DOE University Turbine Systems Research Program

Turbines Role Toward Net Zero

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NATIONAL ENERGY TECHNOLOGY LABORATORY

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AT Program Goals

Mission - Deliver low cost, clean and carbon free electric power

DOE Mission

- Carbon free electricity by 2035
- Net-zero emissions by 2050
- Create new clean energy jobs
- Revitalize communities
- Advance environmental justice

Advanced Turbines Program Goals

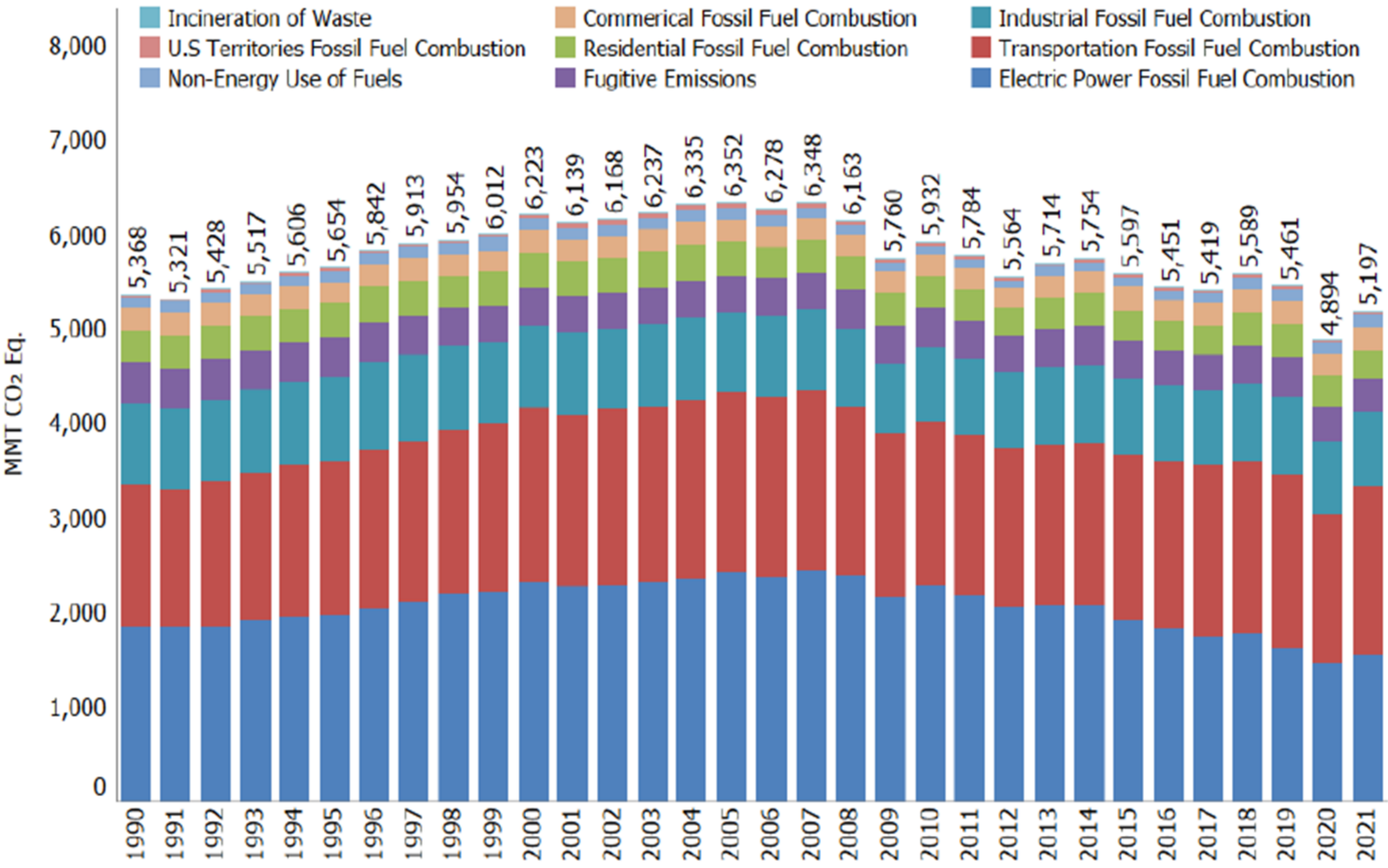
- **RD&D of gas turbines fueled with no-carbon fuels**
  - H_2, H_2 / NG blends, H_2 / NH_3 blends
  - Low NOx and high performance
- **Pursue advanced efficiency**
  - Simple and combined cycle
  - Rotating Detonation Engines
- **Optimization for CCS**

CMC synergies with FECM Advanced Materials Program

GHG Emissions in the U.S. Power Sector

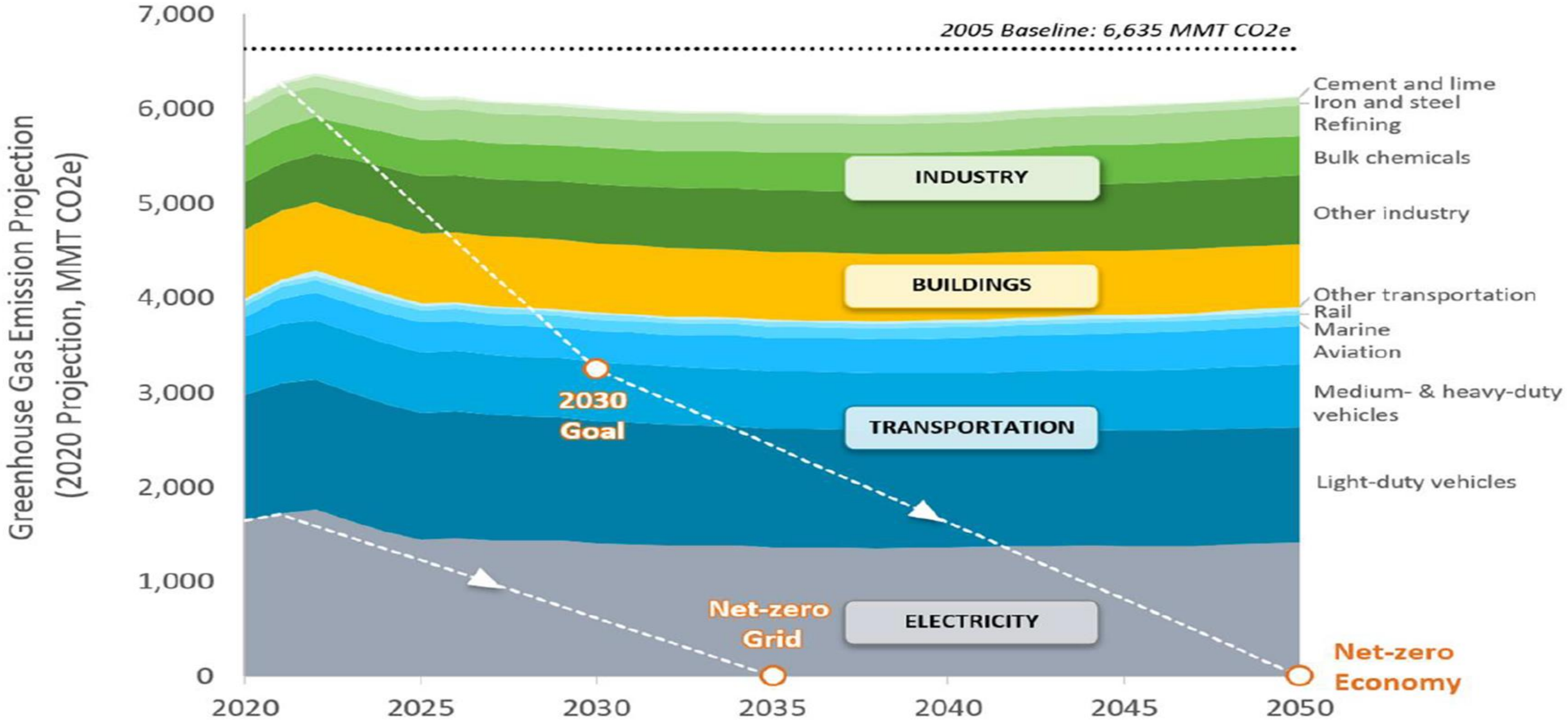
From U.S. Environmental Protection Agency (2023)

