Advanced Combustion Systems Program

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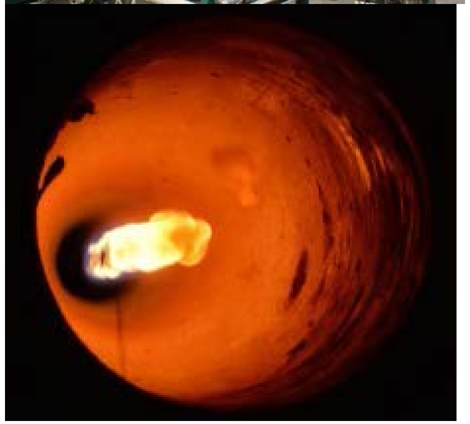
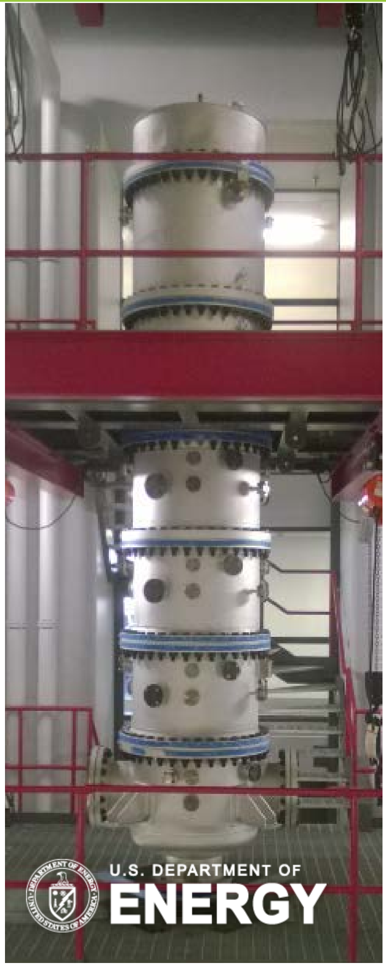



Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

The Big Technology Issues for Coal

Manage CO_2 Emissions

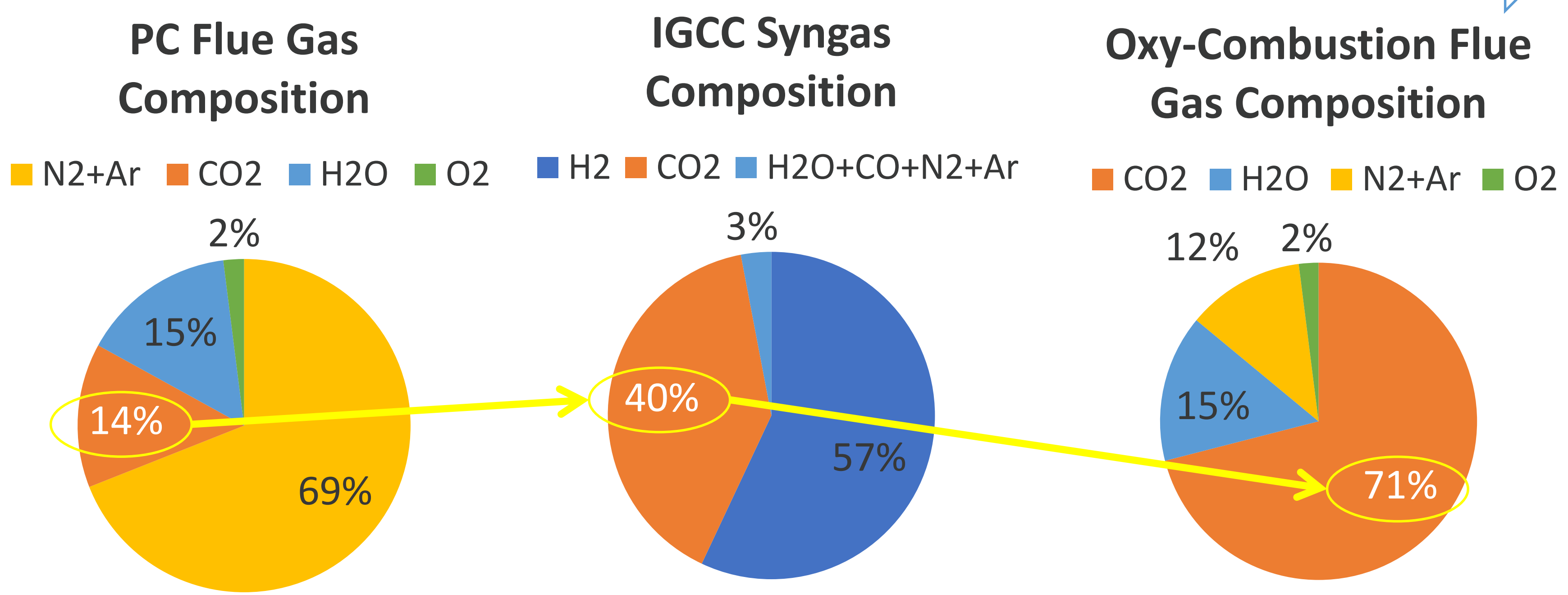
Reduce Criteria Pollutants

Minimize Water Use

Control Costs

What is Advanced Combustion?

INCREASING CO_2 CONCENTRATION -> REDUCED CAPTURE SYSTEM COST AND ENERGY



Advantages of Pressurized Oxy-combustion:

- Mass and volume of flue gas are reduced
- Latent heat recoverable
- Heat transfer rates increased
- No air in-leakage

Advantages of Chemical Looping Combustion:

- In-situ oxygen separation eliminates air separation unit
- Uses conventional material of construction and fabrication

Advanced Combustion Systems Program

KEY TECHNOLOGIES	RESEARCH FOCUS
Pressurized Oxy-Combustion	• Oxy-Pressurized Fluid Bed Combustion • Staged Combustion • Flameless Combustion
Chemical Looping Combustion	• Iron-based CLC • Pressurized CLC (red mud) • Chemical Looping with Oxygen Uncoupling (Cu-based OC) • Copper Hybrid Oxygen Carrier Development • Limestone-based CLC (mothballed)
Novel Concepts	• Pressure Gain Combustion • Pulse Detonation Engine for Direct Power Extraction • High-efficiency power cycles (SCO2)

■ Transformational Technology

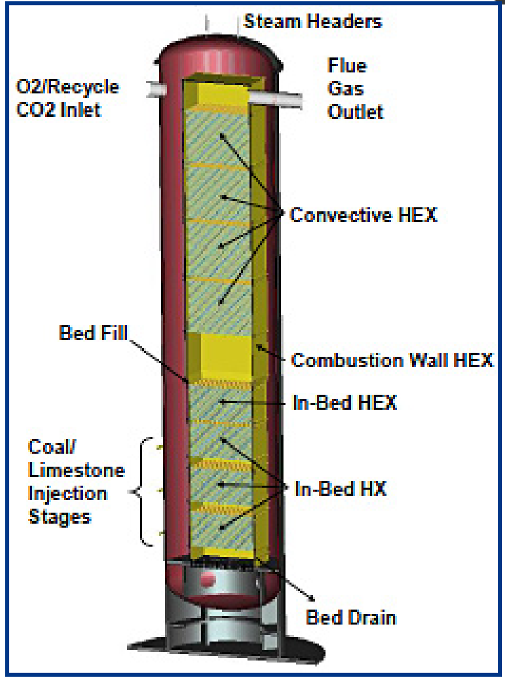
“Gas Separation”

at the Front End Rather Than the Back End

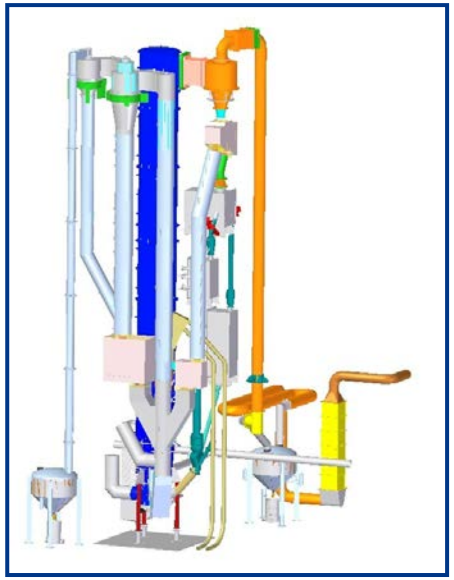
Advantages of Pressurized Oxy-combustion:

In pressurized oxy-combustion, the mass and volume of flue gas are reduced relative to atmospheric combustion in air:

- Latent heat recoverable and heat transfer rates increased… *increases efficiency*
- Reduces equipment size…*decreases capital costs*
- No air in-leakage… *increases CO_2 purity*
- Projected CO_2 capture costs of $30/tonne or less



Aerojet Rocketdyne 1-3 MWe



Alstom 1 MWe

Advantages of Chemical Looping Combustion:

In chemical looping, oxygen is created in-situ…

- Eliminates need for oxygen production…*reduces parasitic energy demand and potentially system costs*
- Uses conventional material of construction and fabrication
- Projected CO_2 capture costs approaching $25/tonne

Advanced Combustion Systems

Technical Overview

NATIONAL ENERGY TECHNOLOGY LABORATORY

1. ***What is the problem?***
   - *Coal plants with CCS too expensive*
   - *Efficiency low (<30 %), cost high (>$8,000/kW)*
   - *Lack of commercial-scale demonstration*

2. ***What are the barriers to solve this problem?***
   - *Costly oxygen requirements*
   - *Energy intensive flue gas processing*
   - *Low overall efficiency*

3. ***How will the barriers be overcome?***
   - *Increased performance (pressurized oxy)*
   - *Alternative processes (chemical looping)*
   - *Advanced power cycles (AUSC & SCO2)*

4. ***What is the capability being developed?***
   - *Highly efficient, low cost electric power generation with intrinsic carbon capture*

5. ***What is the result/product of the effort?***
   - *Advanced Oxy-Combustion Power Plant*
   - *Chemical Looping Combustion Power Plant*

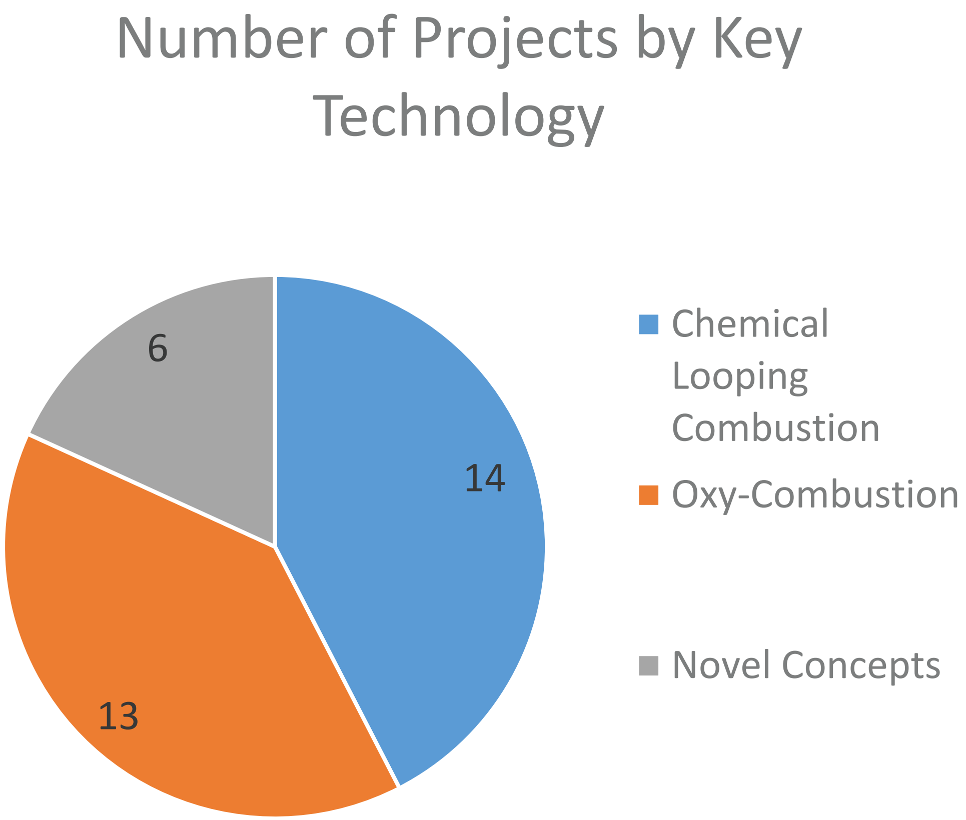
6. ***What are the quantitative metrics?***

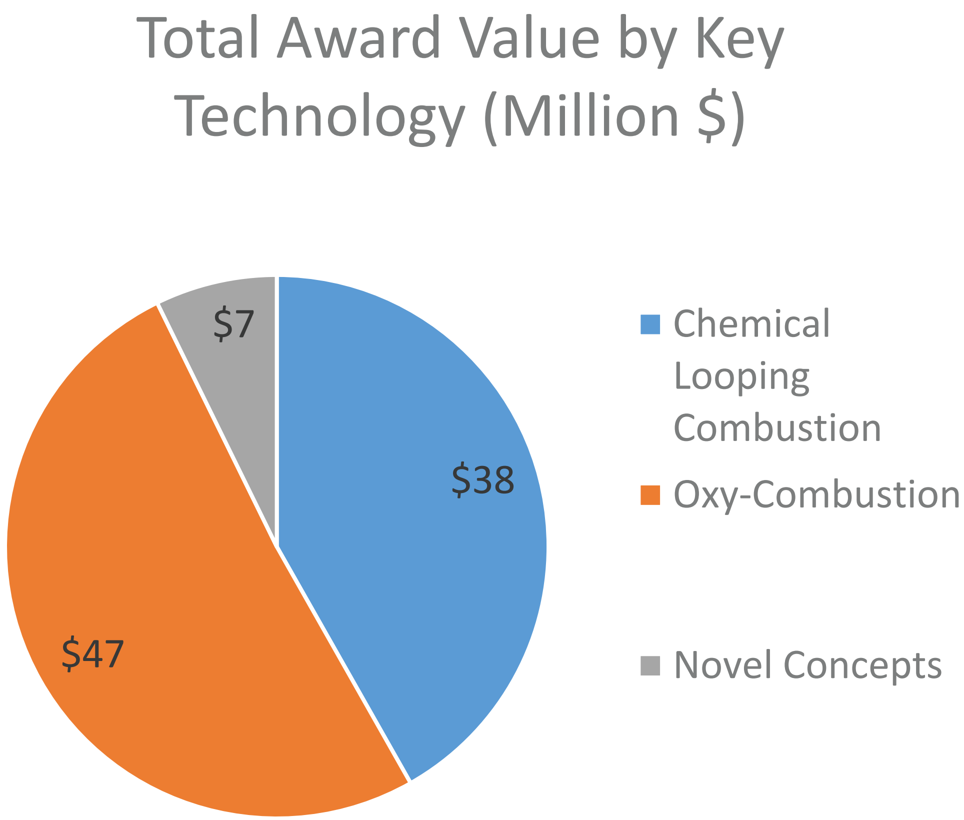
	Current	2020 Target	2025 Target
Total Plant Cost	>$8,000 / kW	<$5,000/kW	<$2,500 / kW
Net Efficiency (HHV)	<30%	32%	>35%
Demonstration Scale	0.1 - 1 MWt Small Pilots	10-25 MWe Integrated Pilot System Designs	~70 MWe FOAK Advanced Combustion Coal Power Plant Designs

