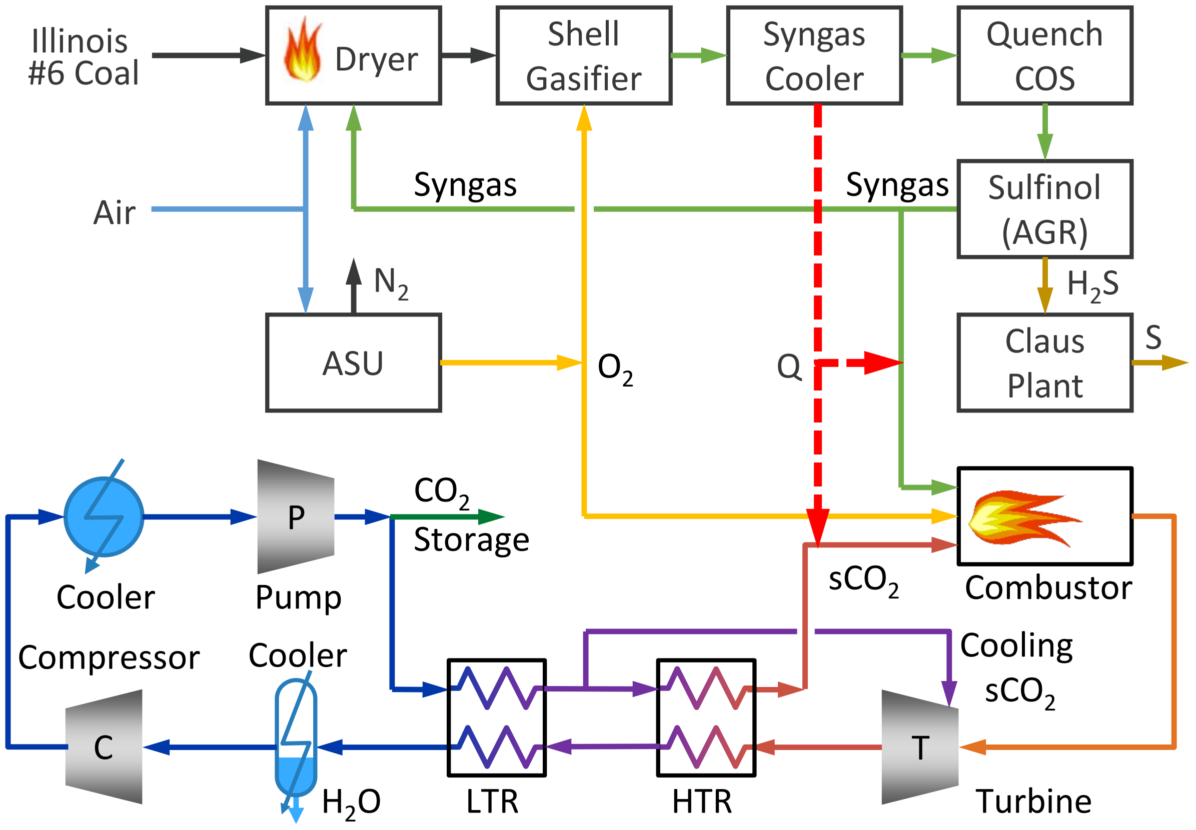
COE vs. Process Efficiency Analysis, with CCS

- Reference: Supercritical Oxy-combustion CFB with Auto-refrigerated CPU (Case B22F)
  - $0/tonne CO_2 Revenue
  - 550 MWe
- COE reductions are relative to an air fired, supercritical PC coal plant with CCS (B12B)
- Higher efficiency and lower COE for sCO_2 cycles relative to steam
  - Large uncertainty in commercial scale sCO_2 component costs
- Further improvements to the sCO_2 cycle are currently under investigation