- From EPA – total GHG emissions in Energy Applications > 5 billion tonnes in 2021
  - 4.86 billion tonnes CO_2 from fossil fuel comb.
  - 1.54 billion tonnes CO_2 from electricity
- Total emissions have steadily declined since 2007



GHG Emissions in the U.S. Power Sector

From U.S. National Clean Hydrogen Strategy and Roadmap



Coal Retrofit/Repowering Trends

Replacing Coal with Natural Gas and/or Hydrogen

- ~290 GW (worldwide) coal fired plants scheduled for retirement over 15 years
- Repowering focused on nuclear, renewables with energy storage
  - Natural gas generation necessary stop-gap, "hydrogen ready"

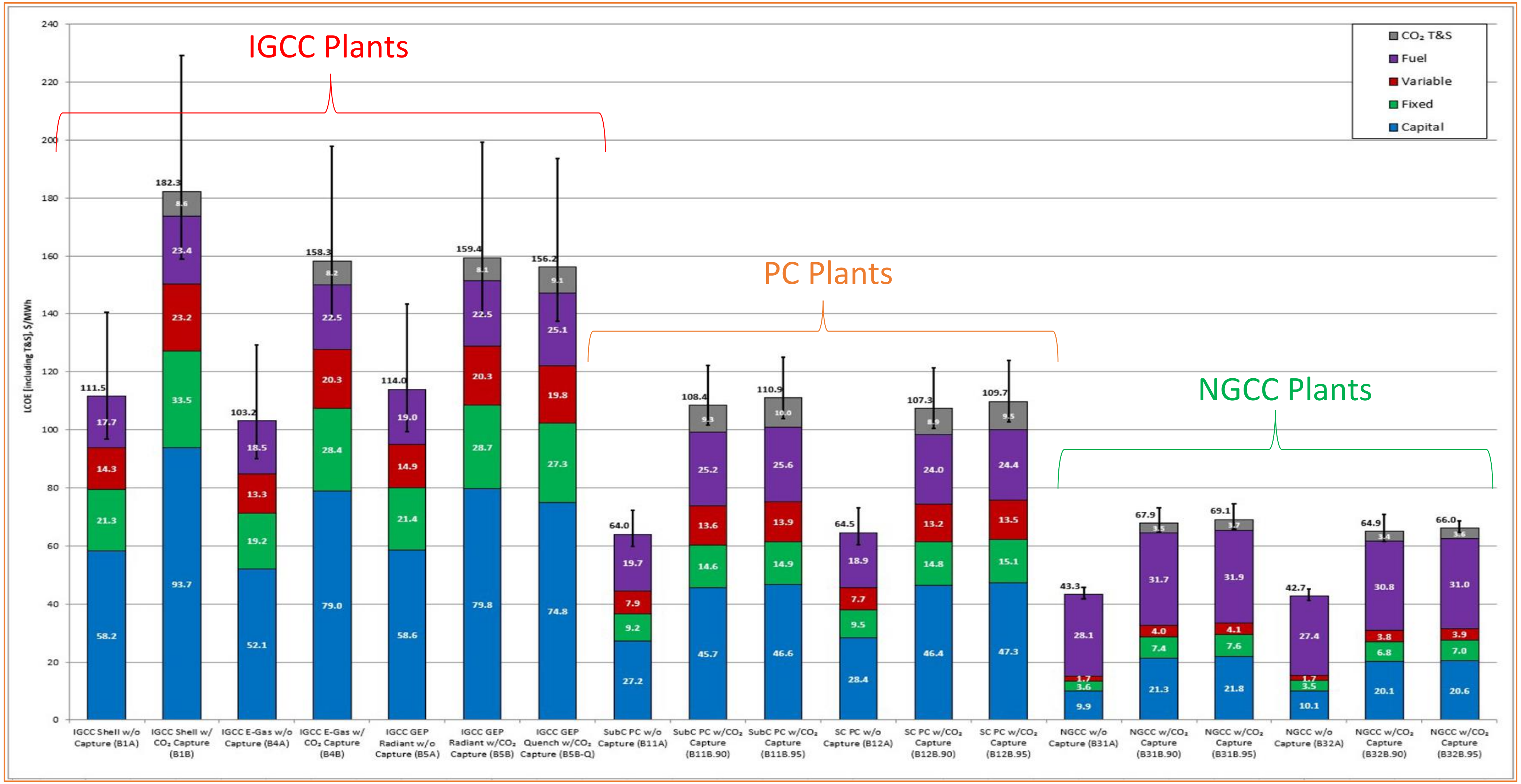
PC Power Plants vs. NGCC Emissions

Fuel	Coal		Natural Gas		Reduction
	lb/MWh	kg/MWh	lb/MWh	kg/MWh	%
NO_x	1.40	0.64	0.39	0.18	72%
SO_2	1.96	0.89	0.02	0.01	99%
CO_{2e} [1]	2182	992	898	408	59%