7. ***How are other technology efforts being leveraged?***
   - *DOE STEP initiative on SCO2 power cycles*
   - *NETL Gasification O2 production*
   - *NETL Gasification multi-phase flow modeling*
   - *NETL CCR Advanced sensors and materials work*
   - *NETL CCT AUSC materials*

Active Project Portfolio by Key Technology

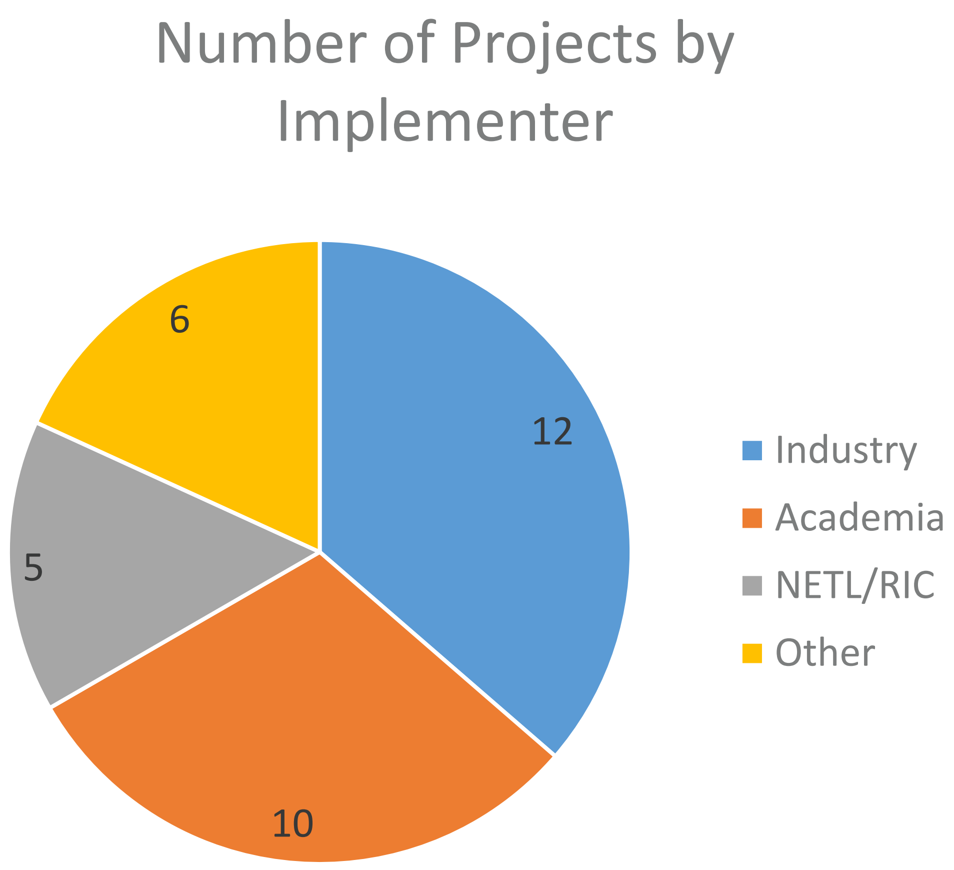
Advanced Combustion Systems

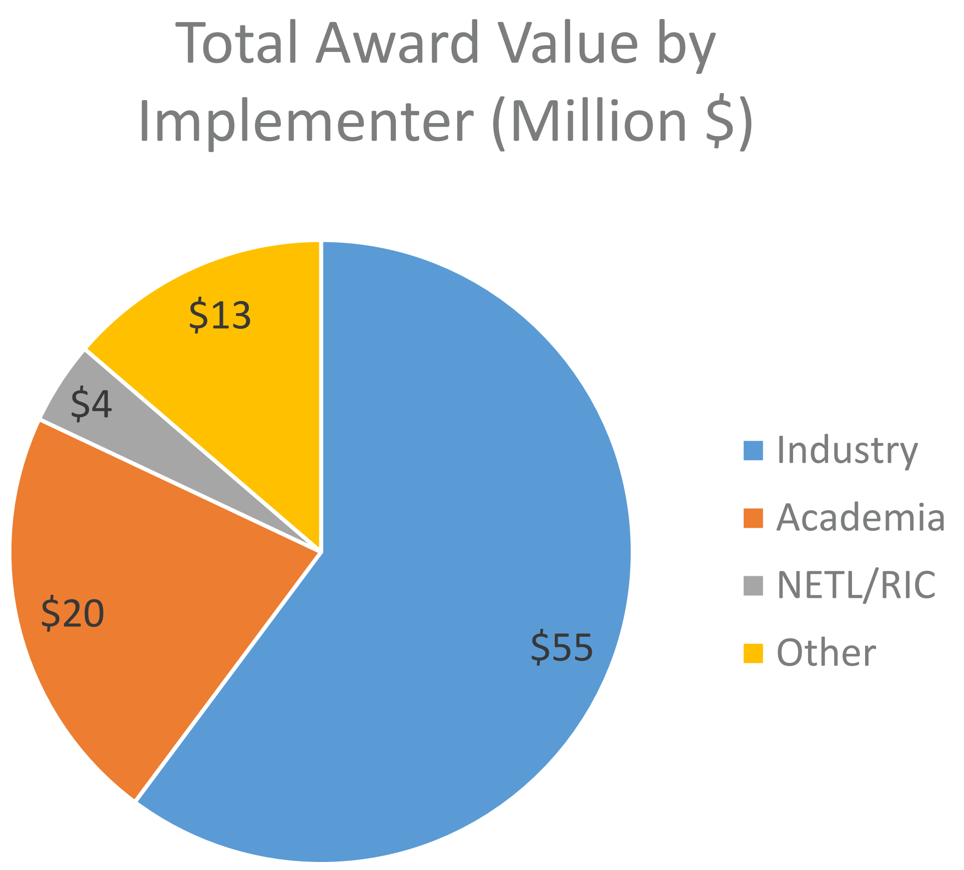




Active Project Portfolio by Implementer

Advanced Combustion Systems

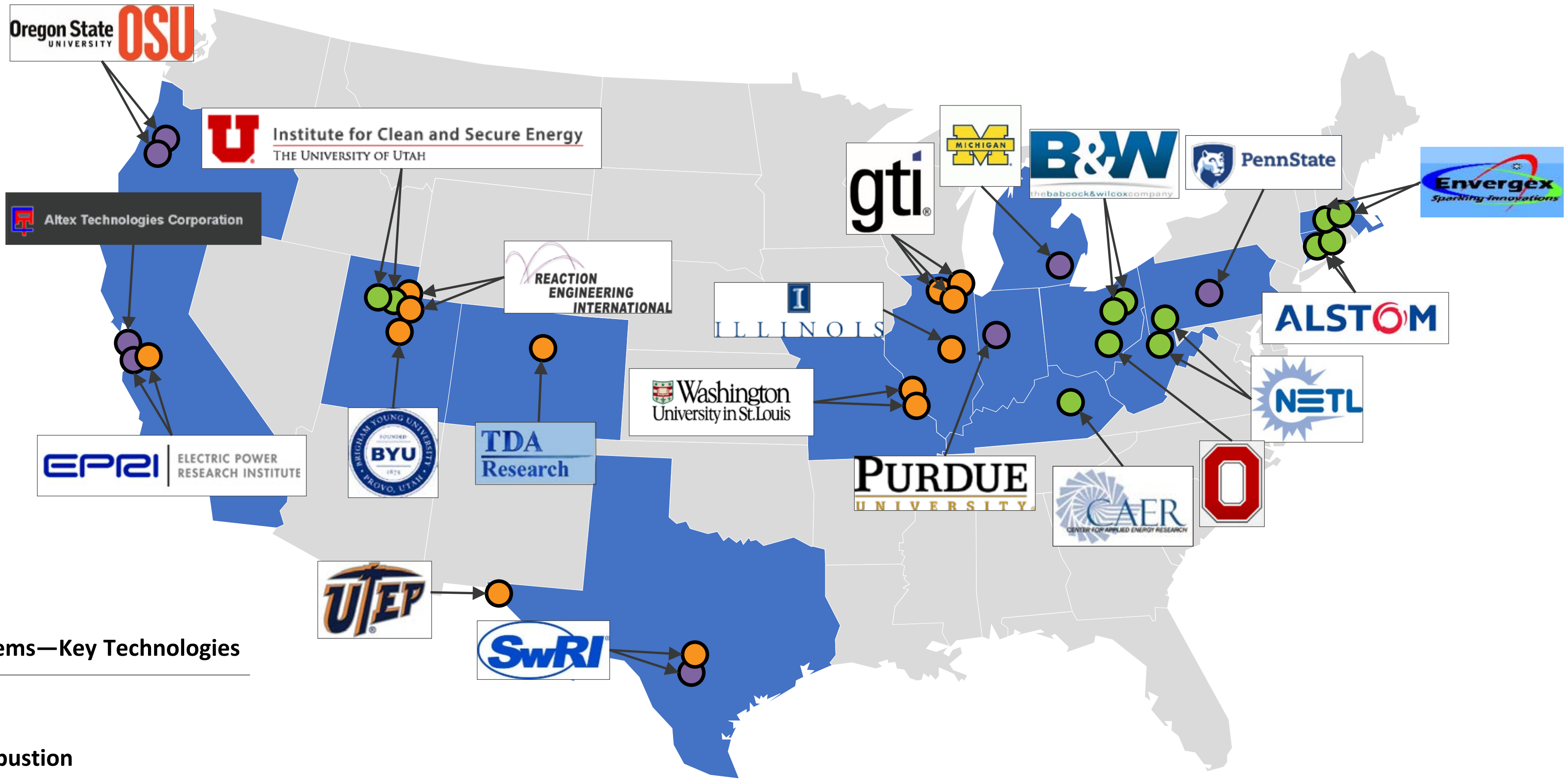




R&D Objectives to Meet Challenges of Transformational Technologies

Technology Challenges	R&D Objectives
Pressurized Oxy-combustion	
• Cost and complexity of pressure • Combustion • Materials • Heat transfer • Oxygen demand • CO2 purification & compression	– Validate process and system performance – Model validation – Collect engineering data for scale up
Chemical Looping Combustion	