Analysis of Integrated Gasification Direct-Fired sCO_2 Power Cycle

- **<u>NETL Study Objective</u>: Develop a performance and cost baseline for a syngas-fired direct sCO_2 cycle**
- **Gasification-direct sCO_2 plant design:**
  - Low pressure cryogenic Air Separation Unit (ASU) with 99.5% oxygen purity [3]
  - Down-selected to commercial Shell gasifier with standard AGR technology
    - Dry-fed gasifier with high cold gas efficiency
  - CO_2 purification unit (CPU) used to meet CO_2 pipeline purity specifications
  - sCO_2 turbine cooling flows included [4]
  - Condensing sCO_2 cycle operation (CIT = 27 °C)
  - Thermal integration between sCO_2 cycle, gasifier, and Balance of Plant (BOP)
    - Preheats syngas and sCO_2 prior to combustion
    - Includes process steam plant for BOP thermal duties



Source: NETL

sCO_2 and IGCC Economic Comparison

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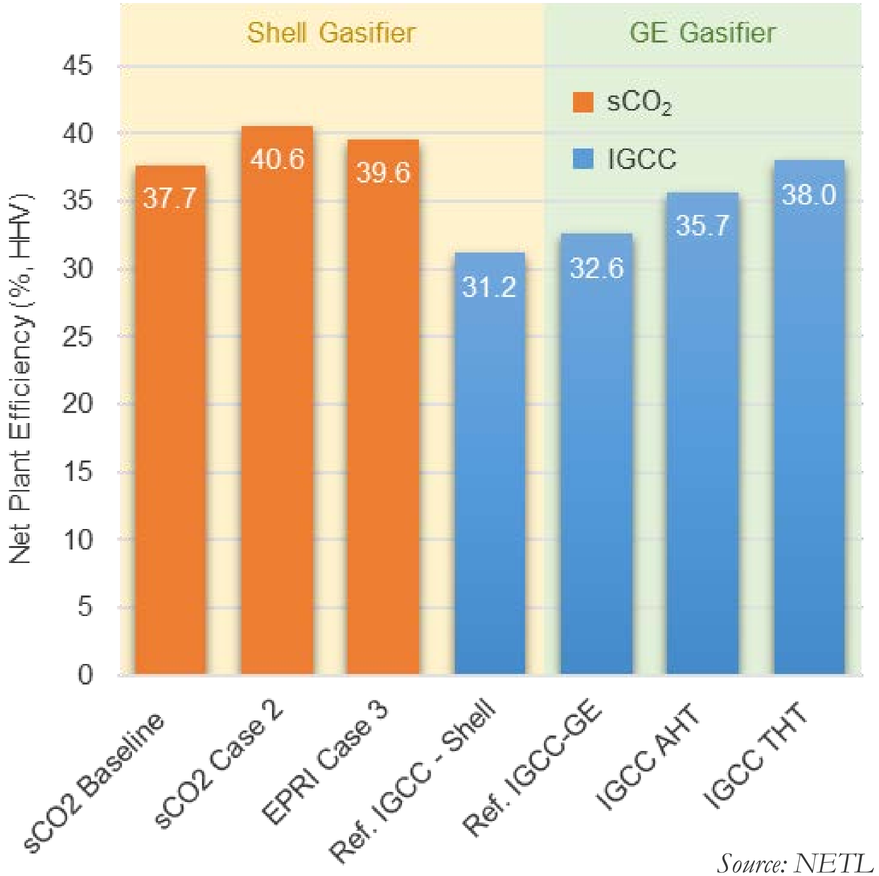
- **sCO_2 Total Plant Costs are similar relative to reference IGCC plant:**
  - Higher syngas cooler and ASU costs
  - Lower gas cleanup and CO_2 storage compression costs
  - Comparable Power cycle + HRSG + Steam Plant costs
- **Case 2 TPC is 5% lower than the Baseline sCO_2 Case**
  - Syngas cooler cost reduced by eliminating HT sCO_2 preheating
  - sCO_2 cycle cost increases with CO_2 flow rate, recuperator duty, and increased power output
- **sCO_2 plants have lower COE than IGCC plant**
  - TPC better on a $/MW basis
  - sCO_2 Baseline COE is 10% lower than IGCC plant, Case 2 is 20% lower
  - Case 2 has 11% lower COE compared to Baseline sCO_2 plant, due to lower TPC and increased efficiency