https://www.epri.com/research/sectors/lcri/research-results/3002025894

Coal Retrofit/Repowering Trends

LCOE Summary – from Vol. 1 Report

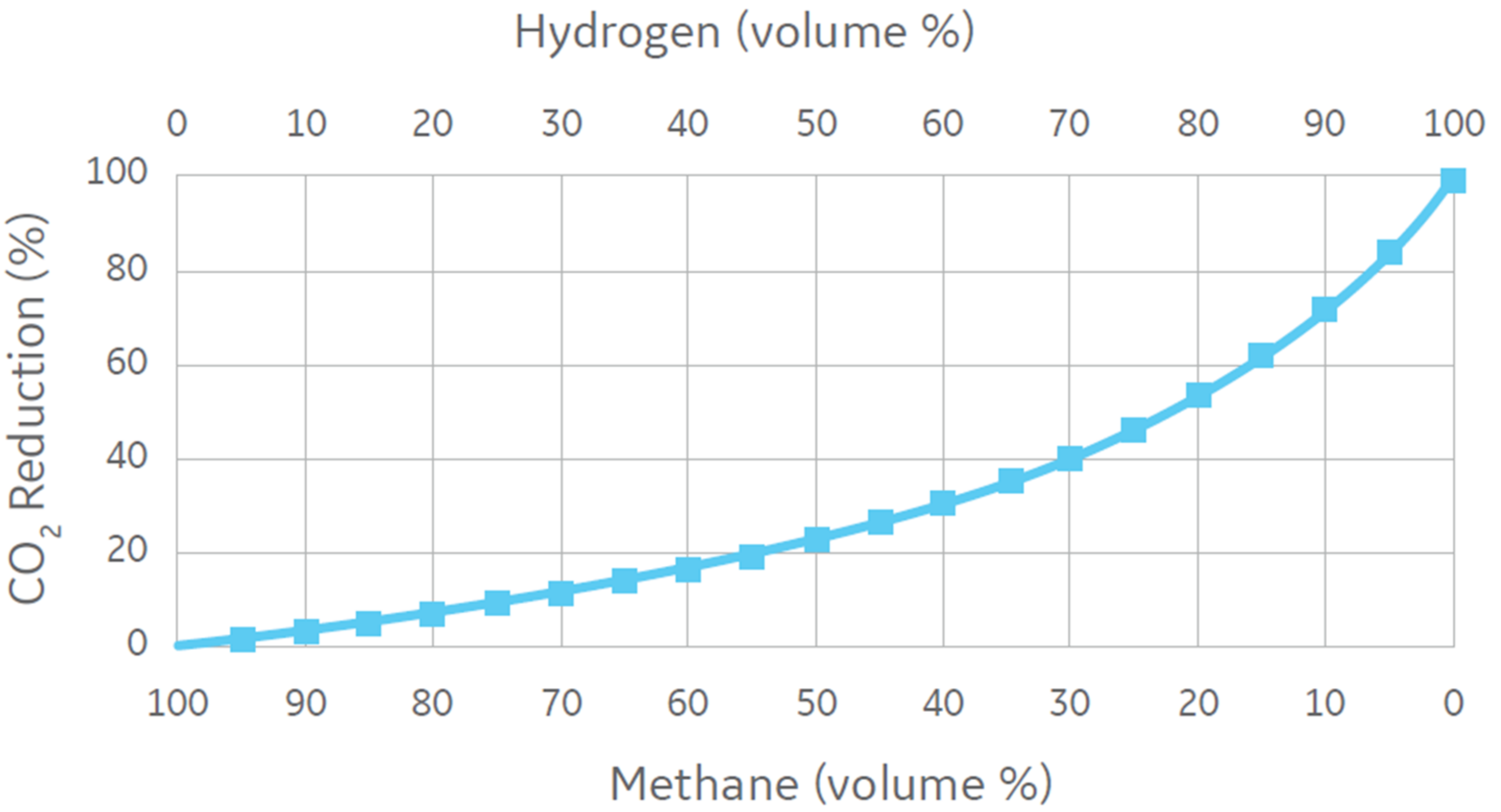


Schmitt et al., 2022, “Cost and Performance Baseline for Fossil Energy Plants.” Volume 1: Bituminous Coal And Natural Gas To Electricity. DOE/NETL-2023/4320. https://www.osti.gov/biblio/1893822.

Hydrogen Effect on CO_2 Emissions

High Non-Linearity Due to Differences in Fuel Properties

- **A 50% reduction in CO2 requires a 75/25 hydrogen/NG blend.**
- **Trend is linear when an energy basis is used (i.e., 1 BTU of H_2 + 1 BTU of NG produces 50% less CO_2 than 2 BTU of NG).**



Challenges with Carbon-Free Fuels

Hydrogen vs. Ammonia

Hydrogen

- High Flame Speed (~3 m/s – 10 times faster than CH_4)
- High Flame Temperature (>2200°C/4000°F)
- Low mass density/atomic weight (8 times lighter than CH_4)
- Low energy density (10,050 kJ/m^3 H_2 vs. 32,560 kJ/m^3 CH_4)
- Combustion Instabilities
- High thermal NO_X emissions concerns.

