



# Emerging and Innovative Technologies

## Staged Pressurized Oxy-Combustion

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in collaboration with

**AECOM**

**Altrad Babcock (formerly Doosan Babcock)**

**EPRI**

**Linde**

**Nexant ECA**

**Reaction Engineering International**

# A History of Helping to Securing the Future of Coal



## Consortium for Clean Coal Utilization at Washington University (est. 2009)

Tackling the scientific & technological challenges for coal's future

\$14M Investment from industry

\$20M in follow-on federal funding

### Founding Sponsors



### Delivering Solutions for Coal



*Advanced Emission Controls: Reducing mercury & HAPS*



*Critical Minerals, etc.: extracting REE and valuable products*



*Wastewater treatment: removal of selenium from wastewater*



*CCUS: Near-zero emissions*

### Demonstrated Expertise & Impact

- ✓ 19 WashU faculty engaged
- ✓ 20 Research projects executed
- ✓ 90 Peer-reviewed publications & 1 book



*Advanced Coal and Energy Research Facility (1 MWth)*

# The Premise:

*To be future-proof, next-gen power should be low carbon*

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Options being explored for solid fuels (e.g., coal, biomass and waste) with Carbon Capture Utilization/Storage (CCUS):

- Pre-combustion
  - Integrated Gasification Combined Cycle (IGCC)
- Post-combustion
- Oxy-combustion
  - Atmospheric pressure
  - Allam Cycle (Supercritical CO<sub>2</sub>)
  - Pressurized

# The Perspective:

*We need to find the correct balance of risk versus reward*

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Existing approaches tend to fall into one of two categories:

1. High Risk

- Complicated integrated systems with many components (IGCC)
- Sophisticated cycles that push the limits (Allam Cycle)

2. Limited Reward: No benefit to the grid other than carbon capture and with a large parasitic load

- Post combustion capture
- First-generation oxy-combustion

# Balancing risk and reward

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**Can we identify a solution that  
not only removes carbon  
but offers many other benefits,  
and without unnecessary risk?**

**Introducing  
Staged, Pressurized, Oxy-Combustion**

# Why Pressurized Oxy-Combustion?

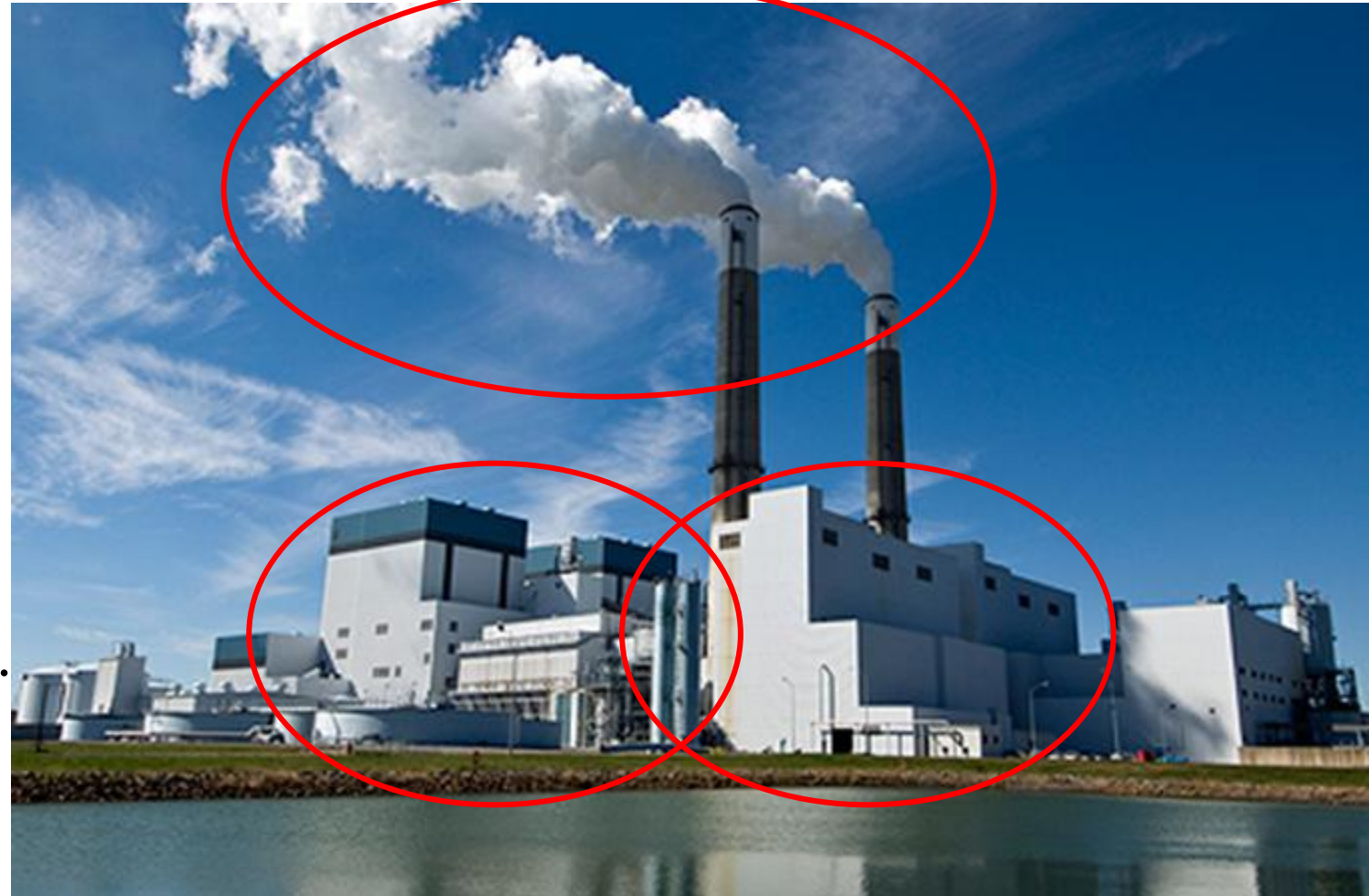
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When CO<sub>2</sub> is sequestered/utilized, the final pressure of the CO<sub>2</sub> needs to be high.