• Oxygen carrier reactivity, stability and durability • Solids circulation & separation • Reactor design • System engineering	– Long-term, continuous auto-thermal operation – Validate process and system performance – Develop improved oxygen carriers – NETL researcher collaborations with industry
Supercritical CO_2 Cycle	
• Materials Compatibility • Recuperator Cost • Heat Integration • New Working Fluid	– Maximize heat transfer efficiency – Compact recuperator designs – Materials characterization and performance studies – Match materials and manufacturing with advanced designs – Optimize cycle integration with heat source

Advanced Combustion Systems Project Map



Advanced Combustion Systems—Key Technologies

- Oxy-Combustion
- Chemical Looping Combustion
- Enabling Technologies/Innovative Concepts

Oxy-combustion Projects

NETL
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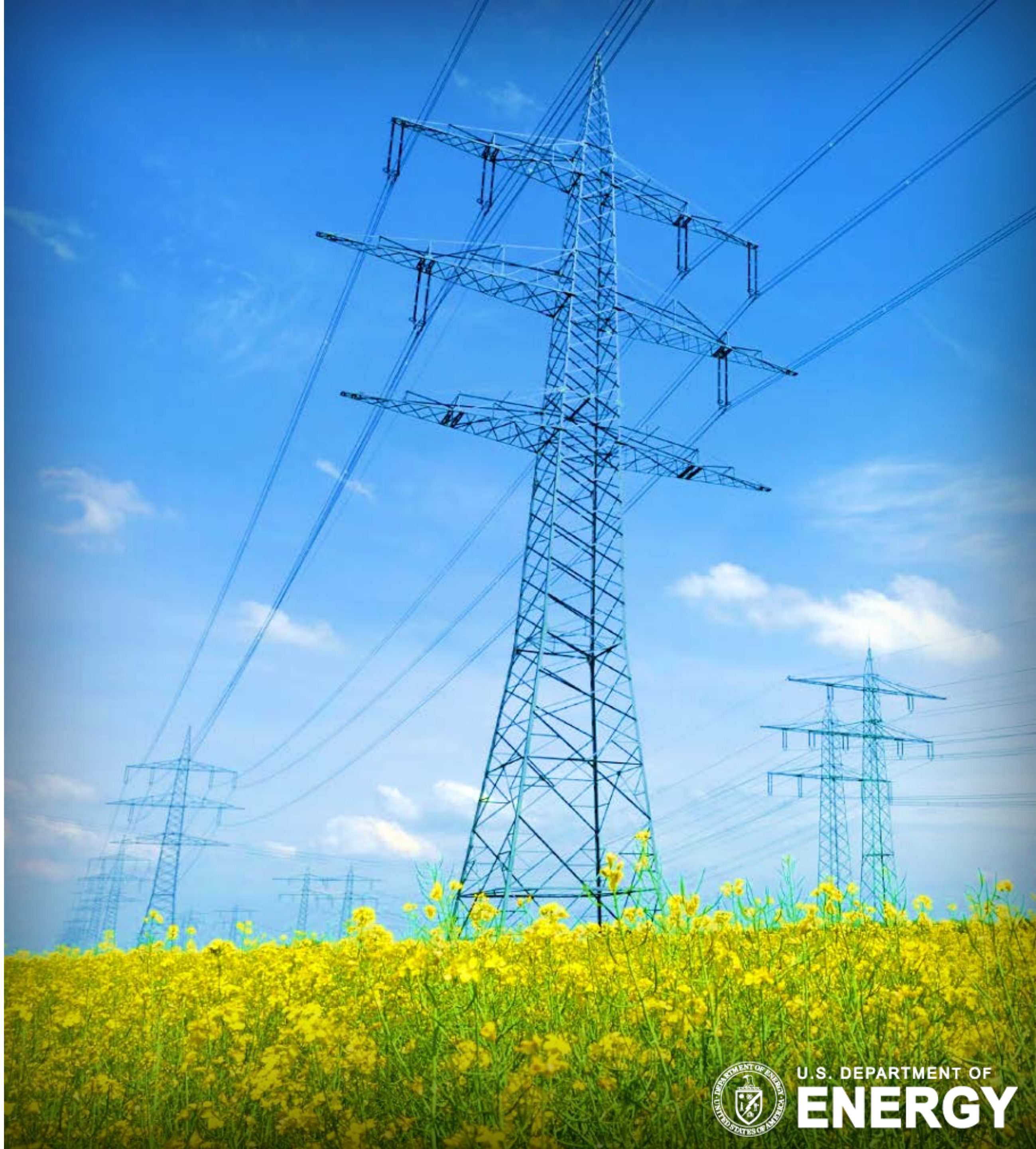