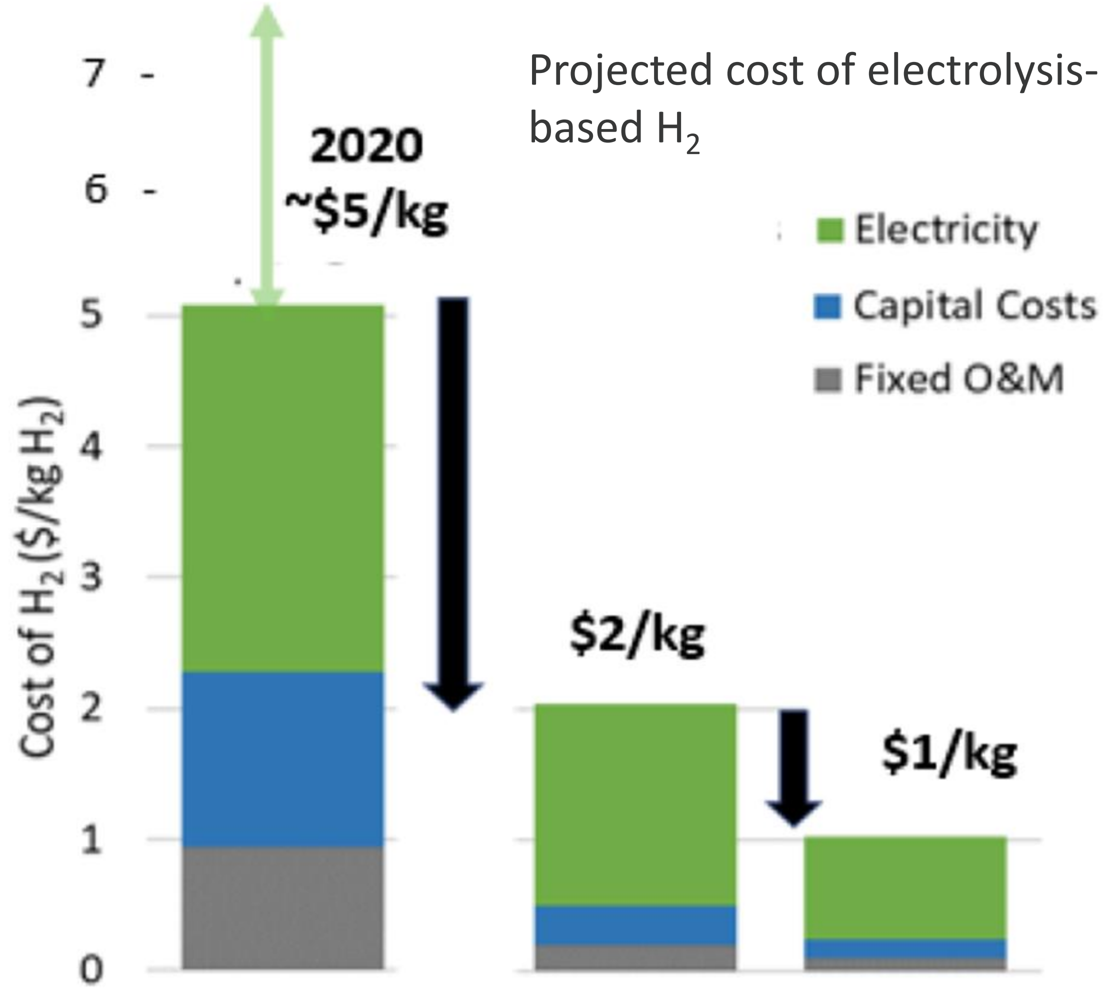
Ammonia

- Low Flame Speed (4-10 cm/s – 3-9 times *slower* than CH_4)
- Slow Combustion Kinetics
- High Ignition Temperature (651°C/1,204°F NH_3 vs. ~540°C/1004°F CH_4)
- Even higher NO_X generation than hydrogen (fuel NO_X)
- No viable one-step production method – hydrogen must be produced first (Haber Process)

Cost of Hydrogen Production

Pathway to Parity with Natural Gas

- **DOE Goal (Hydrogen Shot): \$1/kg H_2.**
- **Current (Henry Hub) Natural Gas Price (9/2023): \$2.64/million Btu + ~\$1.10 HHV fuel-equivalent for 90% CCS (assuming a 650MW NGCC plant).**
- **Current (EIA estimate) Ammonia Price: ~\$1650/tonne (=\$89.79/million Btu)**
- **\$1/kg H_2 = \$8.79/million Btu (LHV) or \$7.45/million Btu (HHV).**
- **Thus, price parity with natural gas occurs at a *sales* price of \$0.30-0.35/kg H_2 (\$0.42-0.48/kg H_2 if 90% CCS is mandated for NG).**

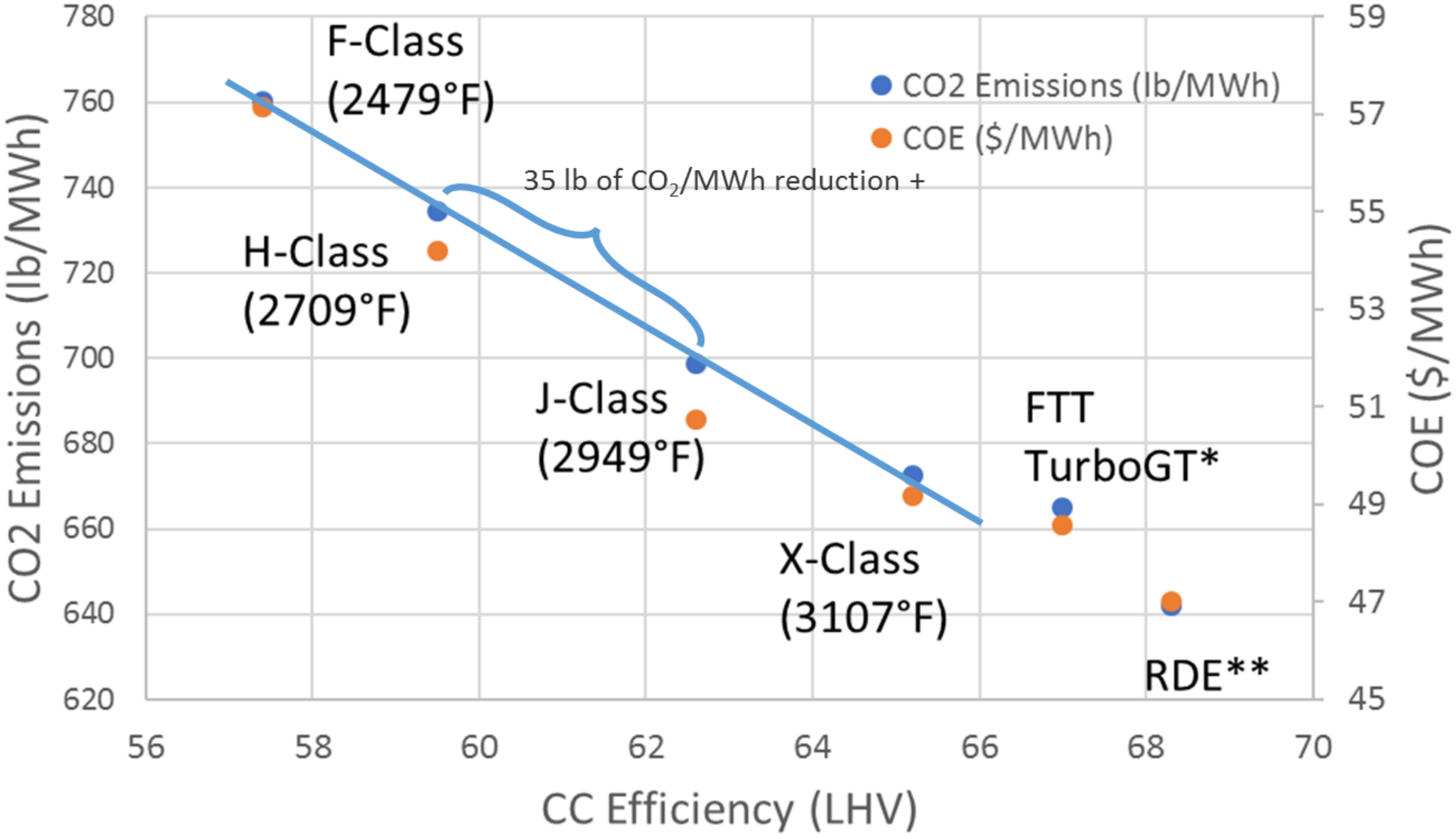


From U.S. National Clean Hydrogen Strategy and Roadmap

https://www.eia.gov/dnav/ng/hist/rngwhhdM.htm
https://www.eia.gov/todayinenergy/detail.php?id=52358