Parameter	IGCC [5]	sCO_2 Baseline	sCO_2 Case 2
Capital Costs (TPC, $1,000)			
Coal Handling System	43,156	41,775	41,775
Coal Prep and Feed	218,724	199,571	199,571
Feedwater & Miscellaneous BOP	65,849	21,252	21,363
Gasifier and Accessories	429,678	667,292	540,793
Cryogenic ASU	251,490	346,824	348,623
Gas Cleanup & Piping	323,580	160,519	160,528
CO_2 Compression & Storage	81,688	60,601	61,460
sCO_2 Cycle/Comb. Turbine & Acc.	160,049	261,793	290,387
HRSG Ductwork & Stack	56,527	0	0
Steam Plant	85,322	34,428	29,214
Cooling Water System	39,217	39,523	39,332
Balance of Plant	222,322	226,634	230,227
Total Plant Cost (TPC)	**1,977,603**	**2,060,211**	**1,963,273**
Operating & Maintenance Costs ($1,000/yr)			
Fixed O&M	71,389	76,877	73,508
Variable O&M	45,146	45,479	43,573
Fuel	111,740	104,867	104,867
COE (w/o T&S) (2011$/MWh)	**152.6**	**137.3**	**122.7**

Comparison with Other Gasification Studies

Plant Design and Performance Comparison

- **Thermal integration in Case 2 improves thermal efficiency by 2.9 percentage points relative to Baseline sCO_2 case**
- **Both cases compare favorably to the EPRI sCO_2 study, which does not include turbine blade cooling or combustor pressure drops [3]**
- **sCO_2 cases deliver higher efficiency than IGCC cases with a gas turbine + steam combined cycle power island**
    - Change to GE gasifier may improve efficiency [5]
    - Optimized sCO_2 outperforms advanced (AHT) and transformational hydrogen turbine (THT) cases from the IGCC Pathway Study [8]
        - Turbine only comparison, with GE gasifier

