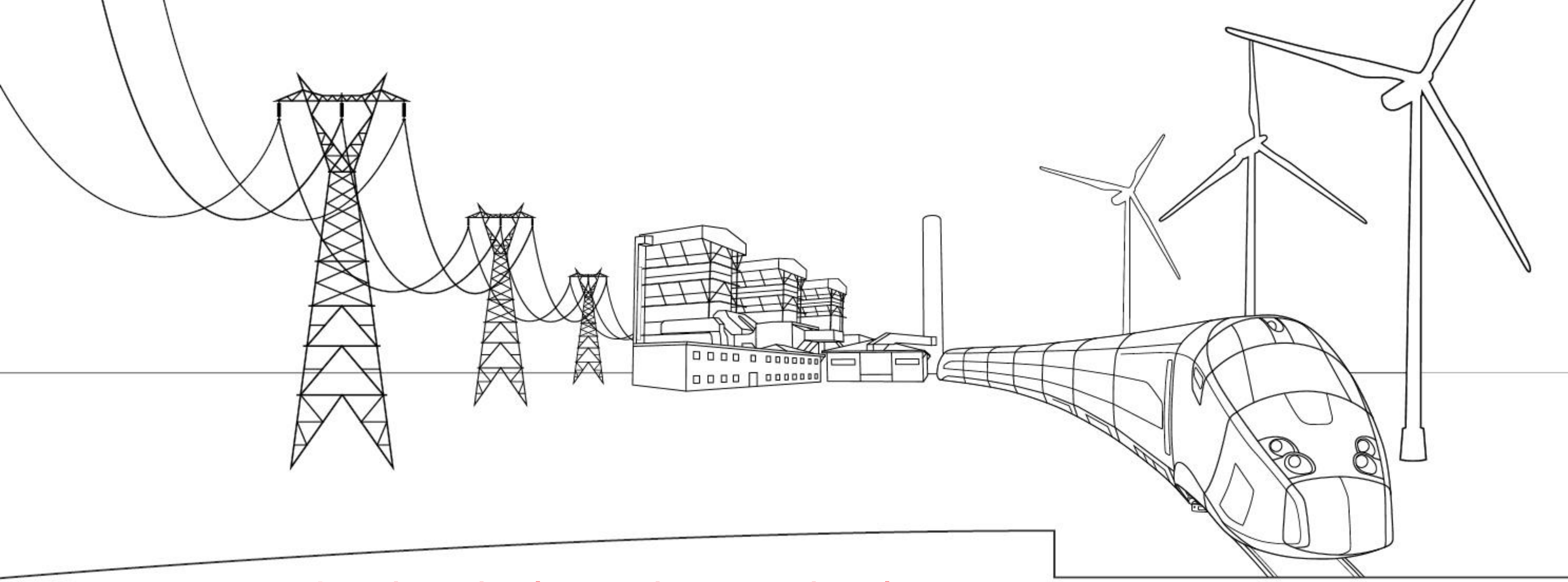


# Alstom's Chemical Looping Technology Program Update


John Chiu

Herb Andrus (PI)

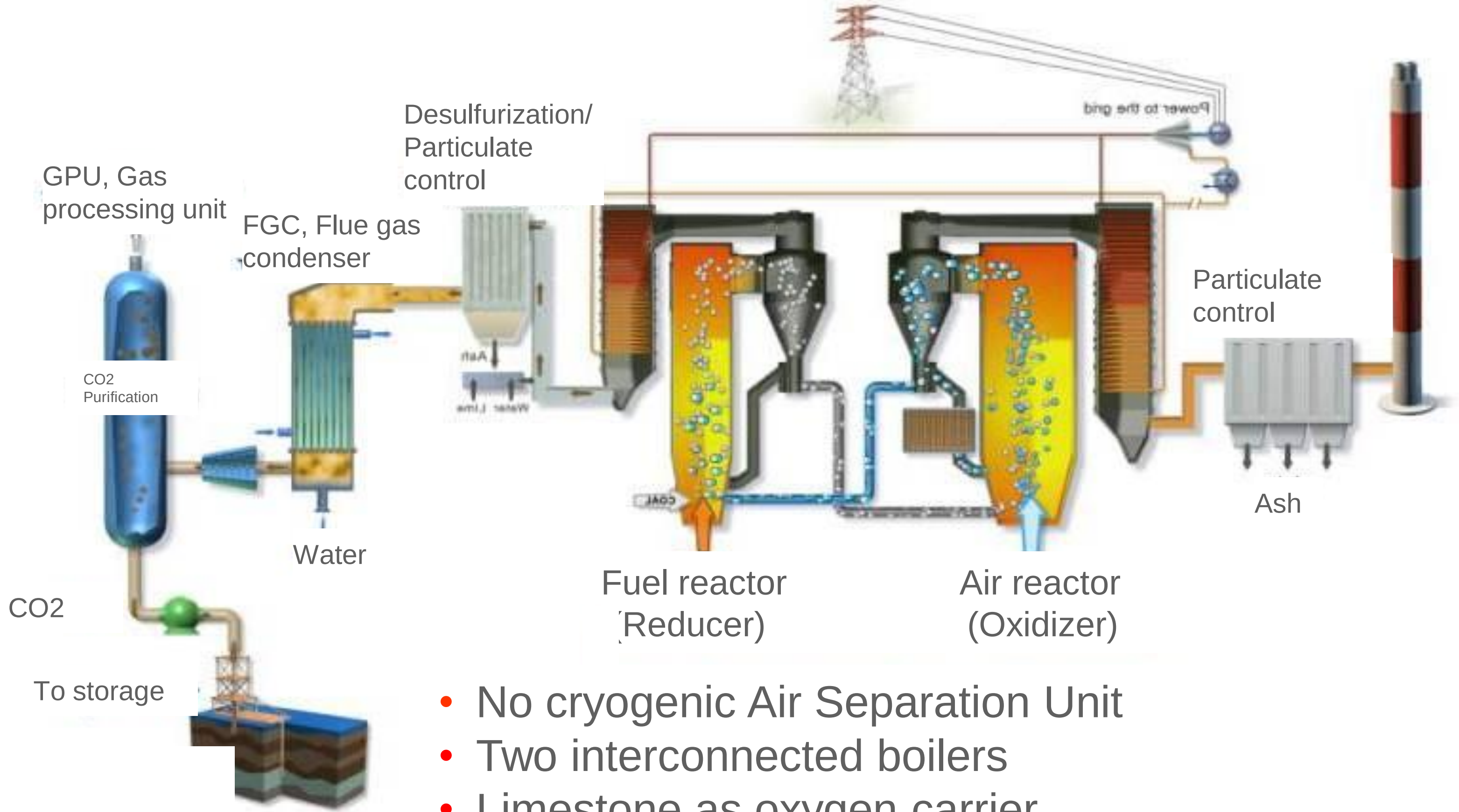
Alstom Power, Inc.