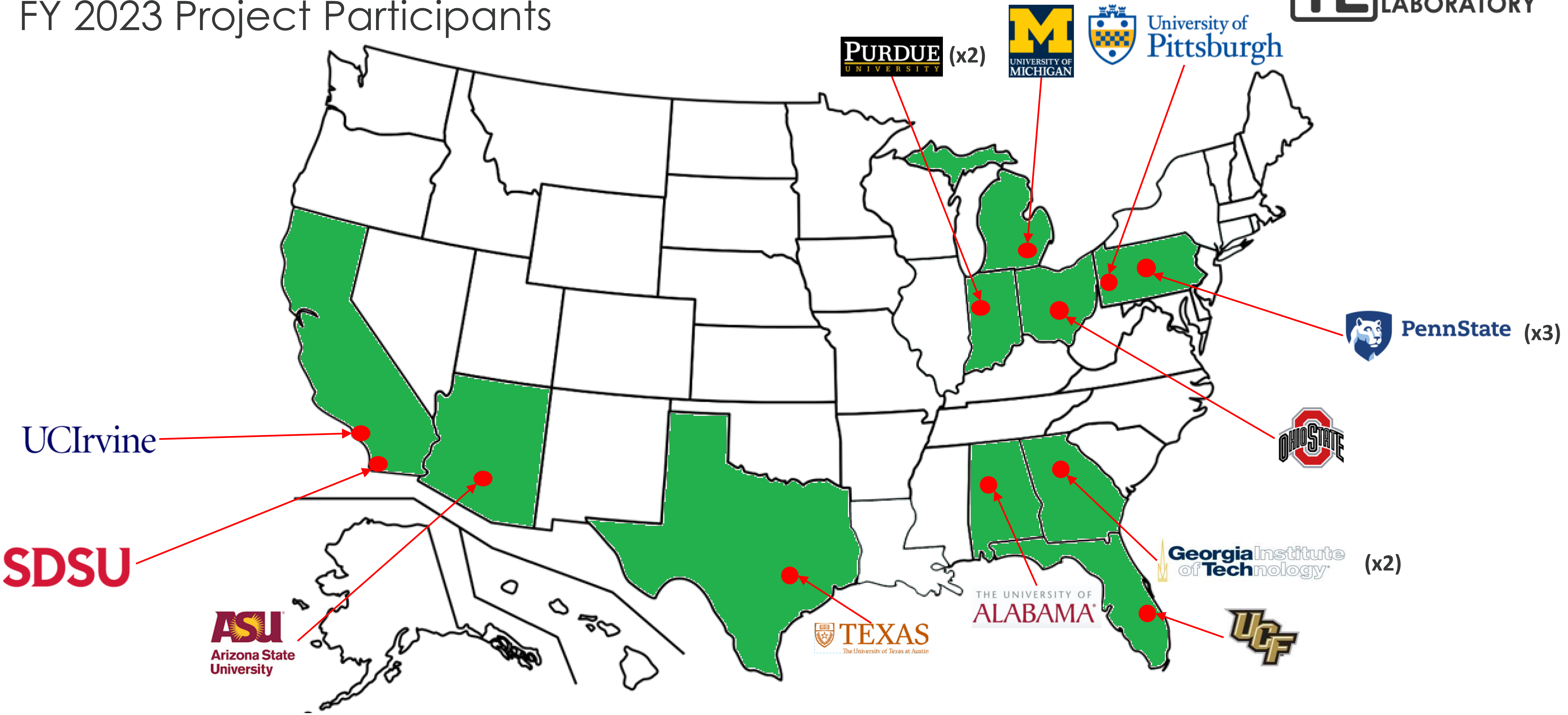
Efficiency vs. Decarbonization

Pathway to OPEX Cost Parity



AT Program Projects Map

FY 2023 Project Participants



Current Projects Supporting Efficiency Gain

Hydrogen, Aerothermal, and Component Studies

NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Title	Applicant
Improving Turbine Efficiencies Through Heat Transfer and Aerodynamic Research in the Steady Thermal Aero Research Turbine (START)	Penn State
Integrated Turbine Component Cooling Designs Facilitated by Additive Manufacturing and Optimization	UT Austin
Pressure Gain, Stability, and Operability of Methane/Syngas Based RDEs Under Steady and Transient Conditions	U. Michigan
An Effective Quality Assurance Method For Additively Manufactured Gas Turbine Metallic Components Via Machine Learning From In-Situ Monitoring, Part-Scale Modeling, and Ex-Situ Characterization Data	U. Pitt
Development And Evaluation of a Novel Fuel Injector Design Method Using Hybrid-Additive Manufacturing	Penn State
Fundamental Experimental and Numerical Combustion Study of H2 Containing Fuels for Gas Turbines	UCF
Development and Application of Multipoint Array Injection Concepts for Operation of Gas Turbines on Hydrogen Containing Fuels	UC Irvine
Investigation Of Flame Structure For Hydrogen Gas Turbine Combustion	Purdue
Physics-Based Integration of H2-Air Rotating Detonation into Gas Turbine Power Plant (HydrogenGT)	Purdue
Hydrogen Fuel Effects On Stability And Operation Of Lean Premixed And Staged Gas Turbine Combustors	Ohio State
A Robust Methodology To Integrate Rotating Detonation Combustor With Gas Turbines To Maximize Pressure Gain	U. Alabama

Current Advanced Turbines UTSR Projects

Hydrogen, Ammonia, sCO2, Aerothermal, and Component Studies

NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Title	Applicant
Ignition, Turbulent Flame Speeds, and Emissions from High Hydrogen Blended Fuels	GA Tech
Development of Design Practices for Additively Manufactured Micro-Mix Hydrogen Fueled Turbine Combustors with High-Fidelity Simulation Analysis, Reduced Modeling and Testing	SDSU
Advanced Model Development for Large Eddy Simulation (LES) of Oxy-Combustion and Supercritical Carbon Dioxide Power Cycles	GA Tech
Development of Additive Manufacturing for Ceramic Matrix Composite Vanes	Penn State
A Multiphysics Multiscale Simulation Platform for Damage, Environmental Degradation, and Life Prediction of Ceramic Matrix Composites (CMCS) in Extreme Environments	Arizona State

Other projects outside UTSR Program from GE, Raytheon, Siemens, Solar Turbines, GTI, Argonne National Lab, Ames National Lab, Oak Ridge National Lab, Duryea Technologies, and Creative Power Solutions.