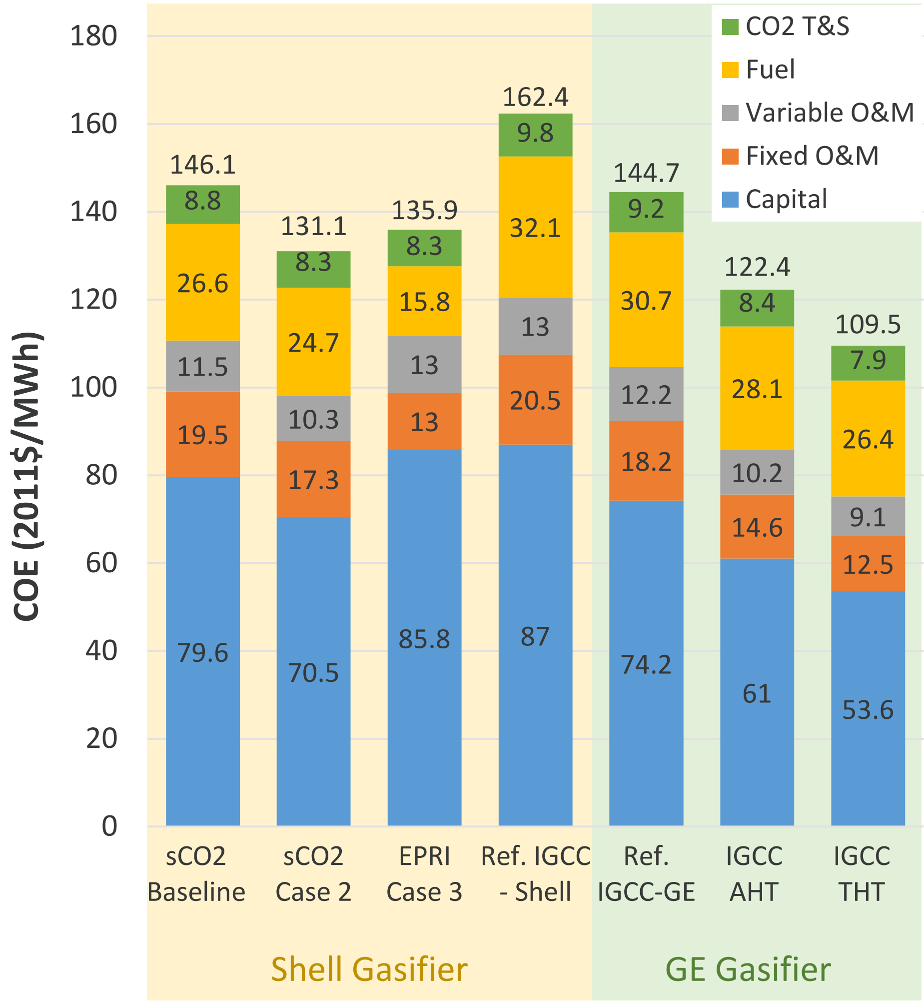


Source: NETL

Comparison with Other Gasification Studies

Economic Analysis Results – COE

- The COE for the sCO_2 plant is 11-20% lower than the COE for the reference IGCC plant
- Decrease in COE is primarily due to the higher efficiency of the sCO_2 plant
- Comparable COE to EPRI study, though this uses lower cost PRB coal [3]
- IGCC AHT and THT cases based on a GE gasifier with a radiant syngas cooler [8]
  - TPC 15% lower than Shell gasifier [5]
  - COE $17.2/MWh lower (-11.3%)



Source: NETL

Core projects of the AT program

Component development for combustion turbines and SCO2 turbomachinery

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- **Phase II 2016 awards 6 projects supporting 3100 F TIT and SCO2 turbomachinery**
  - **GE - Low-Leakage Shaft End Seals for Utility-Scale sCO_2 Turbo Expanders**
  - **SwRI - High Inlet Temperature Comb. for Direct Fired Supercritical Oxy-Combustion**
  - **Aerojet Rocketdyne – RDC for GT and System Synthesis to Exceed 65% Eff.**
  - **GE - High Temperature Ceramic Matrix Composite (CMC) Nozzles for 65% Efficiency**
  - **Siemens – Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle**
  - **GE – Advanced Multi-Tube Mixer Combustion for 65% Efficiency**