Oxy-Fired Pressurized Fluidized Bed Combustor

Gas Technology Institute

Project Objectives:
– Validate oxy-PFBC process through system modeling
– Test system at pilot-scale
– Develop and validate models using component and pilot test data
– Collect engineering data for scale-up

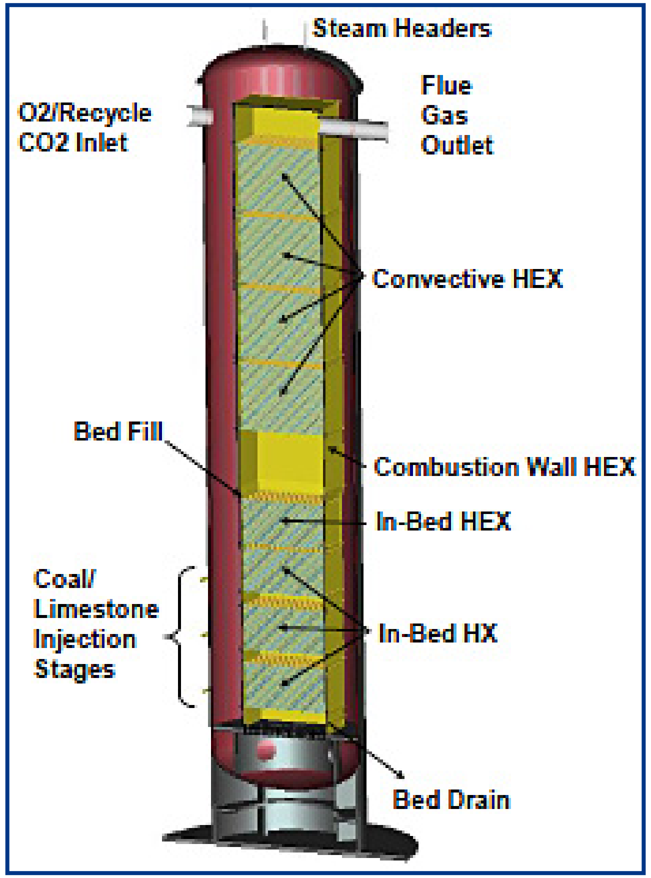
Advantages:
– Best features of atmospheric CFB and bubbling fluidized bed in smaller package
– Predictable over wide range of flows
– Constant temperatures throughout bed

Challenges:
– Achieve appropriate reaction rates
– In-bed heat exchanger and convective heat exchanger corrosion

Maturity: Pilot-scale (1 MWth)

Status: Pilot facility at CANMET opened Oct 2016

Key 2017 Milestones: Complete small pilot-scale testing; develop commercialization plan



GTI's Oxy-PFBC Concept

Enabling Technologies for Oxy-PFBC Development

Gas Technology Institute

Project Objectives:

– Integrate key design modifications into the current Oxy-PFBC pilot plant:
  – In-bed supercritical carbon dioxide (SCO_2) heat exchanger (HEX)
  – Staged coal combustion
  – Isothermal Deoxidation Reactor (IDR)

– Complete pilot-scale testing of integrated system

– Use test results to develop design rules for the respective technologies

Advantages:

– Improved system efficiency

– Reduced cost of electricity

Challenges:

– Uneven mixing in the Oxy-PFBC

– Staged combustion temperature exceeds expectations

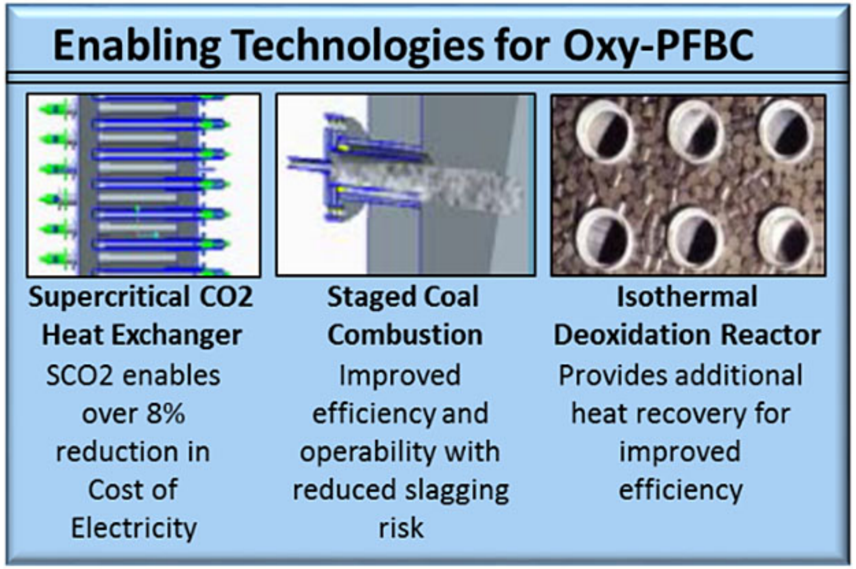
– Unpredictable behavior of supercritical CO_2 working fluid

– Insufficient IDR cooling

Maturity: Pilot-scale (1 MWth)

Status: Component designs complete; component installation in 1 MWth pilot at CANMET underway

Key 2017 Milestones: Complete installation of components; complete pilot-plant testing



Staged, High-Pressure Oxy-Combustion

Washington University in St. Louis

Project Objectives:

– Design, simulate and test at lab-scale a staged, high pressure combustion process
– Evaluate technical feasibility and economics
– Validate process and system performance through simulations and testing
– Collect data to prepare for scale-up

Advantages:

– Latent heat recovery with integrated NOx/SOx capture
– Excess oxygen acts as the diluent rather than recycle
– Near-zero flue gas recycle
– Reduced flue gas volume and equipment size
– Temperature and heat transfer can be controlled

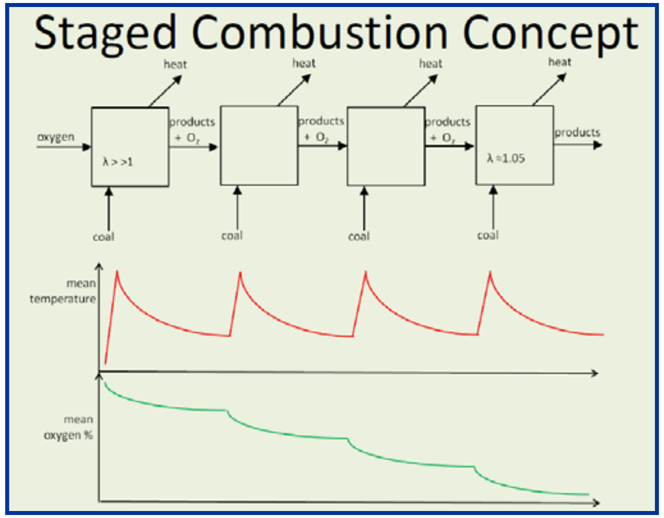
Challenges:

– Controlling high heat flux to allow use of conventional materials
– Deposition control

Maturity: Bench/sub-pilot (140 kWth)

Status: Completed corrosion tests; re-designed burner

Key 2017 Milestones: Update process model and TEA; advance technology to pilot scale



Staged Combustion Reactor

Flameless Pressurized Oxy-Combustion

Southwest Research Institute

Project Objectives:

– Design and layout for a 50-MWth flameless pressurized oxy-combustion (FPO) pilot plant
– Choose a location to host the pilot facility
– Create a testing program that addresses knowledge gaps and advances FPO technology readiness level

Advantages:

– Combustion products in inert slag that drains from the combustor
– No NOx produced
– Highly reduced particulate emissions
– Flue gas is mostly CO_2 and water, facilitating carbon capture

Challenges:

– Coal slurrying technology
– Scale-up of 5 MWth combustor

Maturity: Pre-project planning for FPO pilot

Status: Initiated modeling of the process cycle

Key 2017 Milestones: Complete cycle model; Definition of cycle components; Production of pilot plant cycle diagrams

Itea 5 MWth FPO Plant (Italy)

Chemical Looping Combustion Projects

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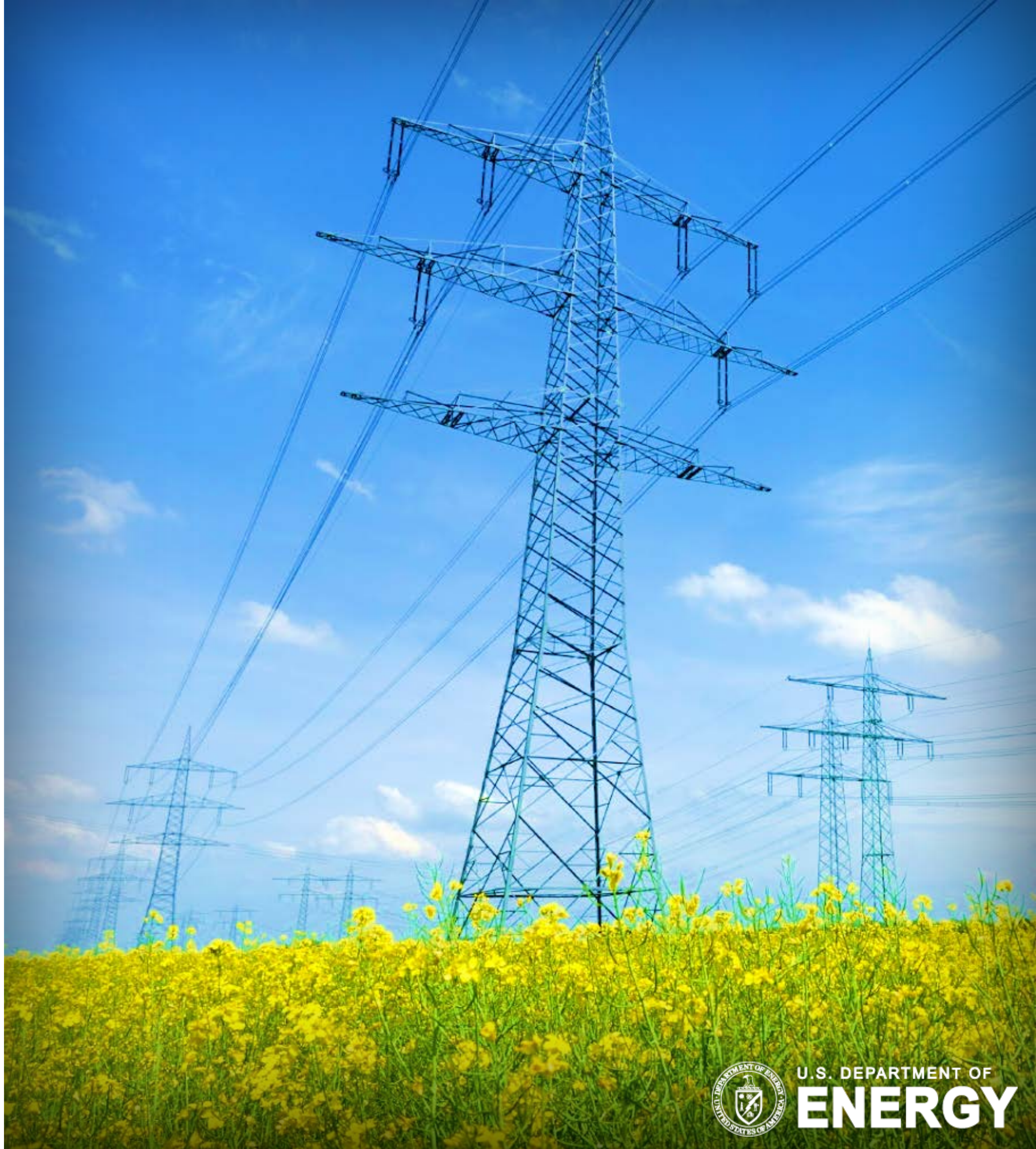


U.S. DEPARTMENT OF ENERGY

Why Chemical Looping Combustion ?

Avoid an ASU and Back-end Separation

Advantages of Chemical Looping Combustion:

In chemical looping, oxygen is created in-situ…

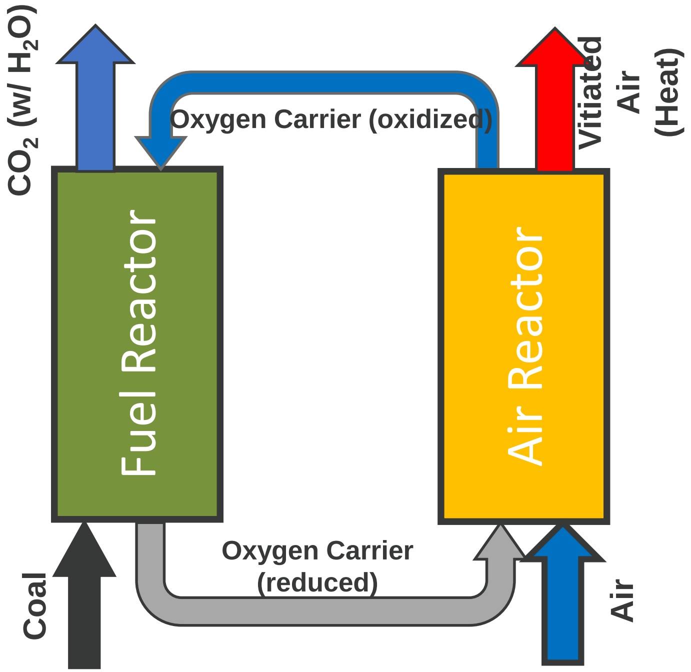
- Eliminates need for oxygen production…*reduces parasitic energy demand and potentially system costs*
- Uses conventional material of construction and fabrication
- Projected CO_2 capture costs exceed program goals

Process Description

- Oxygen introduced via an oxygen carrier – a solid, metal-based compound; either natural or engineered
- Fuel (reduction) and air (oxidation) reactors segregate nitrogen (from air) and CO_2 (from coal)
- Metal oxide is reduced in the fuel reactor, supplying oxygen for combustion of coal, producing CO_2 that is purified, compressed, and sent for storage or beneficial use
- Reduced oxygen carrier sent to air reactor and oxidized, producing hot vitiated air used to produce steam for power
- The oxygen carrier is recycled – a continuous, cyclical process.