2014 USDOE/NETL
CO2 Capture Technology Meeting
29 July to 1 August, 2014
Pittsburgh, PA

ALSTOM
Shaping the future

# Overview

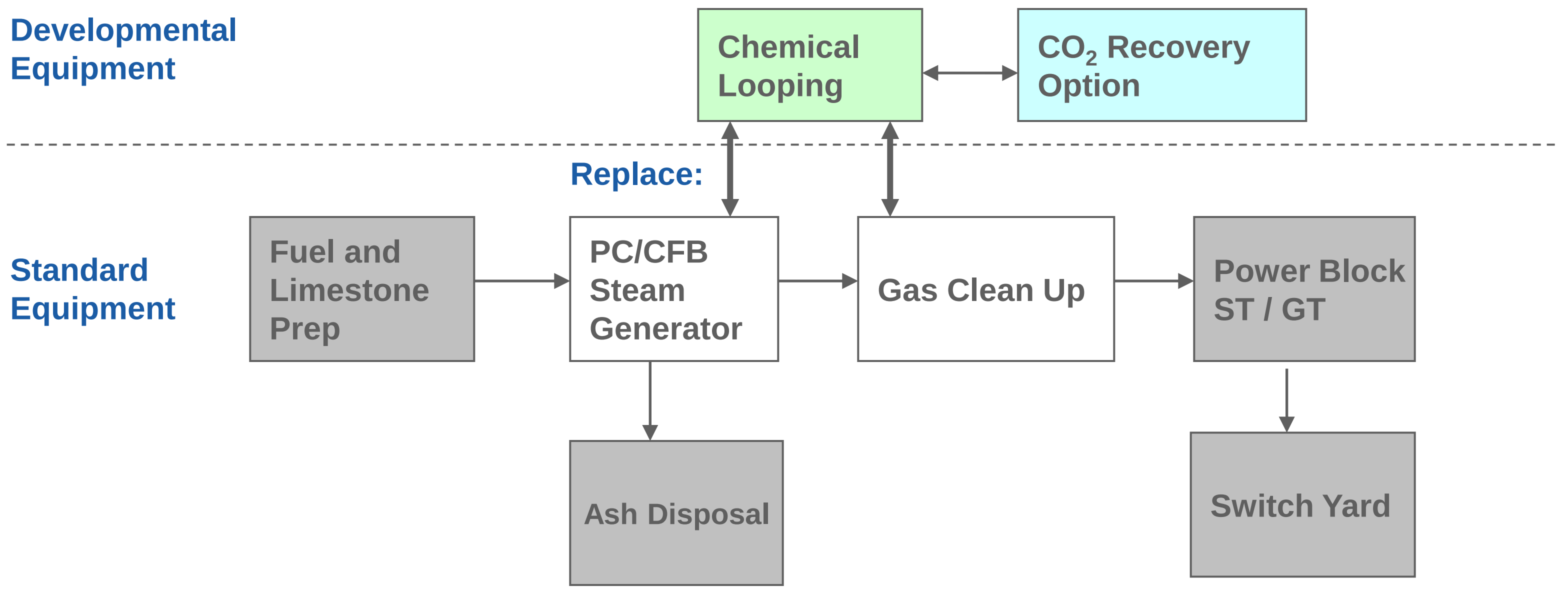
# Chemical Looping Combustion Concept
## What is it?




- No cryogenic Air Separation Unit
- Two interconnected boilers
- Limestone as oxygen carrier

**Advanced oxy-combustion system without Air Separation Unit**

# Chemical Looping Combustion Concept
## How it fits in a Power Plant







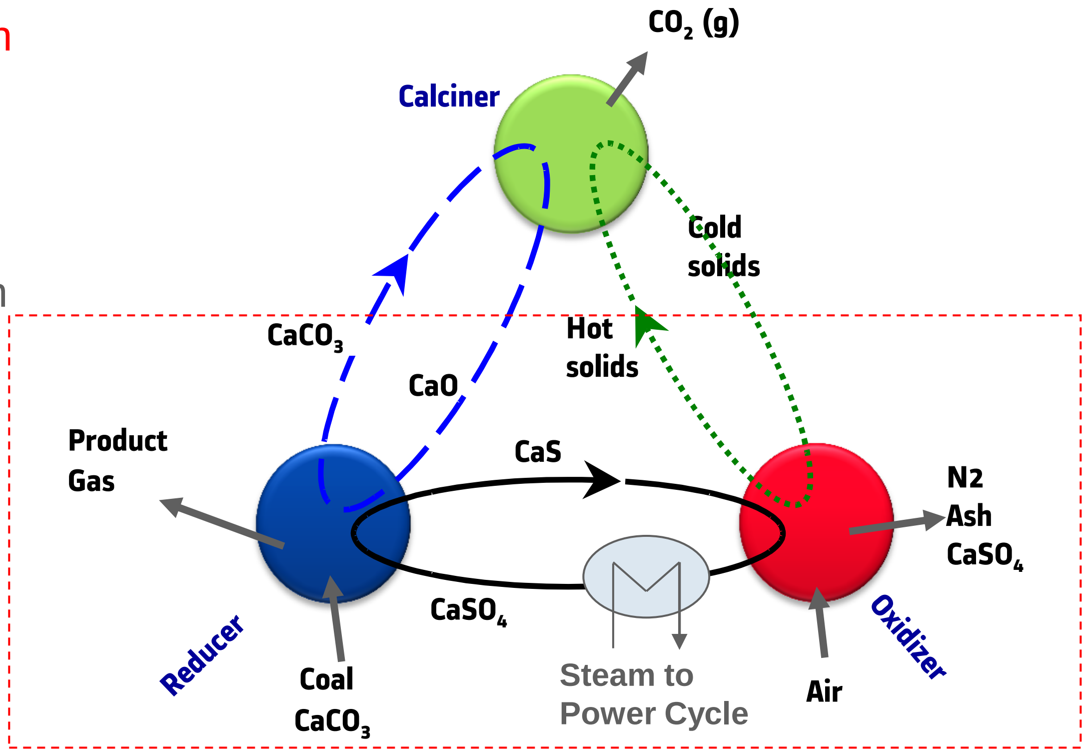
ALSTOM

# Limestone Chemical Looping Concept and Options

**Option 1** – Chemical looping combustion
- Excess air to fuel
- Product gas is $CO_2$
- Heat produces steam for power

**Option 2** – Chemical looping gasification
- Excess fuel to air
- Product gas is Syngas
- No inherent $CO_2$ capture
- High efficiency, low cost IGCC

**Option 3** – Hydrogen production
- Add CaO-$CaCO_3$ loop to option 2
- Add calciner
- Product gas is low cost $H_2$
- Calciner off-gas is $CO_2$




Current prototype setup

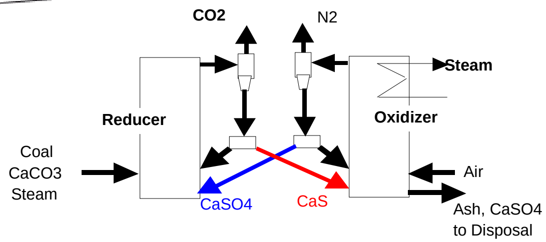
Oxygen Carrier:
- Limestone-based : Alstom – US (3 MWt, Alstom PPL, Windsor, CT)
- Metal oxide based: Alstom – Europe (1 MWt, Darmstadt University)



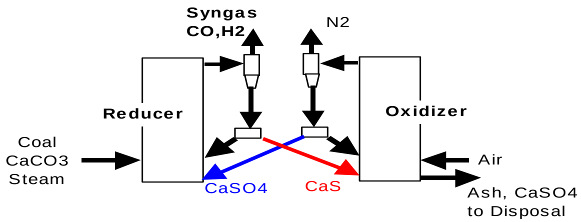


ALSTOM

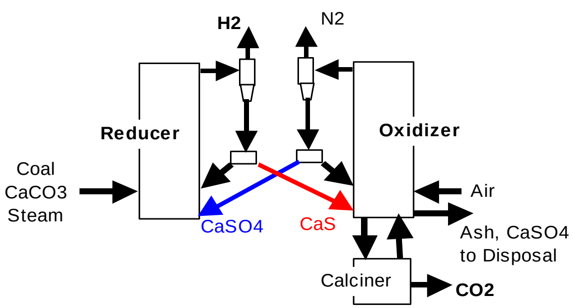
# Chemical looping Process:
## Options and Applications




Option 1 – Combustion with $CO_2$ Capture




Option 2 – Syngas with no $CO_2$ Capture




Option 3 – Hydrogen with $CO_2$ Capture

## Applications

- $CO_2$ Capture – PC Retrofit
- $CO_2$ Capture – CFB Retrofit
- $CO_2$ Capture-Ready Power Plant
- Advanced Steam Cycles

- ICGG with Down-Stream $CO_2$ Capture
- Industrial Syngas
- Coal-to-Liquid Fuels

- $CO_2$ Capture – PC Retrofit
- $CO_2$ Capture – CFB Retrofit
- $CO_2$ Capture-Ready PC/CFB Power Plant
- Advanced Steam Cycles
- IGCC with $CO_2$ Capture
- Fuel Cell Cycles
- Industrial Hydrogen, $CO_2$