With Oxy-combustion there is effectively **no cost to pressurize the combustion process.**

Consider a conventional  
power plant:

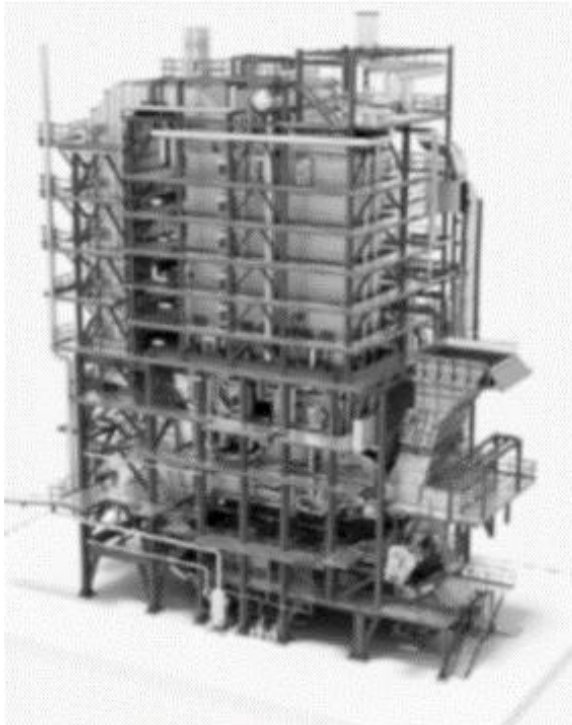
Let's see what pressurization does...



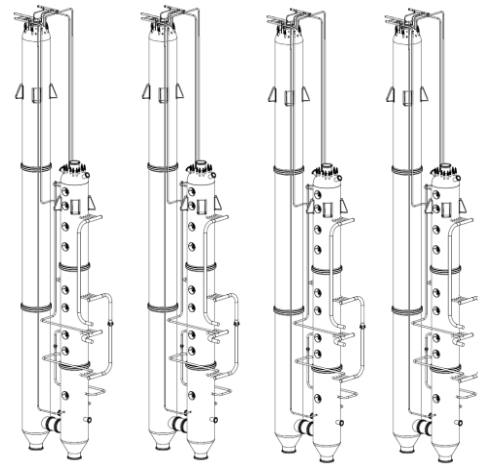
# Size and Cost Reductions of SPOC Components