R&D Challenges

- Oxygen Carrier
- Solids Circulation
- Reactor Design
- System/Process Design



Iron-Based Coal Direct Chemical Looping

Babcock & Wilcox Power Generation Group

Project Objectives:

– Modeling and testing to validate CDCL process and system performance

– Design, construct, and test small-pilot system

Advantages:

– Novel fuel reactor

– Ohio State's Coal Direct Chemical Looping (CDCL) process

– Ohio State's engineered oxygen carrier

Challenges:

– Novel reactor design scale-up

– Solids handling and transport

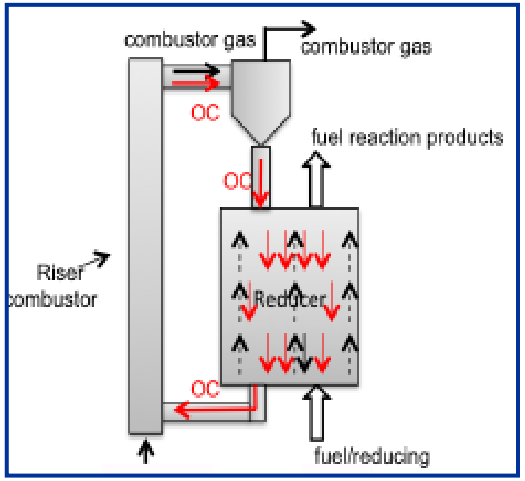
– Long-term oxygen carrying ability, reactivity, durability

Maturity: Sub-pilot scale (25kWth)

Status: Small, autothermal-capable pilot (250kWth) designed.

Key 2016 Milestone: Compete pilot system construction; Operate pilot and initiate testing

25 kWth Sub-pilot at Ohio State



Chemical Looping Combustion with Oxygen Uncoupling

University of Utah

NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Objectives:

– CLOU processing of U.S. coals in sub-pilot scale chemical looping system over a range of conditions, with a focus on carbon conversion and CO_2 capture rate

– Scaling up production of low-cost copper-based CLOU oxygen carriers

– Designing a robust carbon stripper to minimize carbon loss to the air reactor

– Developing modeling and simulation tools for the CLOU process

Advantages:

– Oxygen is evolved from carrier in gaseous form, or "uncoupled"

– CLOU allows for direct processing of solid fuels

Challenges:

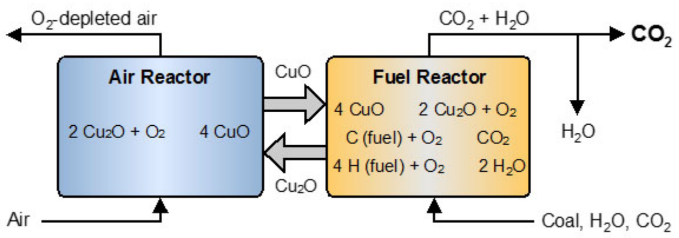
– Carrier options more limited than conventional CLC

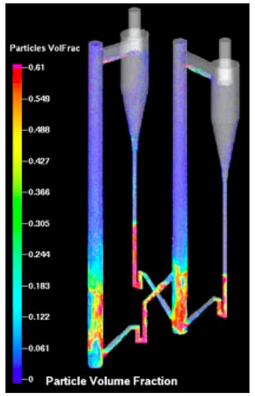
– Solids handling and transport

Maturity: Existing sub-pilot scale, dual-bed, 220-kWth chemical looping system

Status: Project awarded 10/1/15

Key 2016 Milestones: Commission sub-pilot scale system and initiate testing of CLOU carrier





Schematic of the copper-based CLOU process, University of Utah 200 kW pilot-scale chemical looping system and simulation of the dual fluidized bed system.

Enabling Technologies for Chemical Looping Combustion and Chemical Looping with Oxygen Uncoupling

University of Utah

NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Objectives:

- Develop "zero-loss" oxygen carrier processing
- Increase performance of dual bed CLC systems through better loop seal and gas-solid separator design
- Advance implementation of gas-solid chemistry and reaction kinetics into CFD simulations
- Improve heat management and recovery in dual-bed CLC systems
- Investigate novel dual oxygen carrier chemical looping reactor design

Advantages:

- Better control of particle circulation and gas-solid separation can improve reactor performance
- Accurate modeling using improved implementation of reactions valuable in system scale-up efforts

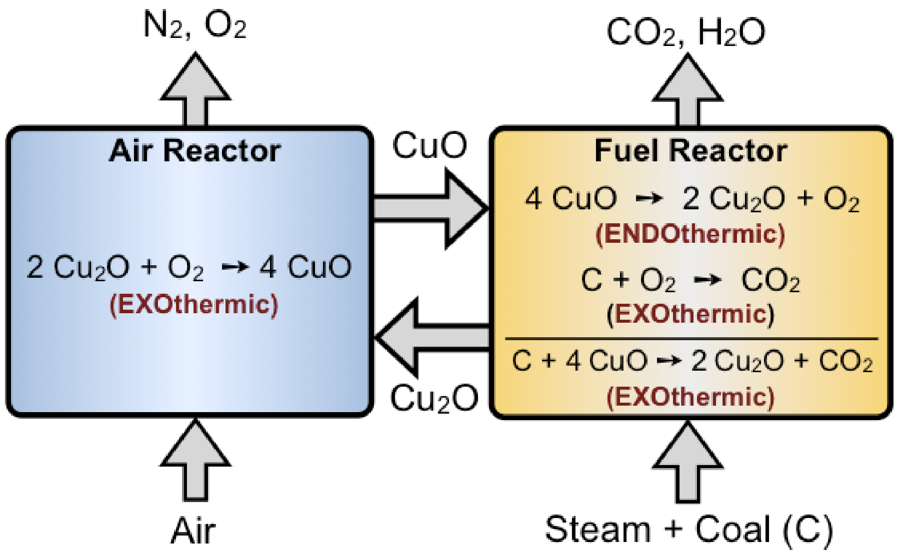
Challenges:

- Solids handling and transport
- Practical implementation of heat extraction from CLC reactors

Maturity: Modeling, simulation, and bench-scale testing

Status: Project awarded 10/1/16

Key 2017 Milestones: Simulation of two new loop seal designs; Initiate carrier/coal ash interactions study; Initial reactor heat balance evaluation



Chemical Looping with Oxygen Uncoupling (CLOU) using Copper.