- Lowest Cost $CO_2$ Capture Option
- Competitive with or without $CO_2$ Capture

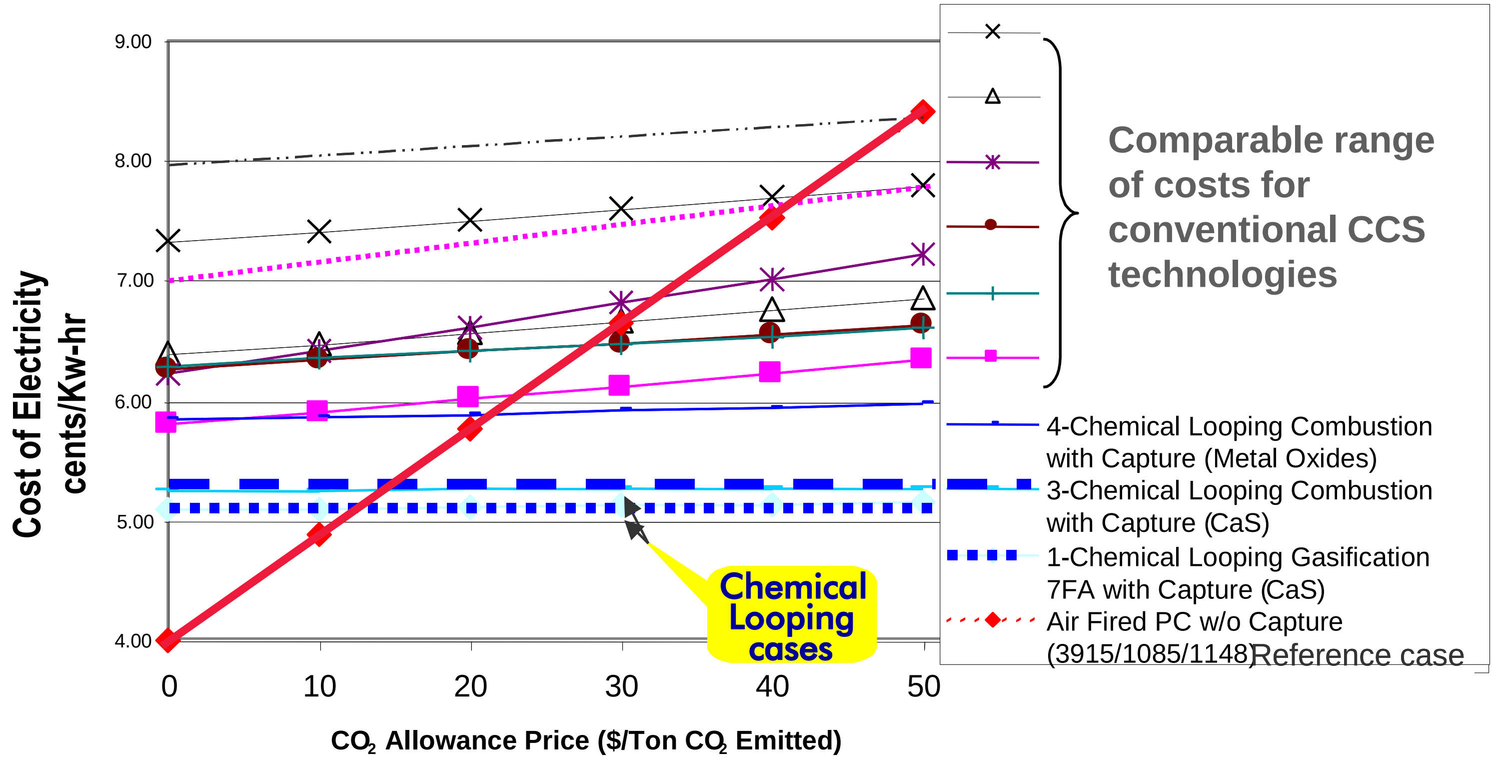




ALSTOM

# Chemical Looping Economics

## Why do we do it?




**Basis:**

- Plant size 400 MWe
- Steam conditions 3915 psia/1085 degF/1148 degF/2.5in Hga
- Cost basis 2006, $US
- Coal cost 1.5 $/MMBtu
- Levelized capital charge 13.8%
- Capacity factor 85%

*Source: 2006 CO2 Product Gas Study*

Chemical Looping, the lowest COE vs. all of the alternatives studied to date.