Current Projects Outside UTSR Program

Hydrogen, Ammonia, sCO2, Aerothermal, and Component Studies

NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Title	Applicant
Development of Low-Leakage Shaft End Seals for Utility-Scale Supercritical Carbon Dioxide (SCO2) Turbo Expanders	GE
High Temperature Additive Architectures for 65 Percent Efficiency	GE
Novel Modular Heat Engines with Supercritical Carbon Dioxide Bottoming Cycle Utilizing Advanced Oil-Free Turbomachinery	GE
Ensemble Manufacturing Techniques for Steam Turbine Components Across Length Scales	Siemens
A Multiphysics Multiscale Simulation Platform for Damage, Environmental Degradation, and Life Prediction of Ceramic Matrix Composites (CMCS) in Extreme Environments	Arizona State
Development of a Retrofittable Dry Low Emissions Industrial Gas Turbine Combustion System for 100% Hydrogen and Natural Gas Blends	Solar Turbines
Low-NOx, Operable Ammonia Combustor Development for Zero-Carbon Power (Load-Z)	Raytheon
Demonstration of a Gas Turbine-Scale Rotating Detonation Combustor Integrated with Compressor and Turbine Components at 7FA Cycle Conditions	GE
Development of Hydrogen Burner for FT4000 Aeroderivative Engine	Raytheon
Investigation of Ammonia for Combustion Turbines	GTI

Current Projects Outside UTSR Program

Hydrogen, Ammonia, sCO2, Aerothermal, and Component Studies

NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Title	Applicant
Advanced Mixed Mode Combustor for Hydrogen F-Class Retrofit	GE
Physics Exploration and Analysis of Hydrogen-Fueled Rotating Detonation Engines Using Advanced Turbulent Combustion Modeling and High-Fidelity Simulation Tools	Argonne NL
Turbines (Gas Turbine Thermal Performance Analysis Tools)	Ames NL
Next Generation Environmental Barrier Coatings	Oak Ridge NL
High Pressure-Ratio Dry-Vane Air-Cooled Compressor (HPVACC) for Enhancing sCO2 Power Plants	Duryea Tech.
Ammonia Gas Turbine Combustor	CPS USA
A Deep Learning Enabled Fast and Robust Chemistry Solver for Reacting Flow Simulations	Argonne NL

Waste Heat Recovery for sCO_2 Cycles

Examples in Industry

- **Indirect sCO_2 cycles have a unique niche for WHR applications**
  - Highly efficiency at small scales (1-20MW)
  - Recuperator(s) can accept heat from any source, including thermal solar and industrial plants.
- **The STEP plant (10MW) could be leveraged for WHR studies in the future.**
- **ECHOGEN developed a WHR system utilizing sCO_2 – a pilot facility was licensed for construction in Alberta, Canada in 2021 (by Siemens).**
  - Will power roughly 10,000 homes.
  - Will reduce GHG emissions by over 44,000 tons/year
  - 25-40% smaller land footprint than equivalent steam systems
- **Cement plant flue gas streams from the preheater and clinker cooler make for viable connection points for sCO_2 cycles as WHR units.**
  - EU-funded CLEANKER project
  - ACC Madukkarai plant in India
  - Prachovice cement plant in the Czech Republic

STEP Pilot Plant Test Facility is approaching Simple Cycle commissioning

Major Team Members: Gas Technology Institute, Southwest Research Institute, GE Research

Design, build, and operate two indirect sCO2 power cycle configurations

Evaluate system and component performance capabilities

Demonstrate potential for producing a lower COE and thermodynamic efficiency greater than 50%

Flexible test bed for cycle reconfiguration and advanced component testing

5 MWe Simple Recuperated Brayton Cycle 500C
10 MWe Recompression Brayton Cycle 700C

Direct-Fired sCO_2 Cycles

Competing with NGCC

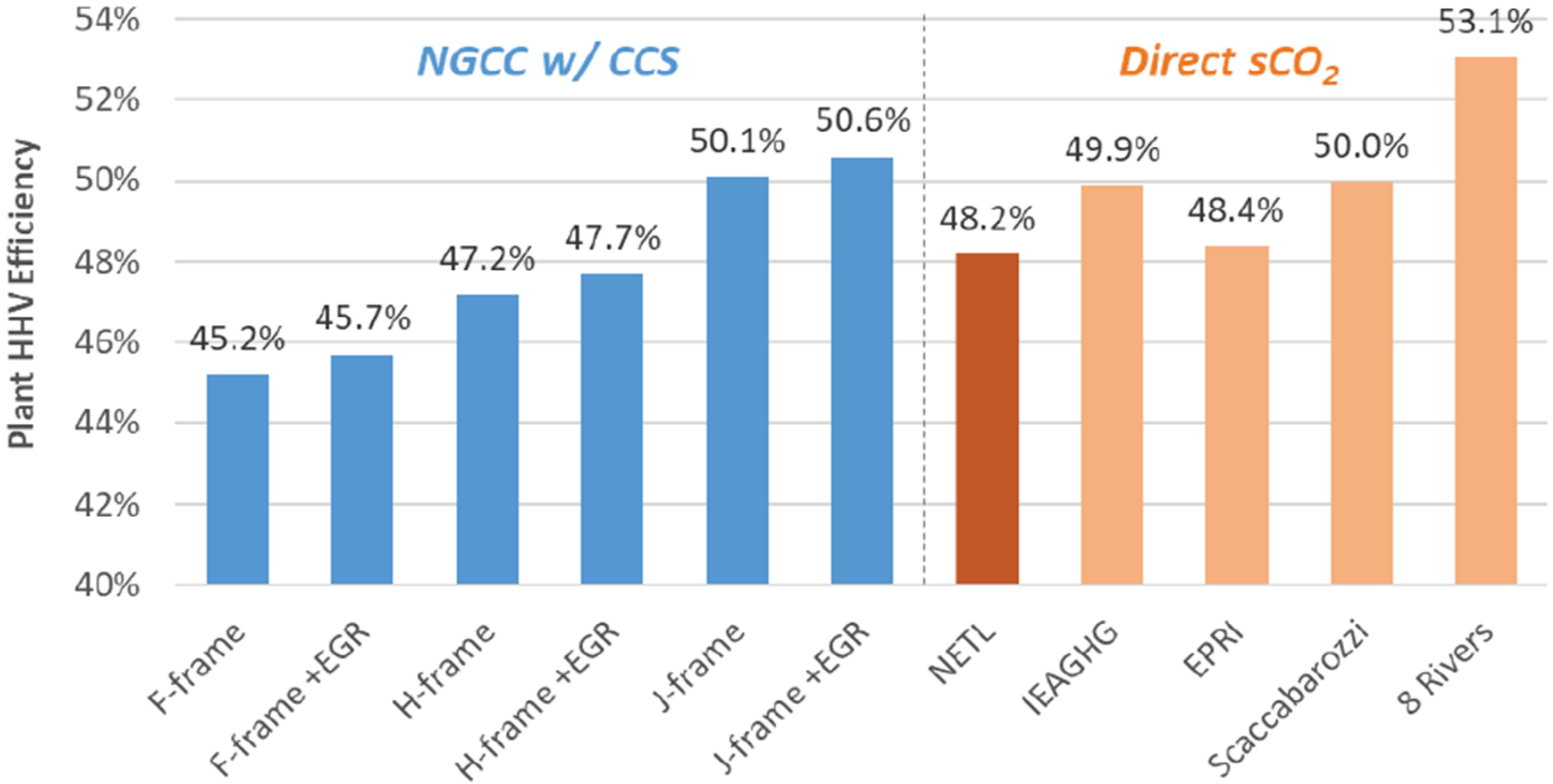
- With CCS included, direct sCO_2 cycles can compete with NGCC due to "free" carbon capture.
- NETL study – LCOEs are comparable ($83.3/MWh for sCO_2 vs. $87.3/MWh for NGCC).
- Carbon Taxes/Credits are needed to favor CCS in NGCC.