UTSR Project Portfolio

Existing / Active Projects

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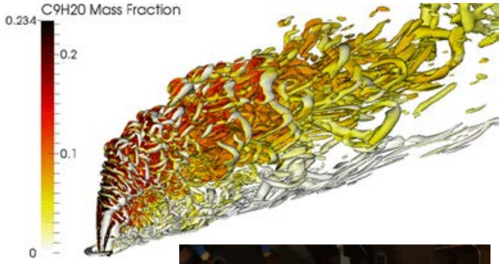
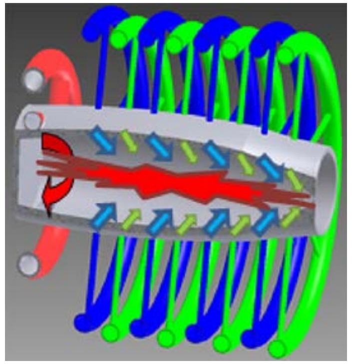
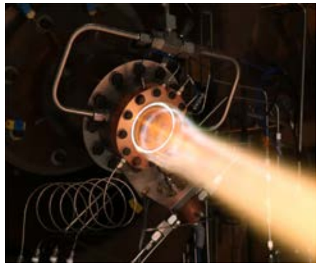
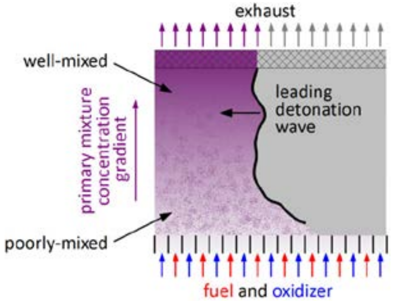
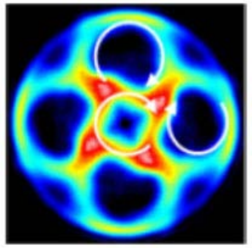
Microstructure Sensitive Crystal Viscoplasticity for Ni-Base Superalloys	Georgia Tech
Evaluation of Flow and Heat Transfer Inside Lean Pre-Mixed Combustor Systems Under Reacting Flow Conditions	Virginia Tech
High-Pressure Turbulent Flame Speeds and Chemical Kinetics of Syngas Blends with and without Impurities	Texas A&M
New Mechanistic Models of Creep-Fatigue Interactions for Gas Turbine Components	Purdue University
Effects of Exhaust Gas Recirculation (EGR) on Turbulent Combustion and Emissions in Advanced Gas Turbine Combustors with High-Hydrogen-Content (HHC) Fuels	Purdue University
Thermally Effective and Efficient Cooling Technologies for Advanced Gas Turbines	U. North Dakota
Abradable Sealing Materials for Emerging IGCC-Based Turbine System	U. California, Irvine
An Experimental and Modeling Study of NOX-CO Formation in High Hydrogen Content Fuels Combustion in Gas Turbine Applications	U. South Carolina
Predictive Large Eddy Simulation Modeling and Validation of Turbulent Flames and Flashback in Hydrogen Enriched Gas Turbines	U. Texas at Austin
Investigation of Autoignition and Combustion Stability of High Pressure Supercritical Carbon Dioxide Oxycombustion	Georgia Tech
Chemical Kinetic Modeling Development and Validation Experiments for Direct Fired Supercritical Carbon Dioxide Combustor	U. Central Florida
A Joint Experimental/Computational Study of Non-Idealities in Practical Rotating Detonation Engines	U. Michigan
Revolutionizing Turbine Cooling with Micro-Architectures Enabled by Direct Metal Laser Sintering	Ohio State
Advancing Pressure Gain Combustion in Terrestrial Turbine Systems	Purdue University
High Temperature, Low NOX Combustor Concept Development	Georgia Tech
Understanding Transient Combustion Phenomena in Low-NOx Gas Turbines	Penn State
Effect of Mixture Concentration Inhomogeneity on Detonation Properties in Pressure Gain Combustion	Penn State
Design, Fabrication and Performance Characterization of Near-Surface Embedded Cooling Channels (NSECC) with an Oxide Dispersion Strengthened (ODS) Coating Layer	U. Pittsburgh