ALSTOM

# Overview

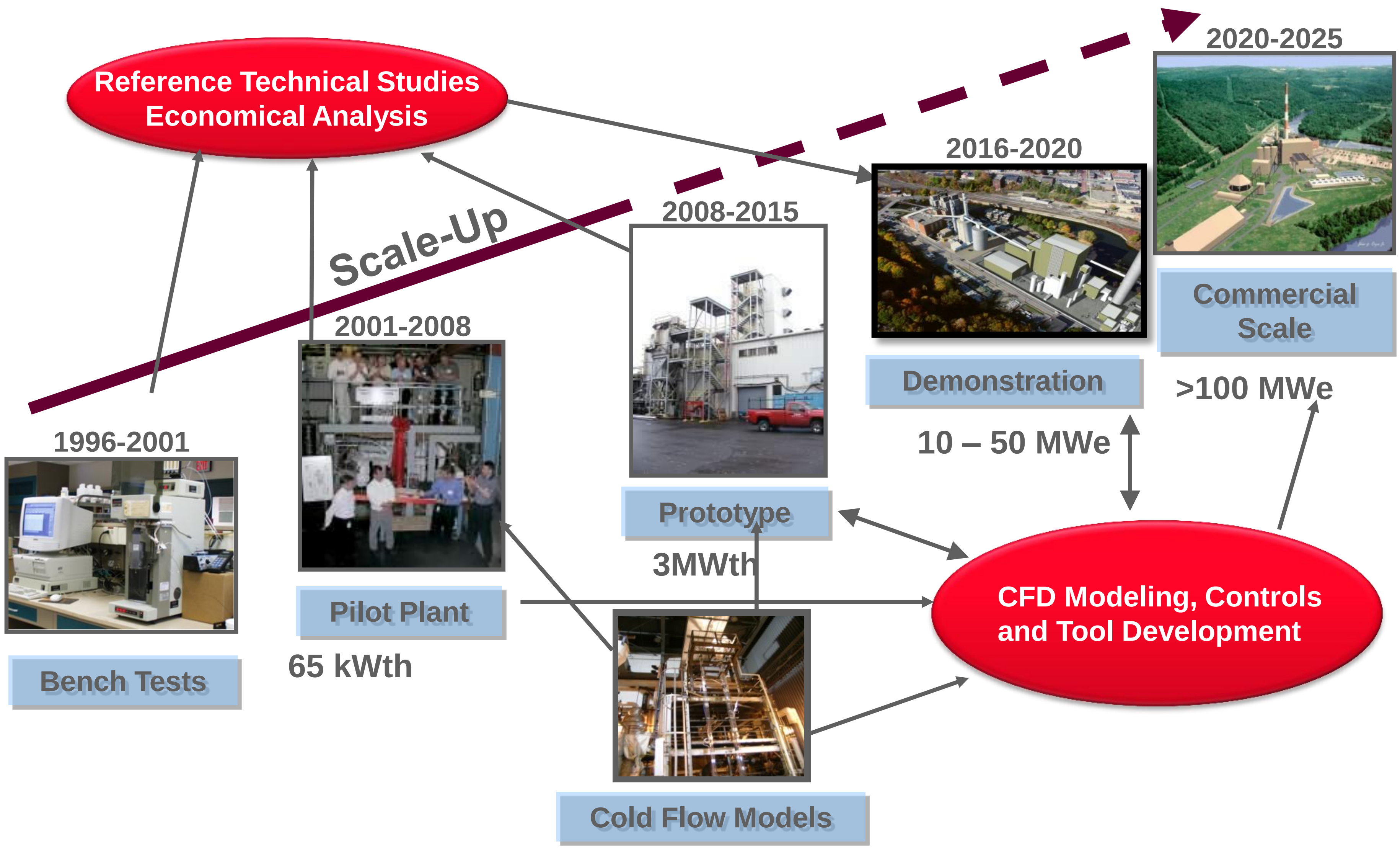






ALSTOM

# Limestone Chemical Looping Combustion (LCL-C™)
## Commercialization Plan

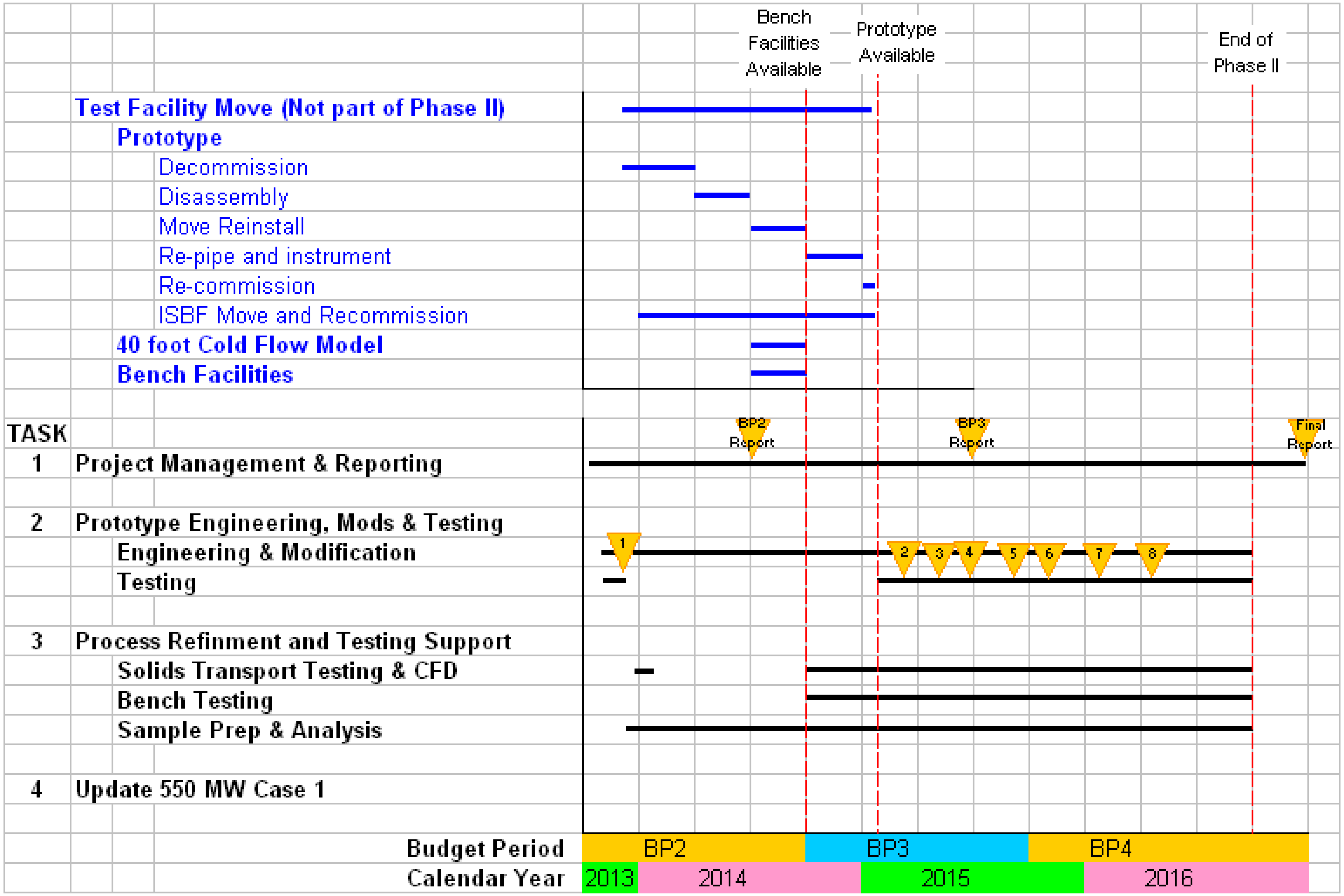







ALSTOM

# Limestone Chemical Looping Combustion
## Project Workscope & Schedule




Phase II Deliverables.xls 1 Nov 2013

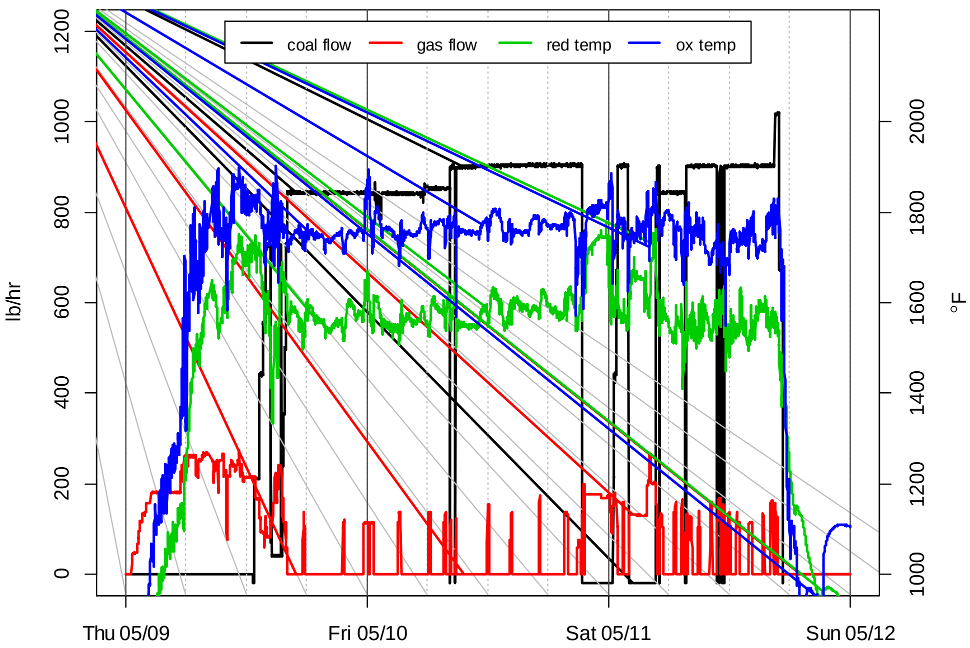
# Phase IV A – Prototype Testing (3 MWt)

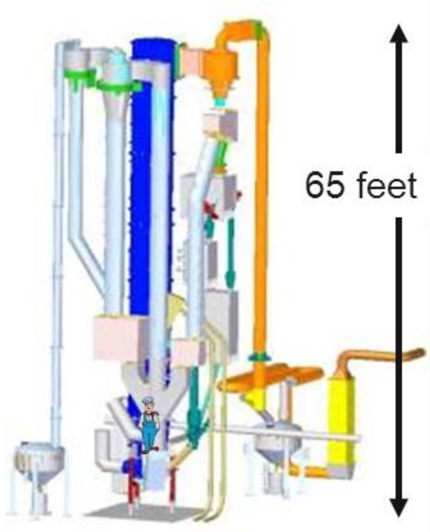
- Main objectives:
  - Design, engineering, construction and operation
  - Autothermal operation of prototype
  - Provide data required to design, build and operate a reliable demonstration plant
- Status:
  - Engineering & go/no-go (Oct 2008 – Apr 2010)
  - EPC, Shakedown (Apr 2010 – Dec 2010)
  - First coal firing - May 2011
  - Autothermal operation achieved in July 2012; 40 hrs May 2013
  - Current activity: Phase II Test 1; Facility Move
- Total DOE-funded budget: $9.2 million (80% DOE):
  - 8.2 for preliminary engineering and EPC
  - 1.0 for preliminary testing
- Additional Alstom funding of $3.5 million to achieve autothermal operation plus a 40 hour autothermal run


Prototype (3 MWt)

# 3 MWth Prototype Performance
## Highlights

- Achieved 1st autothermal operation on two crushed coals.
- Performance is not perfect, but good enough to see:
  - Major chemical looping reactions take place
  - Test results indicate directions for improvement
- No major concept changes have been required.