- Low-cost modular design for boiler and flue gas treatment
  - Smaller units, lower manufacture cost
  - Can be manufactured off-site and delivered in sub-modular assemblies
  - Significantly lower on-site construction costs and time – projects can be on time and on budget

## Conventional boiler

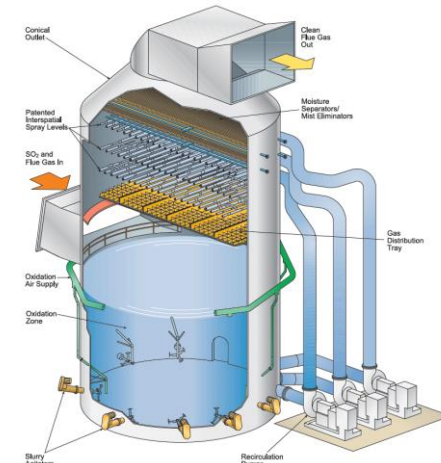


## SPOC Modular boilers



Drawings to scale

## Conventional Flue-gas desulfurization



## SPOC DCC



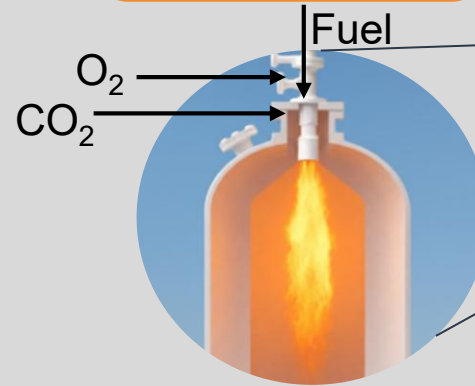
# The Staged, Pressurized Oxy-Combustion Process

## Flexible Fuel Source

Coal  
Natural Gas  
Wood Waste

Enables dynamic switching based on market conditions and supply constraints.

## Oxy Combustion



## CO2 Capture

- Reliable power
- Regulation-proof
- Simple, low-risk design
- Can be carbon negative