Parameter	NGCC	sCO_2 Cycle
Natural Gas Feed Flow, kg/hr	84,134	84,134
HHV Thermal Input, MW_{th}	1,223	1,223
LHV Thermal Input, MW_{th}	1,105	1,105
Total Gross Power, MW_e	601	738
Total Auxiliaries, MW_e	42	148
Total Net Power, MW_e	**559**	**590**
HHV Net Plant Efficiency, %	**45.7**	**48.2**
HHV CT/sCO_2 Cycle Efficiency, %	34.5	58.6
LHV Net Plant Efficiency, %	50.6	53.4
LHV CT/sCO_2 Cycle Efficiency, %	38.1	66.8
Steam Turbine Cycle Efficiency, %	43.5	---
Condenser/sCO_2 Cooler Duty, GJ/hr	888	1,978
Raw Water Withdrawal, $(m^3/min)/MW_{net}$	0.027	0.023
Raw Water Consumption, $(m^3/min)/MW_{net}$	0.020	0.016
Carbon Capture Fraction, %	**90.7**	**98.2**
Captured CO_2 Purity, mol%	99.93	100.00

https://www.netl.doe.gov/projects/files/Performance%20and%20Cost%20of%20a%20NG-Fueled%20Direct%20sCO2%20Plant.pdf

Direct-Fired sCO_2 Cycles

Competing with NGCC



https://www.netl.doe.gov/projects/files/Performance%20and%20Cost%20of%20a%20NG-Fueled%20Direct%20sCO2%20Plant.pdf

Real-Time Health Monitoring for Gas Turbine Components using Online Learning and High Dimensional Data

FE0031288 – Georgia Institute of Technology

NATIONAL ENERGY TECHNOLOGY LABORATORY

OBJECTIVES

- Develop a Big Data analytics framework for critical gas turbine components.
- Create an experimental program that leverages unique industry-class turbine test rigs for the above framework.
- Use state-of-the-art instrumentation techniques to build fault signatures and data trends for key combustor and turbine faults.

BENEFITS

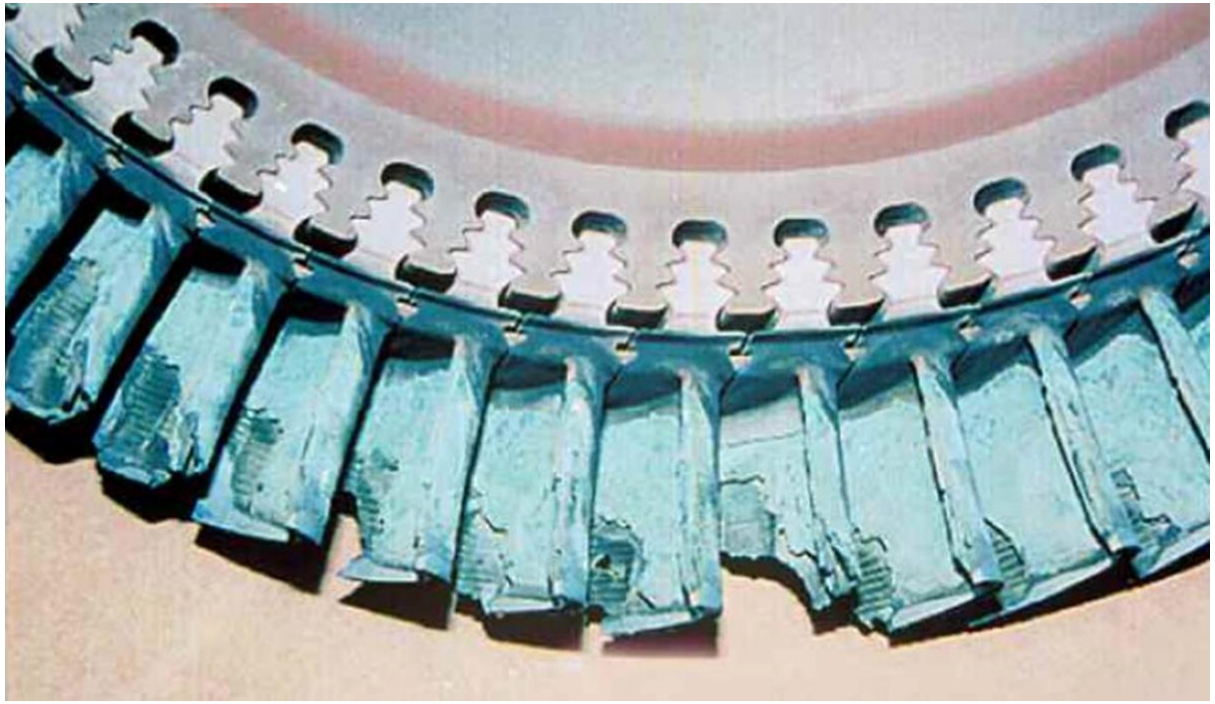
- Improve state-of-the-art real-time monitoring for conditions inside gas turbines during operation.
- Enable a symbiotic relationship between industry professionals and data scientists that improves gas turbine development.