Chemical Looping Combustion

NETL-RIC

Project Objectives:

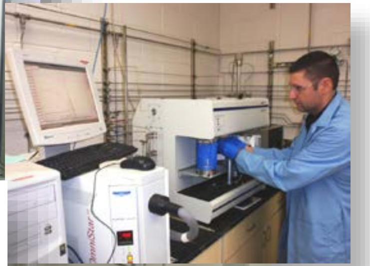
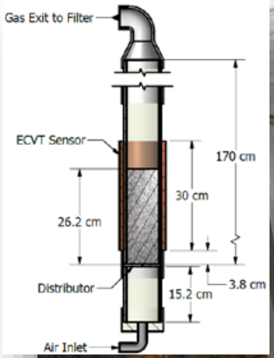
- Test using pilot-scale Chemical Looping Reactor (CLR)
- Improve CLC models leveraging expertise
- Develop improved oxygen carriers
- Share experimental data and results (current collaborations with Alstom and Babcock & Wilcox)

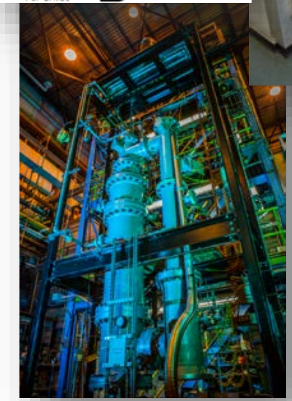
Accomplishments:

- R&D to support CLC technology development
- Designed, constructed, and tested 50kWth Chemical Looping Reactor (CLR)
- Improved sensors for CLC systems
- Developed endothermic oxygen carrier

Maturity: Pilot-scale (50 kWth)

Key 2016 Milestones: Disseminate a best practice for gathering and integrating oxygen carrier kinetic data into CFD reactor sub-models; Demonstrate sensor concept that will improve reliability and operation of CLC system

Institute for the Design of Advanced Energy Systems (IDAES)

Development Of Innovative Advanced Energy Systems Through Advanced Process Systems Engineering

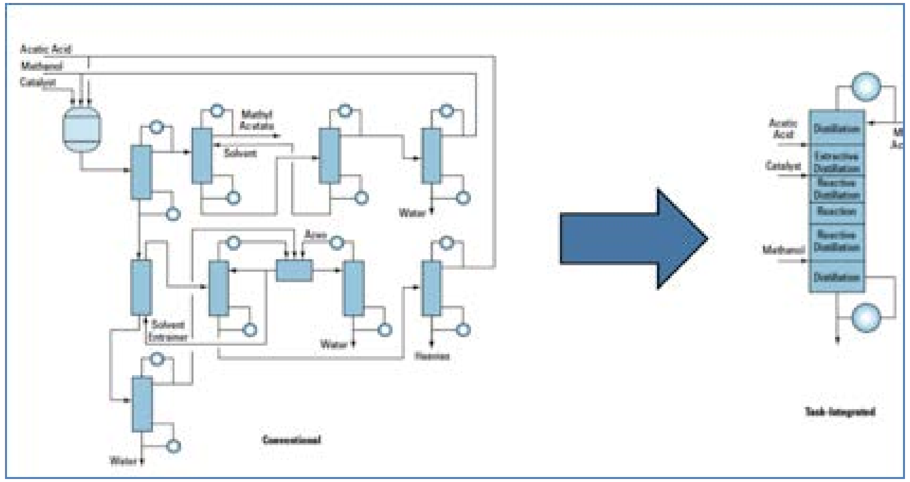
NATIONAL ENERGY TECHNOLOGY LABORATORY

Objective: The Institute for the Design of Advanced Energy Systems (IDAES), will develop and demonstrate next generation computational tools for Process Systems Engineering (PSE) of advanced energy systems to enable their rapid design and optimization.

Challenges:

- Develop and utilize multi-scale, dynamic, simulation-based computational tools and models to support the design, analysis, optimization, scale-up and troubleshooting of innovative, advanced fossil energy systems with carbon capture.
- Identify, evaluate, and prioritize research and development concepts at earlier stages using computational simulations to enable rapid maturation of cost-effective low-carbon energy conversion systems
- Apply tools and models to support and inform NETL-supported projects in advanced combustion and carbon capture
  - Chemical Looping
  - Advanced Combustion Concepts

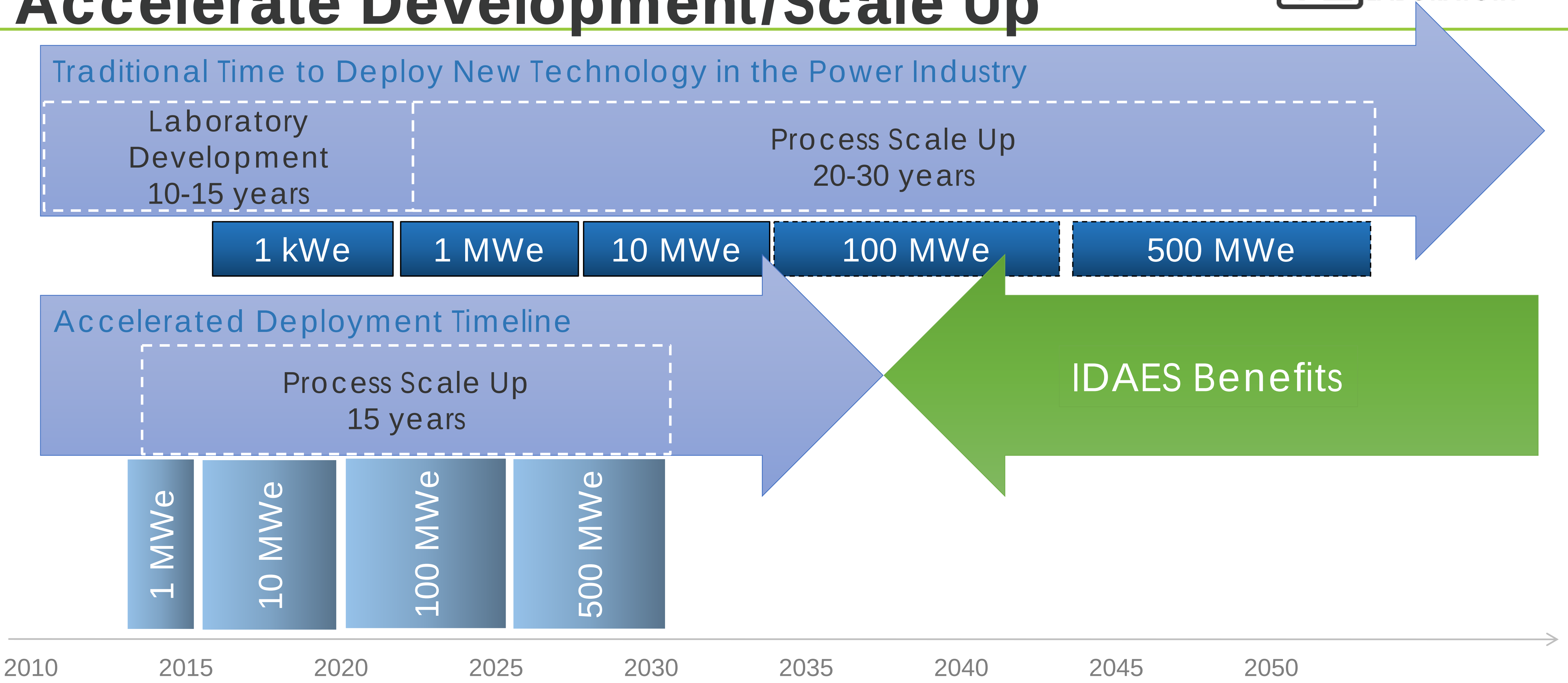
IDAES
Institute for the Design of Advanced Energy Systems



Next generation modeling and optimization platform

- Current tools are insufficient to address demands of integrated advanced fossil energy systems. Needs a more flexible and open modeling environment
- Process Intensification – IDAES will develop highly innovative processes that go beyond current equipment/process constraints
- Large-scale high fidelity, simulation coupled with intrusive uncertainty quantification (UQ), optimization, and advanced process control

Challenge:
Accelerate Development/Scale Up



For More Information About the NETL Advanced Combustion Systems Program

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NETL website:

www.netl.doe.gov

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Office of Fossil Energy website:

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