## Staged + Pressurized



## Small, Modular

- Low CapEx
- Rapid deployment
- Flexible load

## Clean Burning

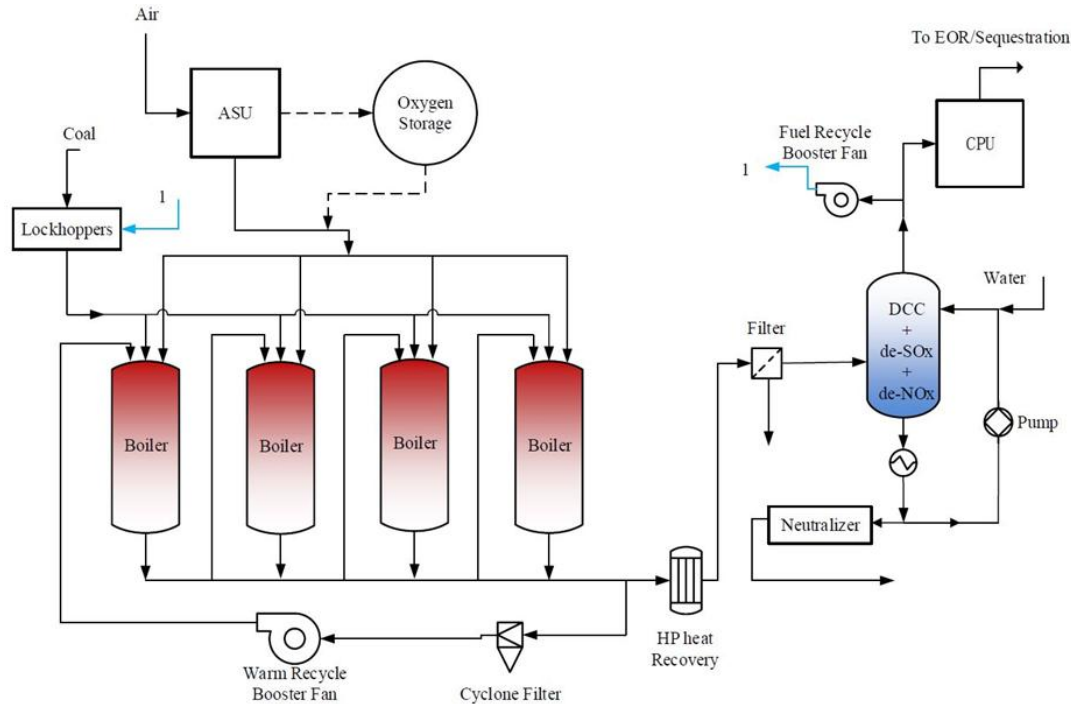
- Low SOx
- Low NOx
- Low particulate

## High Efficiency

- Low OpEx

# Staged Pressurized Oxy-Combustion Process

## 550 MWe SPOC Plant



## Benefits:

- Up to ~7.5 pp efficiency improvement compared with conventional PC plant with carbon capture
  - efficiency boosts due to pressurization and reduced recycle
- Direct Contact Cooler (DCC) captures
  - latent heat in the flue gas
  - SO<sub>x</sub> and NO<sub>x</sub>
- Highly flexible operation for **load following** due to
  - modular design
  - oxygen storage
- And more...

# Additional Advantages of SPOC

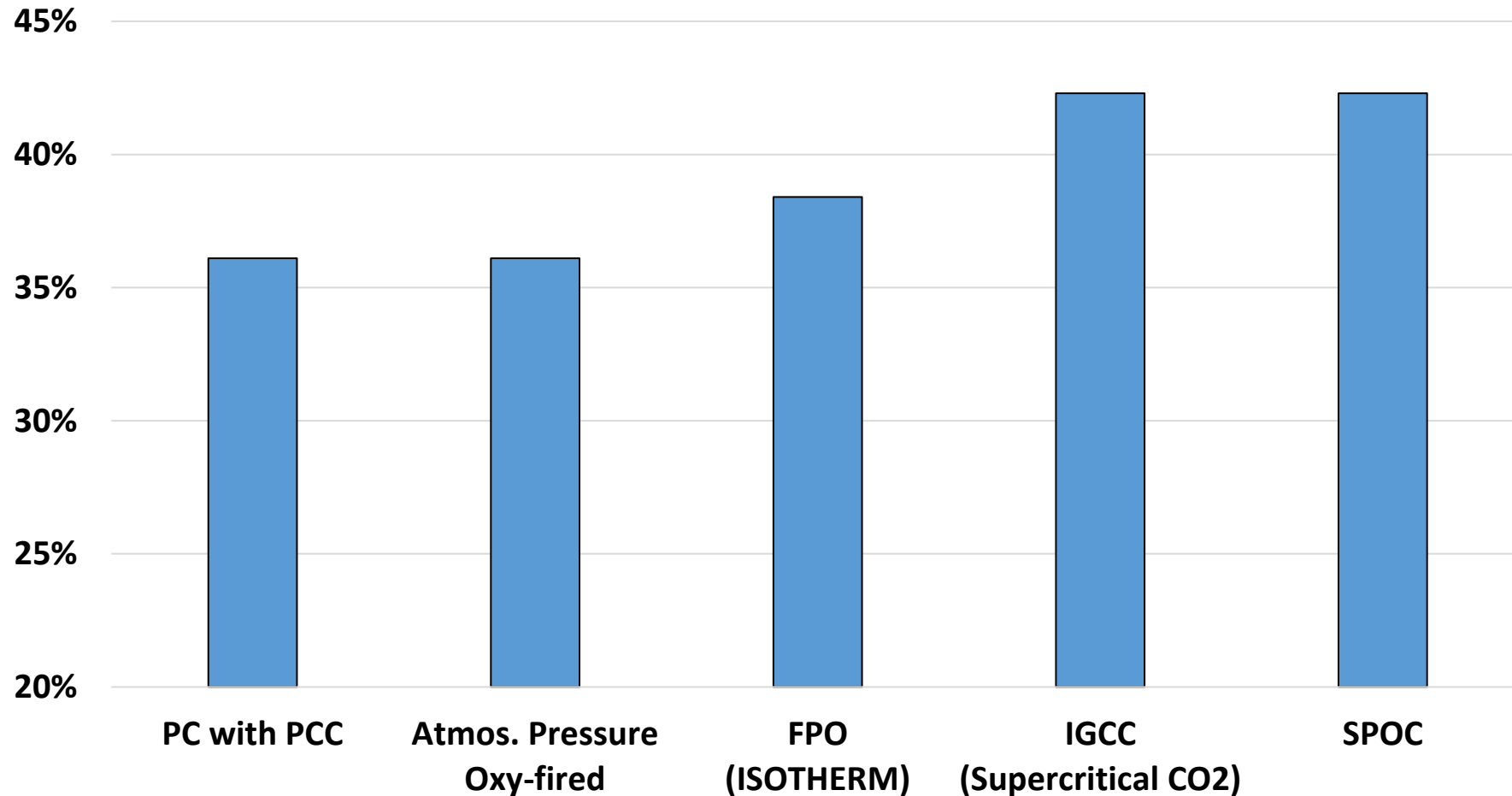
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- Excellent fuel flexibility
  - Suitable for coal, natural gas and biomass
  - Effectively upgrades low-grade fuels by recovering latent heat
- Enhanced combustion performance
  - Improved burnout because pressure enhances oxidation and gasification reactions and results in a longer residence time
  - Enhanced flame stability
- Reduced water consumption
  - The recovered water from DCC can compensate for 10~25% of water consumption (for water-cooled condenser)
- Carbon Capture and Utilization or carbon capture ready