Prototype (3 MWt)

Highlights:

- 40 hour Autothermal Operation
- Coal-only operation (Pittsburgh & Adaro)
- Chemical looping reactions working
- Unburned carbon < 0.5%
- Up to 97% carbon capture achieved
- Sulfur controllable to near zero
- Stable operation for long periods





ALSTOM

# Limestone Chemical Looping (LCL™) Development
## Advanced Oxy Combustion – Phase I and II Objectives and Status

**DOE/NETL Cooperative Agreement No. DE-FE0009484 Phase I – Completed June 2013**

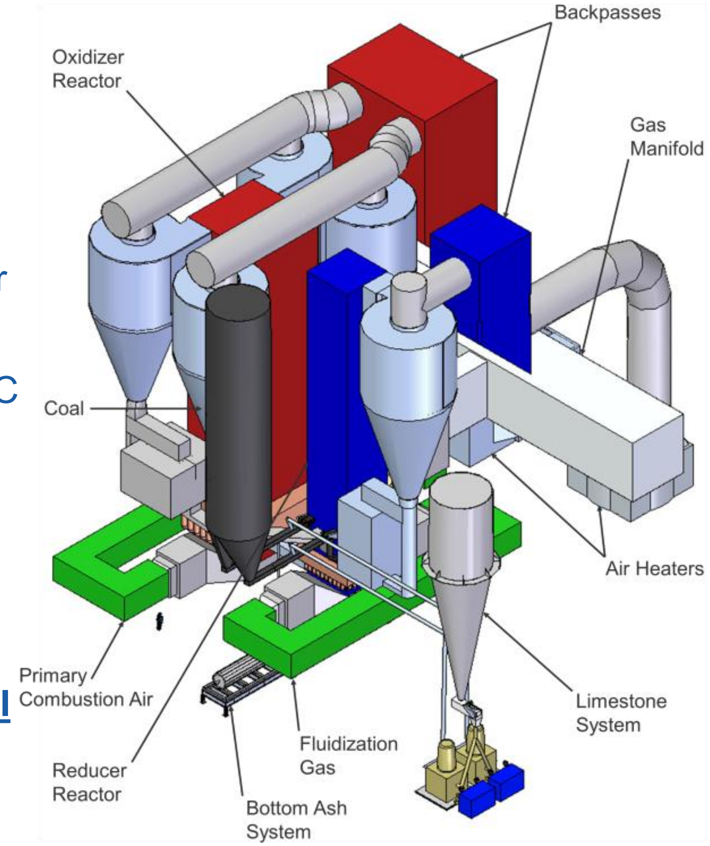
- Techno-economic studies on 4 cases for 550 $MW_e$

Case #
1. Atm. pressure LCL-C™ system using transport reactors
2. An atm. pressure LCL-C™ system with the Reducer reactor in the CFB mode,
3. The atm. pressure LCL-C™ system of Case 1 with an AUSC steam cycle,
4. A pressurized LCL-C™ system with an AUSC steam cycle.

- Engineering Studies
- Bench Scale test – TGA and Plug Flow Static Bed

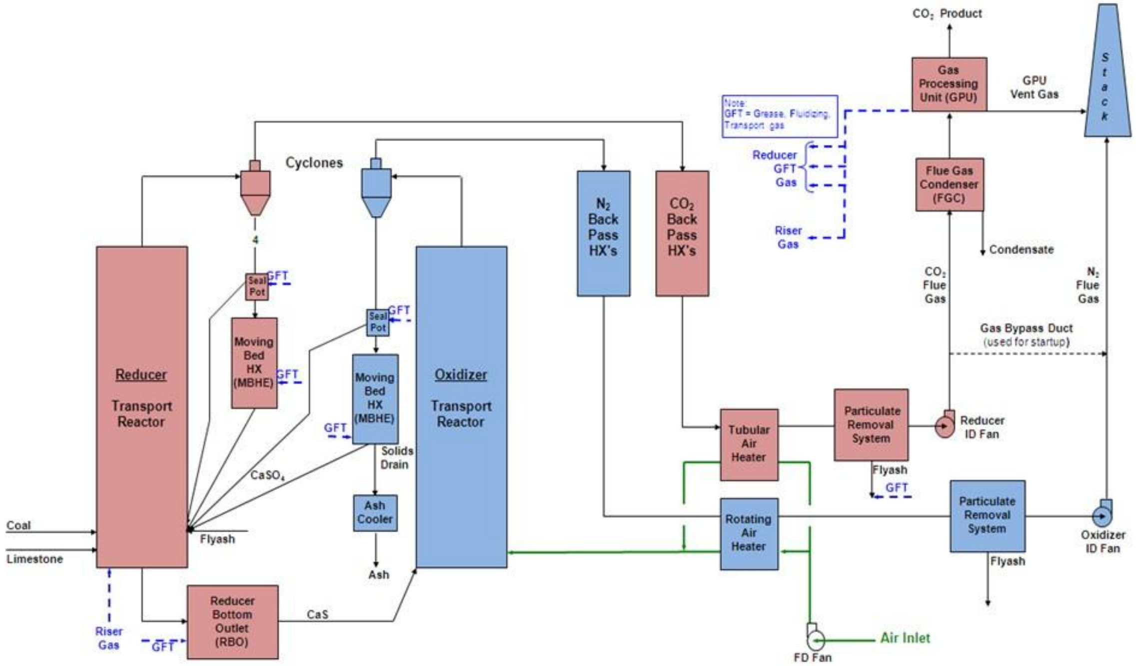
**DOE/NETL Cooperative Agreement No. DE-FE0009484 Phase II – October 2013 to Sept. 2016**

- Address 7 main technology gaps
  - Various Bench tests
  - 6 3MWth Pilot test after modifications
- Update techno-economic study



# Alstom Chemical Looping Reference Studies
## Latest analysis – June 2013

- Case 1 [**base**] **Atm. pressure LCL-C™ system using "fast CFB" transport reactors**
- Case 2 Atm. pressure LCL-C™ system with the Reducer reactor in the CFB mode,
- Case 3 Atm. pressure LCL-C™ system of Case 1 with an AUSC steam cycle,
- Case 4 3 – 7 bar pressurized LCL-C™ system with an AUSC steam cycle