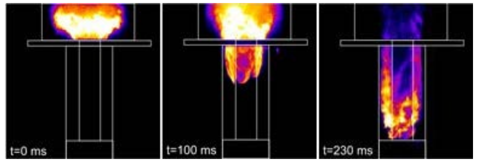


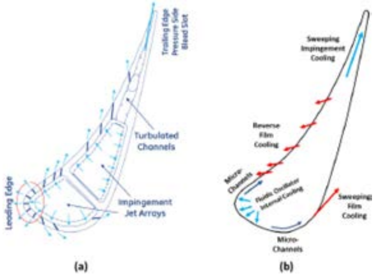












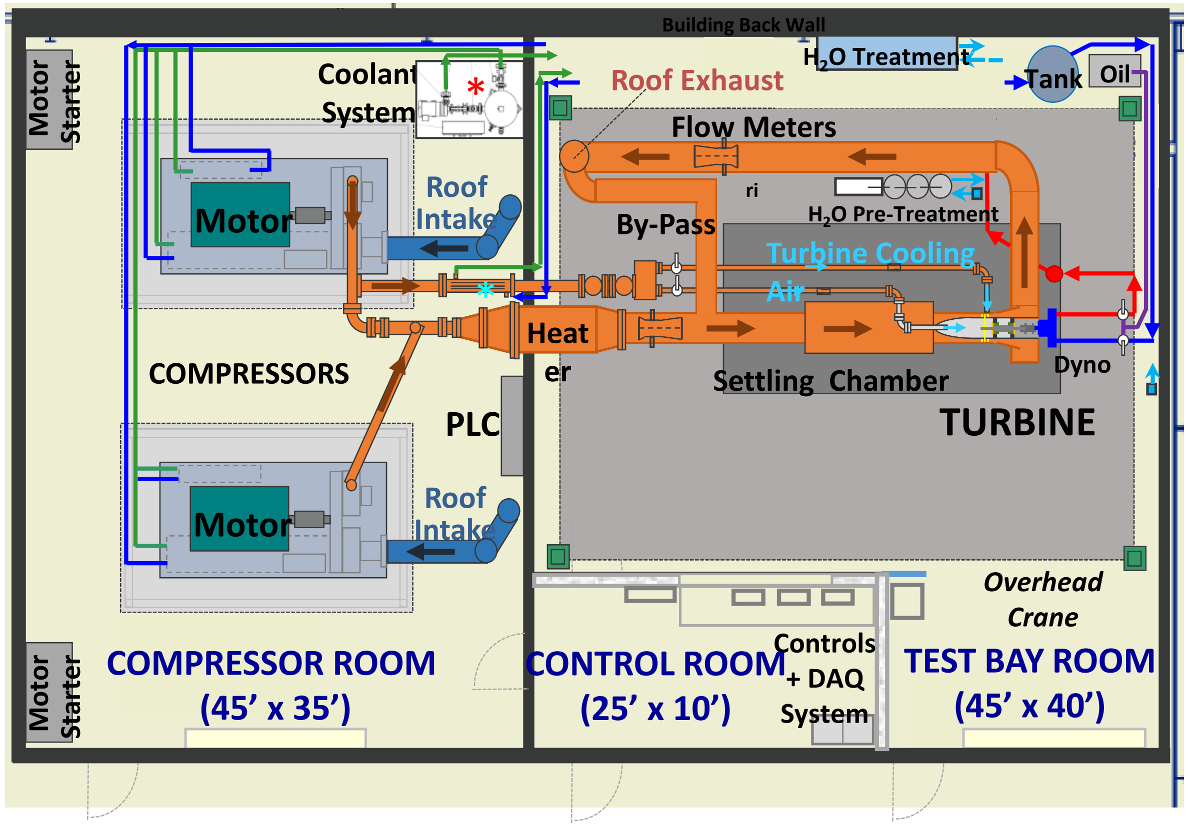
UTSR Project Portfolio

New 2017 UTSR Awards

Discrete Element Roughness Modeling For Design Optimization Of Additively And Conventionally Manufactured Internal Turbine Cooling Passages	PSU
High-Frequency Transverse Combustion Instabilities In Low-Nox Gas Turbines	GA Tech
Real-Time Health Monitoring For GT Components Using Online Learning And High Dimensional Data	GA Tech
Improving NOx Entitlement with Axial Staging	Embry-Riddle
Integrated Transpiration and Lattice Cooling Systems Developed by Additive Manufacturing with Oxide-Dispersion-Strengthened Alloys	U of Pitt
Integrated TBC/EBC for SiC Fiber Reinforced SiC Matrix Composites for Next-Generation Gas Turbines	Clemson
Development of High Performance Ni-Base Alloys for Gas Turbine Wheels using a Coprecipitation Approach	OSU
Optical Monitoring of Operating GT Blade Coatings Under Extreme Environments	UCF
Fuel Injection Dynamics and Composition Effects on RDE Performance	Michigan

Steady Thermal Aero Research Turbine (START) Facility

Government, Industry, and Academia Collaboration



- Collaboration between DOE/NETL, Penn State, and Pratt & Whitney
- Working with NASA, DOD, OEMs
- One of the world's leading gas turbine test facilities for aerodynamics and heat transfer

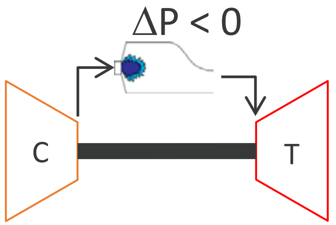
NETL RIC Advanced Turbines Research

Goal – Develop technology toward achieving the program goal of 3-5% points increase in efficiency.