# Comparison of Plant Efficiencies

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## Coal Power Plant Net Efficiency (LHV basis)



Efficiency of PC without carbon capture: 46.1%

Data From Independent Sources:

Hagi, H. et al. (2014);

Hume, S. (2016);

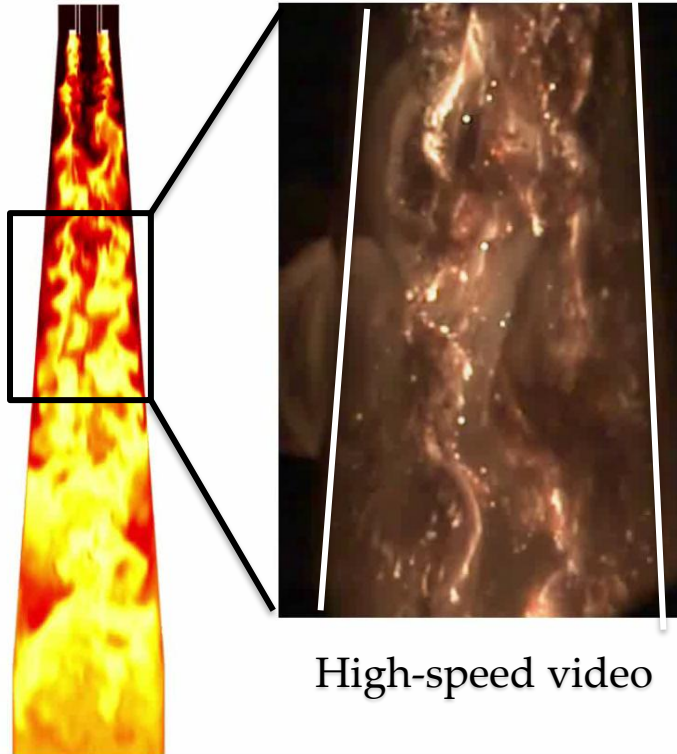
NETL (2011)

# WUSTL Pressurized Combustion Facility

## *WUSTL 15 bar Pressurized Oxy-Combustion Facility*



LES simulation



High-speed video

- **9+ years** operation
- **No significant challenges** have been observed to-date