CURRENT STATUS

- Project has concluded (Final Report: 2/10/2022).

Project Duration: 10/1/2017 – 9/30/2021
Total Award Value: $750,159.47
DOE Share: $599,862.47
Performer Share: $150,297.00
PI: Nagi Gebraeel

ADVANCED TURBINES



From Discovery to Commercialization

Advanced Combustion Turbine - Airfoil Design

Concept to Market Readiness

COMMERCIALIZATION
Technology available for wide-scale market use

DEMONSTRATION
System demonstrated in operational environment

SYSTEM TESTING
System performance confirmed at pilot-scale

DEVELOPMENT
Technology component validated/integrated

DISCOVERY

2017 — TRL 7-8
First-of-a-kind Revolutionary Cooling Architecture Ready for Market

- Advanced Design Incorporated in 1st Commercial Turbine
- Available for Sale in 2017
- Production at Siemens Charlottesville, VA Facility

2013 — TRL 5-6
Pre-Commercial Prototype Validated in Relevant Environment

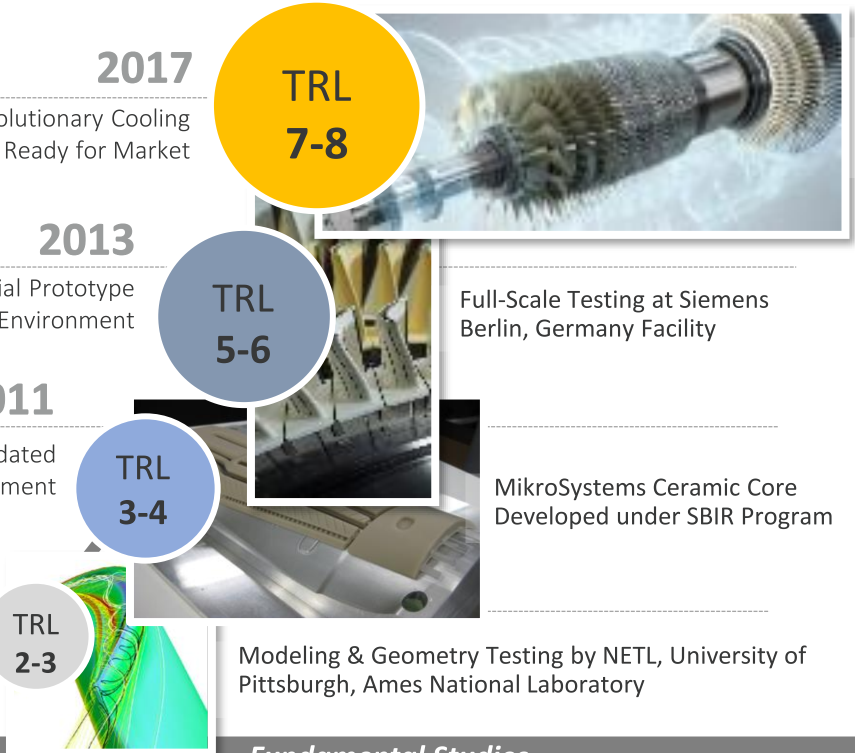
- Full-Scale Testing at Siemens Berlin, Germany Facility

2011 — TRL 3-4
Component/Subsystem Validated in Laboratory Environment

- MikroSystems Ceramic Core Developed under SBIR Program

2009 — TRL 2-3
Proof-of-Concept Developed - Analytical Studies Predict Technology Potential

- Modeling & Geometry Testing by NETL, University of Pittsburgh, Ames National Laboratory



Fundamental Studies

From Discovery to Commercialization

GE CMC for Advanced Gas Path

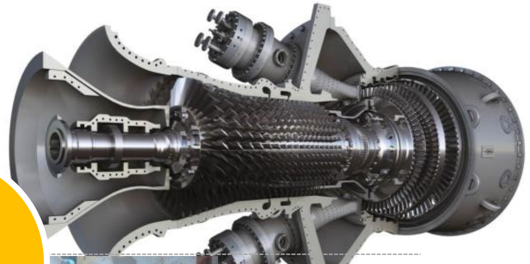
Concept to Market Readiness

Technology available for wide-scale market use

2016

TRL 8

First-of-a-kind Advanced Gas Path Materials Ready for Market



DEMONSTRATION

System demonstrated in operational environment

2011

TRL 6-7

Pre-Commercial Prototype Validated in Relevant Environment

Long term in service shroud durability testing

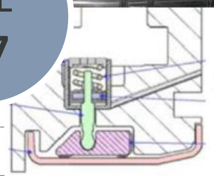
SYSTEM TESTING

System performance confirmed at pilot-scale

2009

TRL 4-5

Component/Subsystem Validated in Laboratory Environment



Test article design, fabrication trials

DEVELOPMENT

Technology component validated/integrated

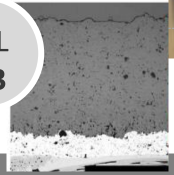
2006

TRL 2-3

Proof-of-Concept Developed - Analytical Studies Predict Technology Potential

Successful ballistic impact testing

DISCOVERY

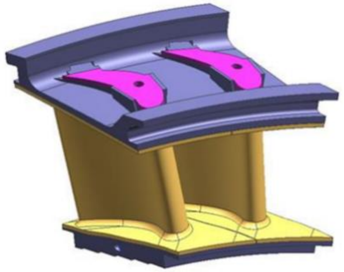


Environmental barrier coating (EBC) characterization, coating trials, stress testing

Fundamental Studies

Resulting Technology Spin-Off/Leveraging R&D

Current TRL **2-3**



High Temp CMC Nozzle

Summary/Conclusions

- DOE/NETL supports the continued efforts in hydrogen and supercritical carbon dioxide research.
- Indirect sCO_2 cycles will continue to have a significant value in waste heat recovery applications.
- Incentives are needed to facilitate carbon capture technologies into the mainstream – reduce the burden on hydrogen price and sCO_2 adoption.
- Even with incentives, getting hydrogen to cost-parity with natural gas will require greater R&D effort beyond 2035.

Questions?

Thank You!

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Additional information can be found at:
https://netl.doe.gov/carbon-management/turbines

Thank You, Patcharin (Rin) Burke!

Attended and/or Organized
15 UTSR Workshops from 2009 – 2023

Managed $Millions$ and Dozens of Advanced Turbines Projects - Universities, National Labs, SBIRs, and OEMs

Managed the Impossible:
Expert Negotiator AND Likable Person!

Best wishes in your new roles!
Sensors & Controls Technology Manager
Solid Oxide Fuel Cell Technology Manager