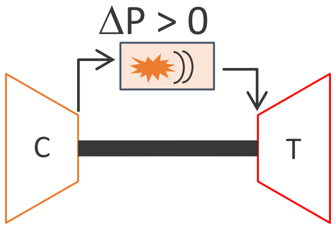
Approach – Perform R&D in three important areas: Combustion, Heat Transfer and Advanced Cycles. Perform systems analyses to support research focus and verify performance targets.

*Pressure Gain Combustion**

Improving efficiency through pressure increase across combustor.



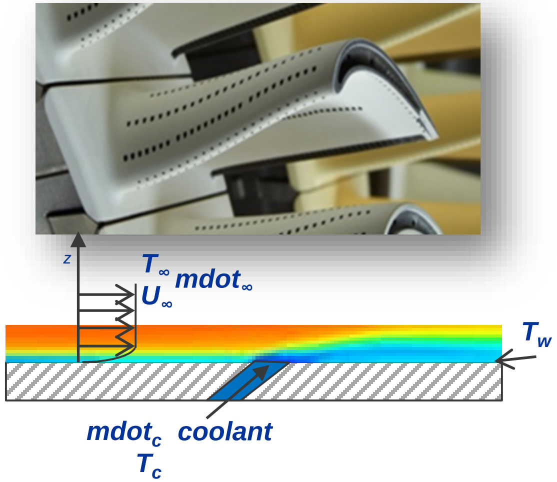
Conventional "**Constant Pressure** " Combustion has pressure loss across combustor



"**Constant Volume**" Combustion incorporates a Pressure Gain with combustion

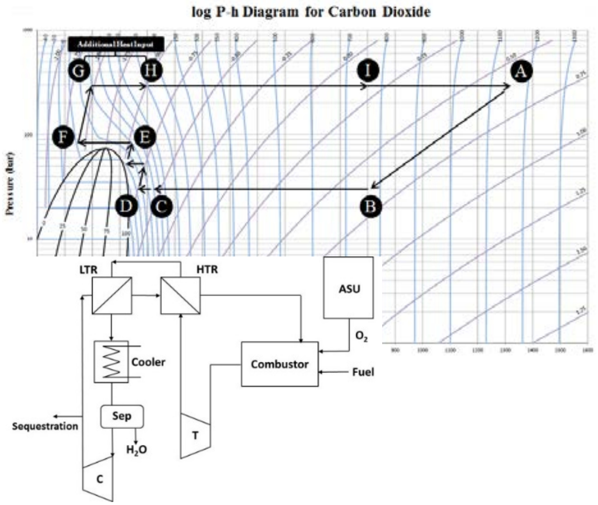
Aerothermal and Heat Transfer

Improving efficiency by increasing firing temperature and reducing cooling load.



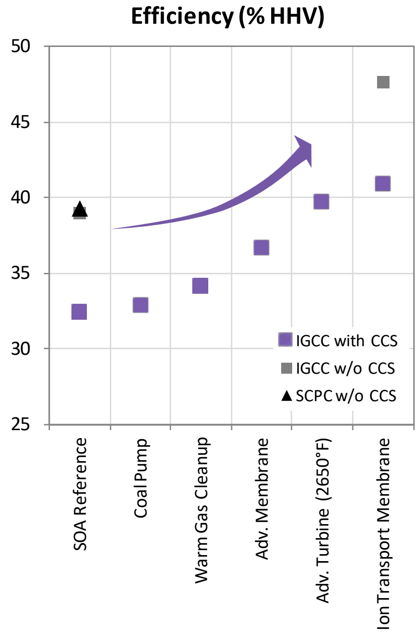
Supercritical CO_2 Cycles

Improving efficiency through unique properties of supercritical CO_2 as a working fluid.



Systems Analysis

Support research focus and verify performance targets.