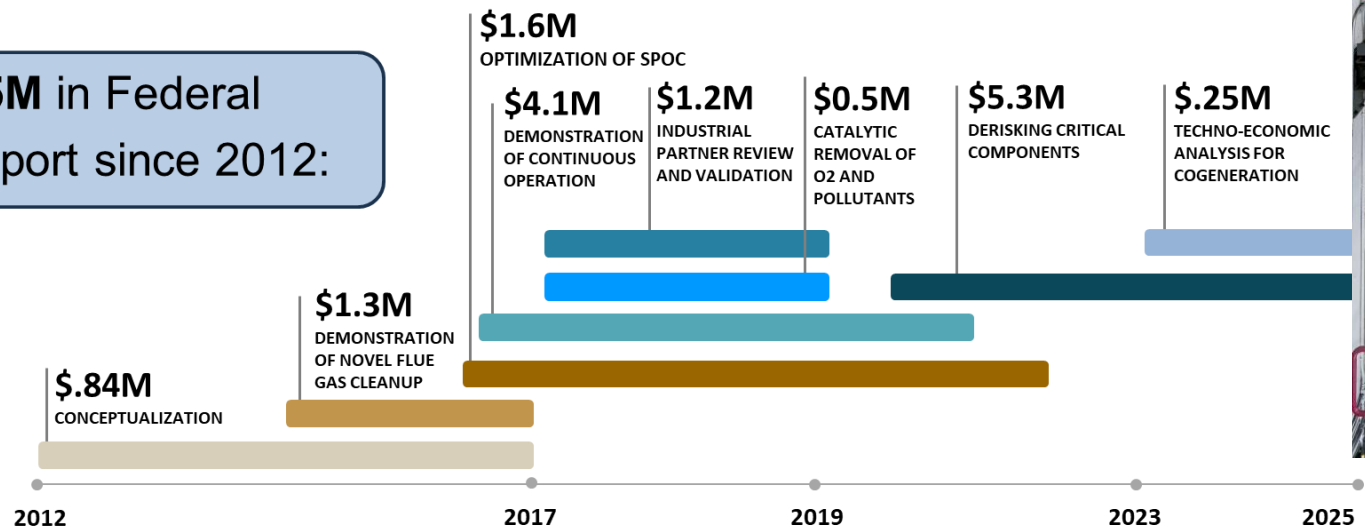
# Summary of Efforts to Date

- Extensive testing (1,500 hours) with a variety of fuels, including coal, natural gas and biomass
- Complete process design – in collaboration with industry leaders
- Optimization of the process via advanced computer modeling
- Techno-economic Analyses (TEA) for power and cogeneration
- 4 Patents (WashU exclusively owns the IP)

SPOC pilot-scale facility



**\$15M** in Federal support since 2012:



*Industrial collaboration*




*Industrial support*



# The SPOC Technology yields low LCOE with Coal: Example for a Commercial-Scale Plant in Wyoming

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## Levelized Cost of Electricity (LCOE), \$ per MWh

	NGCC with CCS*	SPOC	SPOC + EOR
	\$84-125	\$81	\$63
w/ 45Q 	\$46-87	\$13	\$(5)

\*adapted from NETL,  
(range reflects fluctuation in gas turbine price)

NGCC – Natural Gas Combined Cycled  
CCS – Carbon Capture and Storage  
EOR – Enhanced Oil Recovery

- NG price:  
\$3.45 per MMBtu
- Coal price (PRB):  
\$15 per ton
- EOR price:  
\$20 per ton CO<sub>2</sub>
- 45Q tax credit:  
\$85 per tonne CO<sub>2</sub>

# Applying the SPOC Process to Natural Gas

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Supply chain constraints on natural-gas turbines have led to severe shortages and high costs.