**CLC has potential to be lowest COE for coal-based power with CCS**



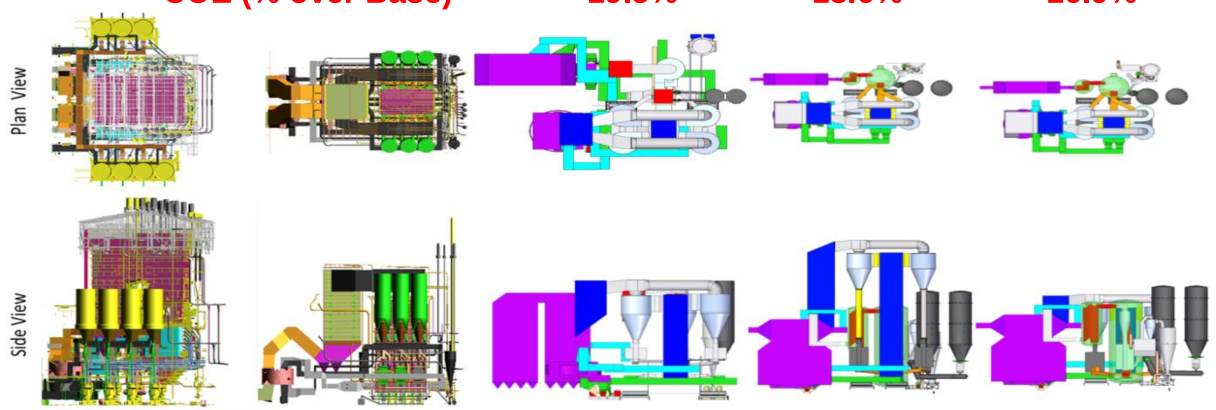


ALSTOM

# Limestone Chemical Looping – Phase I Results

| Phase I - Performance and Cost Summary vs DOE Goals | | | | | | | |
|---|---|---|---|---|---|---|---|
| | DOE/NETL Base Case | DOE GOAL | Case 1 | Case 2 | Case 3 | Case 4 | Case 4A |
| Technology | PC | | LCL-C™ | | | | |
| | | | | | | | |
| Pressure (bar) | 1 | | 1 | 1 | 1 | 7 | 3 |
| Reducer Reactor | | | transport | CFB | transport | transport | transport |
| Steam Cycle | USC | | USC | USC | AUSC | AUSC | AUSC |
| Net Capacity (MW) | 550 | | 550 | 550 | 550 | 550 | 551 |
| Net Efficiency (%) | 39.3 | | 35.8 | 35.8 | 41.1 | 42.7 | 42.0 |
| Investment Cost ($/kW) | 2452 | | 2795 | 2801 | 2944 | 3067 | 2978 |
| COE (cnts/kW-hr) | 8.10 | | 9.67 | 9.68 | 9.51 | 9.60 | 9.46 |
| CO2 Avoided Cost ($/ton) | | | 27 | 27.3 | 24.2 | 26.5 | 23.4 |
| | | | | | | | |
| Carbon Capture (%) | 0 | >90% | 97% | 97% | 98% | 96% | 97% |
| COE (% over base) | | <35% | 19.5% | 19.6% | 17.5% | 18.6% | 16.9% |

**Cycle COE (% over Base)** — **SC 19.5%** — **AUSC 18.6%** — **AUSC 16.9%**




| PC Fired Utility Unit | Coal Fired CFB Unit | Coal Fueled LCL Unit | 7atm Coal LCL Unit | 3atm Coal LCL Unit |
|---|---|---|---|---|
| Relative Boiler Height = 100% | 80% | 70% | 95% | 70% |





ALSTOM

# Chemical Looping Development

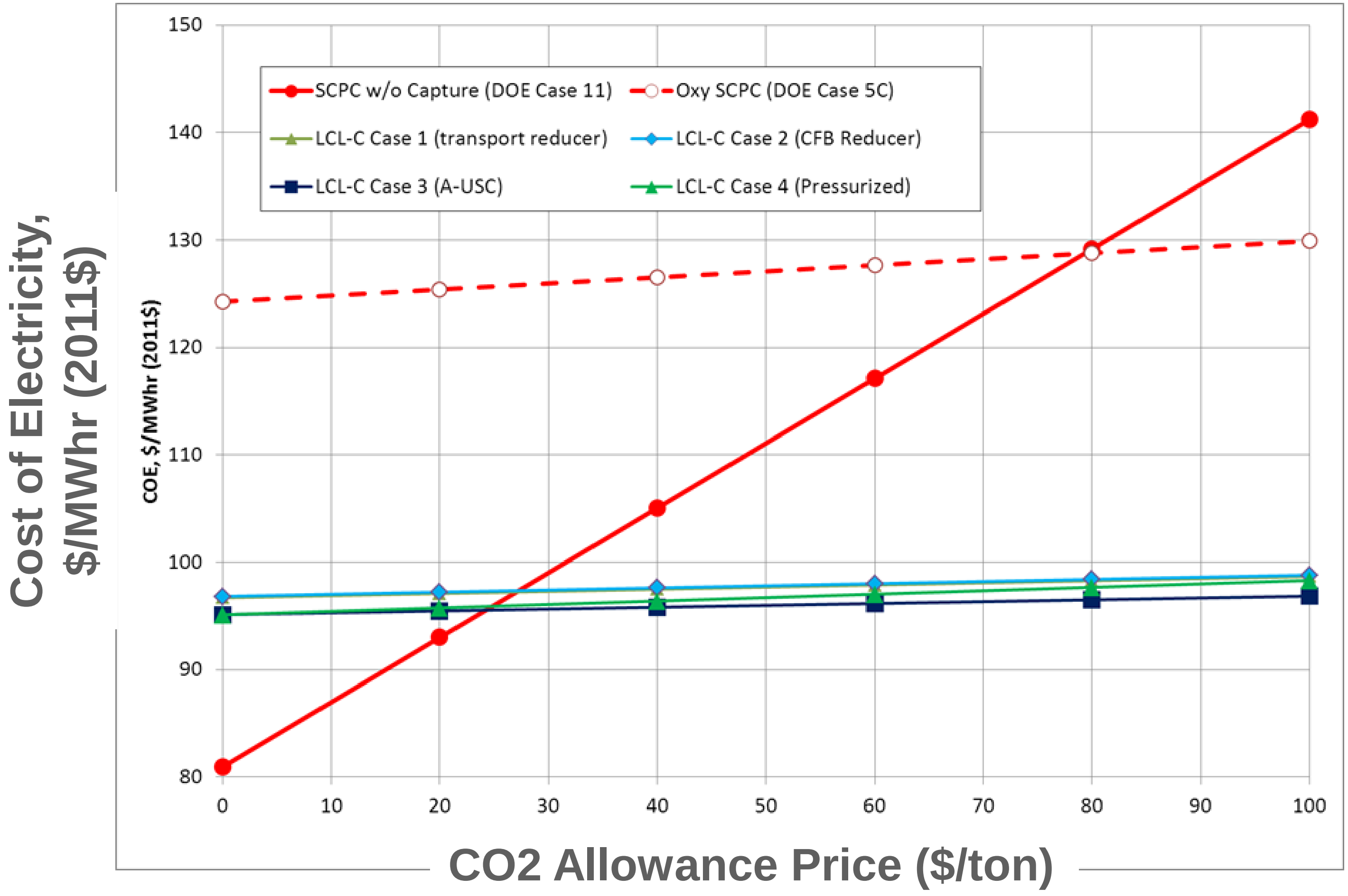
## US DOE-sponsored techno-economic analysis

| | Baseline: US DOE SCPC plant, no capture | US DOE Oxy-SCPC plant | Alstom SC Chem Loop Plant, Case 1 |
|---|---|---|---|
| Nominal output (net, MW) | 550 | 550 | 550 |
| Capacity factor (%) | 85 | 85 | 85 |
| HHV efficiency (% HHV) | 39.3 | 29.3 | 35.8 |
| $CO_2$ capture (%) | **0** | **93** | **97** |
| $CO_2$ emitted rate (lb/MWh) | 1210 | 113 | 40 |
| EPC overnight cost ($/kW) | 2452 | 3977 | 2795 |
| Cost of Electricity Breakdown | | | |
| Fuel ($/MWh) | 25.53 | 34.25 | 28.04 |
| Capital ($/MWh) | 38.19 | 66.23 | 46.55 |
| O&M fixed ($/MWh) | 9.48 | 14.24 | 10.58 |
| O&M variable ($/MWh) | 7.74 | 9.54 | 11.53 |
| T&S adder to COE ($/MWh) | 0 | 8.29 | 7.08 |
| 1st yr COE (w/o T&S, $/MWh) | 80.95 | 124.25 | 96.7 |
| LCOE (w/o T&S, $/MWh) | **102.64** | **157.55** | **122.62** |
| Fuel cost ($/MMBtu) | 2.94 | 2.94 | 2.94 |
| Construction period (yrs) | 5 | 5 | 5 |
| Operational period (yrs) | 30 | 30 | 30 |
| % Increase – Levelized COE | | **53.5** | **19.5** |