*Paid for by Advanced Combustion Systems Program

Supercritical Carbon Dioxide 10 MWe Pilot Plant Test Facility

Gas Technology Institute

NATIONAL ENERGY TECHNOLOGY LABORATORY

Objectives

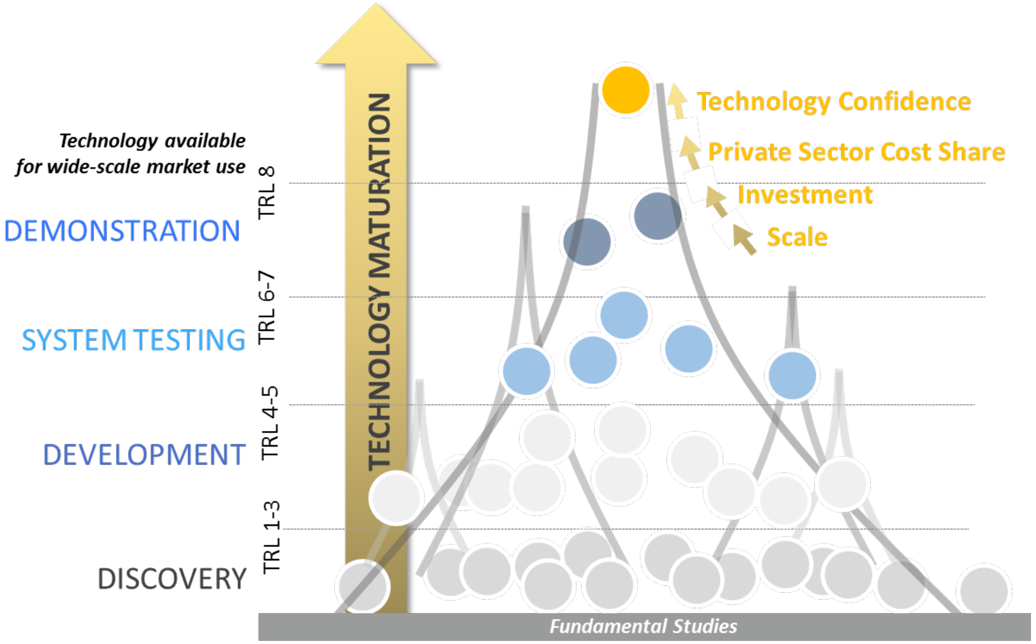
- Plan, design, build, and operate a 10 MWe sCO_2 Pilot Plant Test Facility
- Demonstrate the operability of the sCO_2 power cycle
- Verify performance of components (turbomachinery, recuperators, compressors, etc.)
- Evaluate system and component performance capabilities
  - Steady state, transient, load following, limited endurance operation
- Demonstrate potential for producing a lower COE and thermodynamic efficiency greater than 50%

GAS TECHNOLOGY INSTITUTE		
FE0028979		
Partners: SwRI, GE Global Research		
10/1/2016 – 9/30/2022		
BUDGET		
DOE	*Participant*	*Total*
$79,999,226	$33,279,408	$113,278,634

Technology Maturation

Turbine technology market provides a special case for TRL acceleration

- Competitive market place
  - US, International, and secondary markets
- Synergies with DOE and DOD
- US universities fully engaged
- Significant deployment of NGCC
- Significant small business opportunities
- FE invests in basic R&D at the component scale leading to early applied solutions
- OEMs eager to deploy components in the existing fleet leading to TRL acceleration
- New products by OEMs can then incorporate FE sponsored advanced technology at lower risk



Turbine market place accelerates this model for TRL maturation process

Next Steps

- **Status of the current CC goal 65 %**
  - Are higher efficiencies on our current path
- **Advanced manufacturing to realize GT performance goals**
  - Additive, coatings, castings, MRO, ceramics, materials, digital solutions, instrumentation, etc.
- **Raising the digital twin**
- **The existing fleet**
- **Advanced power systems**
- **Technology maturation**

Summary

- **Advanced Turbines Program focused on three areas**
  - Combined cycle combustion turbine
  - Turbomachinery for SCO2 power cycles
  - Pressure gain combustion
- **System to realize these benefits**
- **Technology / market synergies in manufacturing, across agencies, applications etc. will facilitate program success**