But we can **use natural gas as the fuel in the SPOC process.**

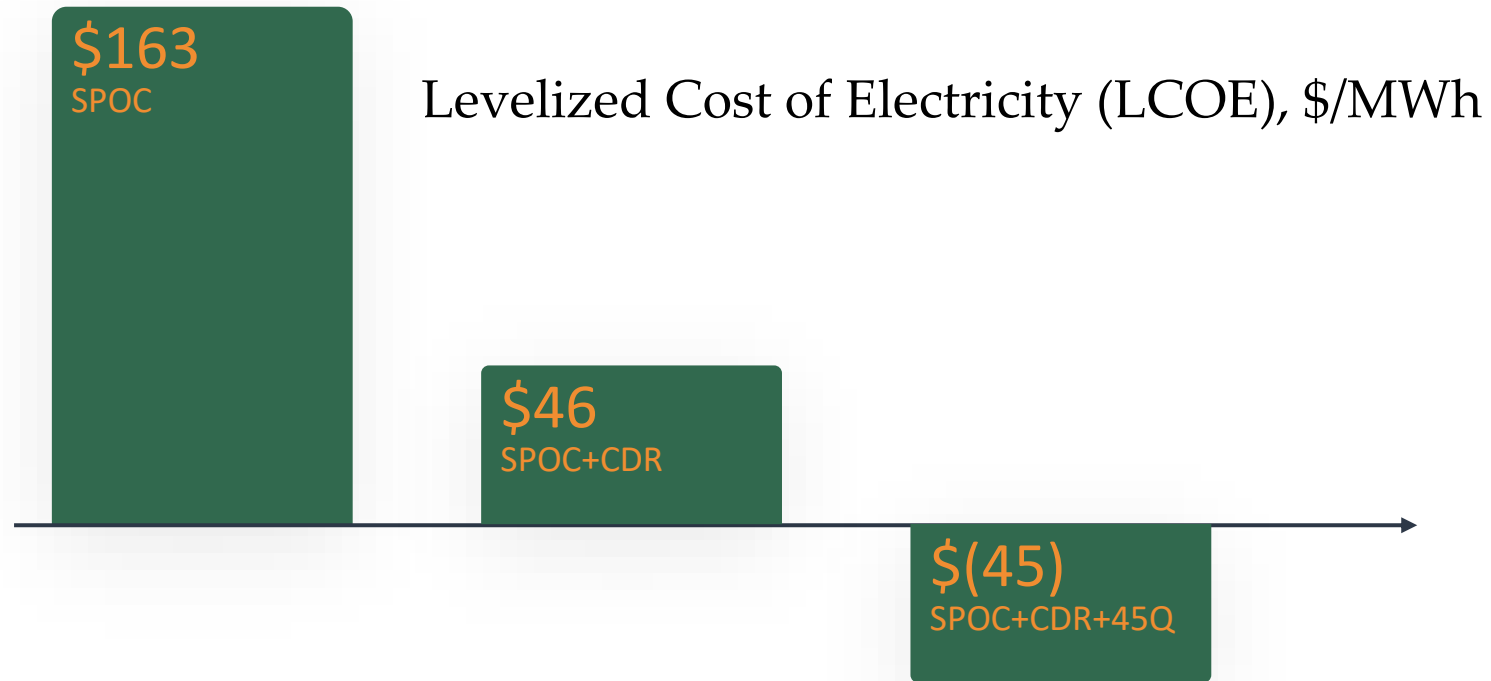
SPOC offers an opportunity to **use readily-available, low-cost steam turbines** combined with advanced steam cycles to supply efficient, low-carbon power from natural gas

—————→ SPOC eliminates supply-chain constraints, and more...

Efficiency of SPOC is lower than NGCC with CCS,  
but CapEx is substantially lower,  
resulting in a **10% lower LCOE**

# Applying the SPOC Process to Biomass

## Carbon Negative Power at a Fraction of the Cost



Carbon credits generated from carbon-negative power AND carbon sequestration generate uniquely strong unit economics.

- **CDR credits:** Carbon Dioxide Removal (CDR) of atmospheric carbon
- **45Q Tax credits:** from carbon sequestration or utilization

- Biomass price: \$80 per ton
- CDR price: \$100 per ton CO<sub>2</sub>
- 45Q tax credit: \$85 per tonne CO<sub>2</sub>

# SPOC Technology is Ready for Demonstration

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Current (at WashU)

Largest pressurized combustion research facility in the U.S.

- Since 2016
- Over 1,500 hours of operation



5 MWth  
(4 x 5MWt = 7 MW)

In advanced discussions with SER at UWyo to site the 5 MW facility in Wyoming Integrated Test Center (ITC) and with the Wyoming legislature with respect to cost share.

# SPOC: the ideal technology for the modern grid

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- ❑ **Small, modular design**
  - ❑ Low-cost factory fabrication and faster onsite construction
- ❑ **High efficiency**
- ❑ **Low LCOE**
- ❑ **Dispatchable**
  - ❑ Flexible operation to match demand of the grid
  - ❑ Low-cost energy storage (liquid oxygen)
- ❑ **New build or retrofit**
- ❑ **Fuel flexible (coal, natural gas and biomass)**
- ❑ **Small (5-50 MWe) to large scale (550 MWe)**
- ❑ **Carbon Dioxide Removal (CDR), if incorporated with biomass**
- ❑ **Very low-risk technology (SPOC is based on proven technologies)**
- ❑ **Future-proof!**



# Thank you!



## Acknowledgements

This work has received supported from the U.S. Department of Energy and the Consortium for Clean Coal Utilization at Washington University in St. Louis. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