**DOE goal: >90%**

**DOE goal: <40%**

# COE Sensitivity to $CO_2$ Allowance Price



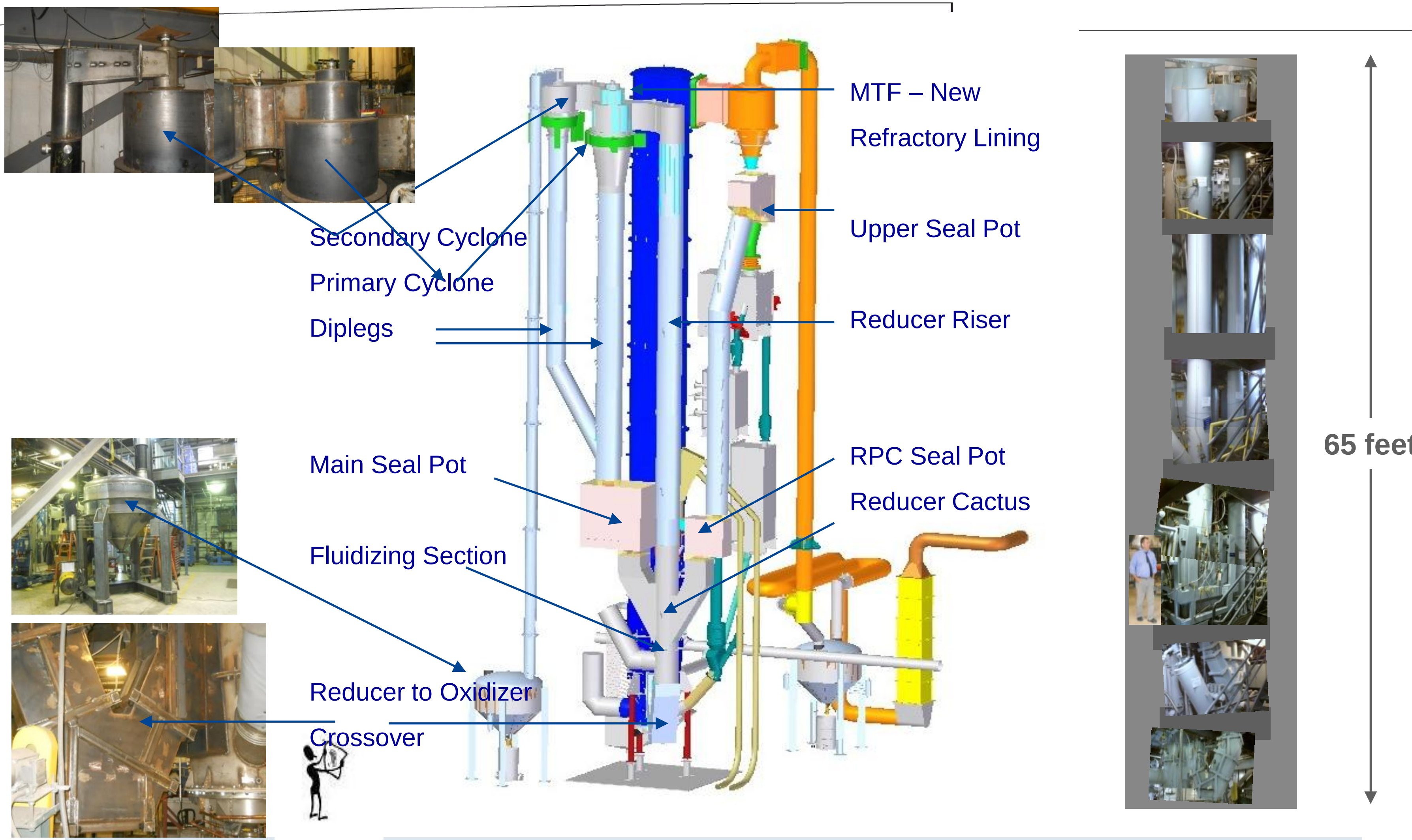

LCL-C™ process at economic parity at \$24-26/ton $CO_2$





ALSTOM

# Chemical Looping 3 MWth Prototype
## Component Construction



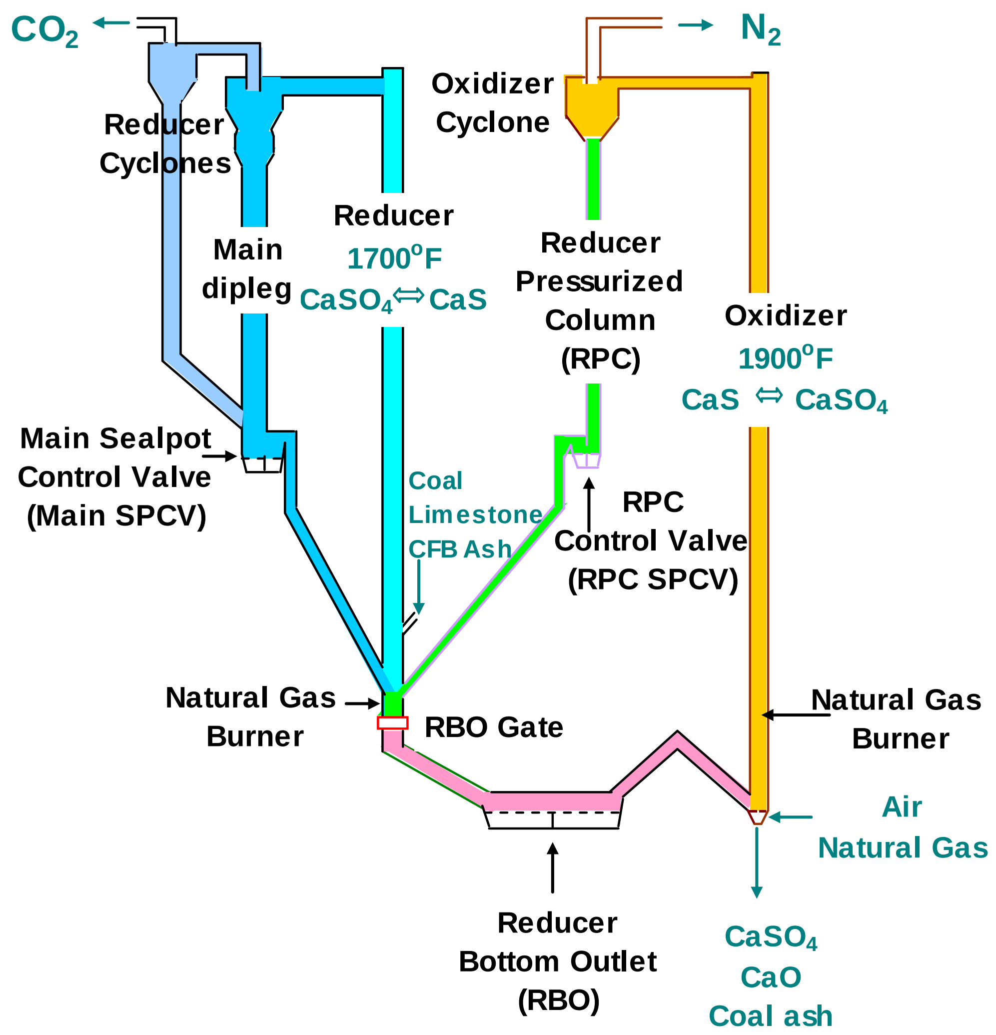

Retrofit of Alstom’s existing Multi-use Test Facility (Windsor, CT)





ALSTOM

# Chemical Looping 3 MWth Prototype Schematic




**Design Flow Rates:**

| | |
|---|---|
| Coal | 700 lb/hr |
| Limestone | 125 lb/hr |
| Air | 8,000 lb/hr |
| RPC flow | 170,000 lb/hr |
| Inventory | 6,000 lb |

**Sorbent Constituents:**

$CaSO_4$ ⇔ CaS
CaO
Coal ash

**Reactions:**

Reducer:

$CaSO_4$+ Coal⇔CaS + 2 $CO_2$

Oxidizer:

CaS + Air ⇔$CaSO_4$ + heat

**Reducer "Combustion"**

**$CaSO_4$ + 4 CO ⇔ CaS + 4 $CO_2$**

**2 C(coal) + 2 $CO_2$ ⇔ 4 CO**

**$CaSO_4$ + 2 C(coal) ⇔ CaS + 2 $CO_2$**





ALSTOM

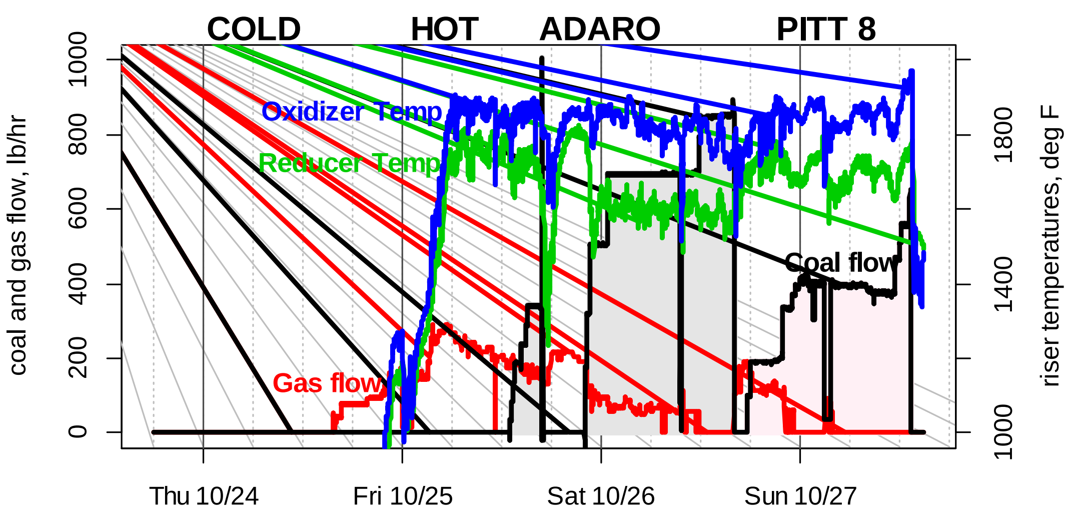
# Limestone Chemical Looping – Phase II

## Phase II Objective:

- Resolve the 3 MWth Prototype Technology Gaps identified in Phase I

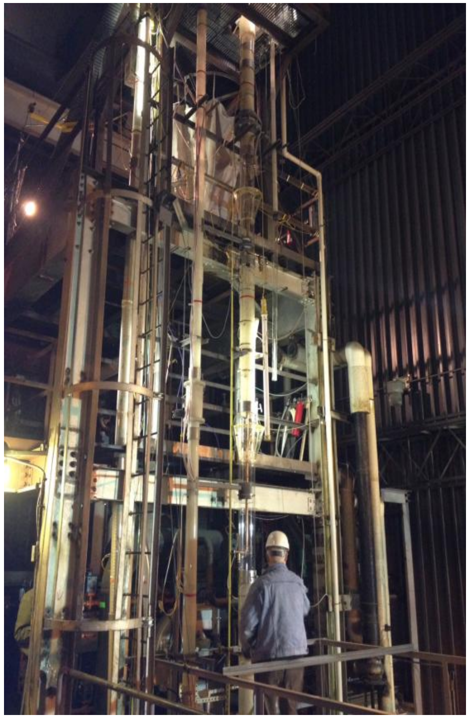
## Phase II Status:

- Phase II is in progress
- 3 MWth Prototype - Test 1 Completed
- 40-Foot CFM Tests Underway
- Prototype Move & Modifications




**Prototype Test 1- Performance Survey**

**40-ft Cold Flow Model (CFM)**



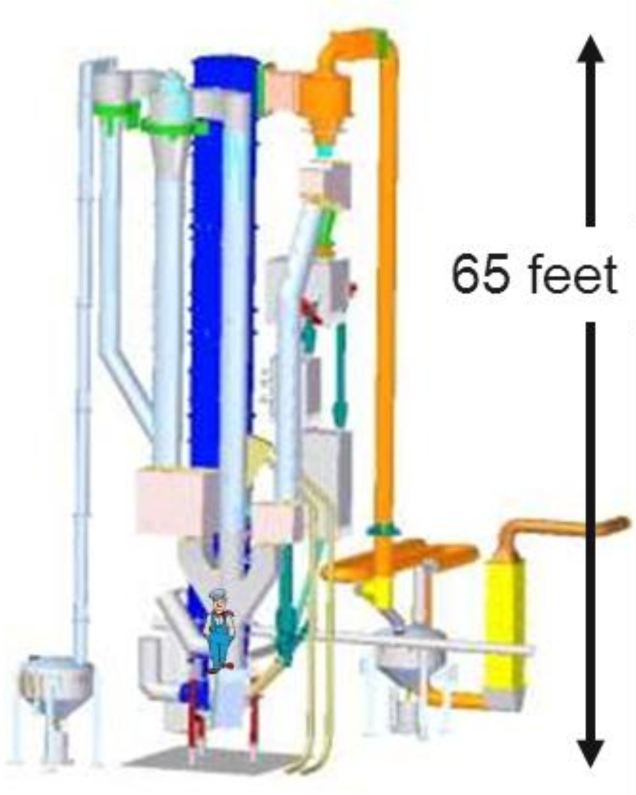




ALSTOM

# Limestone Chemical Looping (LCL™) Development

## Modifications & Planned Work




Prototype (3 MWt)

| ID | TECHNICAL GAP | AFFECTS |
|---|---|---|
| 1 | High Solids Loss Rate | operability |
| 2 | Main DipLeg Flushing | operability |
| 3 | Solids stability | operability |
| 4 | Sorbent Activation | operability |
| 5 | Sulfur Capture / Loss | operability |
| 6 | Low temperatures during some tests | operability |
| 7 | Carbon Carryover to Oxidizer | performance |

**Define Gap / check solution:**

Prototype Performance Shortfall
Analyze Prototype Data
Define Bench Test

**find solution:**

40-Ft CFM for Solids Transport

50-Ft & Bench Test Rig(s) for Chemistry, Conversions, Transport





ALSTOM

# Limestone Chemical Looping (LCL™) Development Current 3 MWth Prototype Modifications

| | MODIFICATION | | INTENDED GAP IMPROVEMENT | STATUS | EXPECTED COMPLETION |
|---|---|---|---|---|---|
| 1 | Main SPCV Repair | Structural Repair & Eliminate Gas Leakage | 2, 3, 4 | Fab' Complete | 22 June 2014 |
| 2 | Main DipLeg Gas Drains | Drain process gas; improve stability | 1, 2, 3 | Fab' Complete | 15 Aug 2014 |
| 3 | RPC Gas Drain | Improve RPC solids stability | 3, 6 | Fab' Complete | 15 Aug 2014 |
| 4 | Steam Activation Heat Exchanger | Permit full load; improve sulfur capture; reduce CO | 4, 5 | In Engineering | 15 Sep 2014 |
| 5 | Secondary DipLeg Plug | Improve Main DipLeg testing/troubleshooting | 1, 2, 3 | In Fab' | 15 Aug 2014 |
| 6 | Lower RPC SPCV Fluidizing Nozzles | Increase Oxidizer-to-Reducer Solids Flow | 3, 6 | Fab' Complete | 15 Sep 2014 |
| 7 | 100 kWt LCL-C™ Test Facility | Provide quick-turn-around, low-cost Trial-Horse for Prototype | 1 thru 7 | Engr' & Fab' | 30 Dec 2014 |
| 8 | Gas Sample System Upgrades | Improve In-process Solid/Gas Sampling ability | 1 thru 7 | In Engineering | 30 Dec 2014 |
| 9 | Gas Analyzer System Upgrades | Improve H2O, N2, sulfur measurement & Mat'l Bal | 1 thru 7 | In Engineering | 30 Dec 2014 |
| 10 | Coal/Limestone Prep Upgrades | Replace inadequate crusher with cone crusher | 5, 7 | In Engineering | 15 Mar 2015 |
| 11 | Improve Operator Solids Mgt' Display | Make solids transport management easier for Operators | 1, 2, 3 | In Engineering | 15 Mar 2015 |
| 12 | Prototype/CFM testing & analysis | Develop improved tools for Operators | 1 thru 7 | Ongoing | Ongoing |
| | | | | BP2PrototypeMods.xls | |
| | | | | 25 June 2014 | |





ALSTOM

# Overview







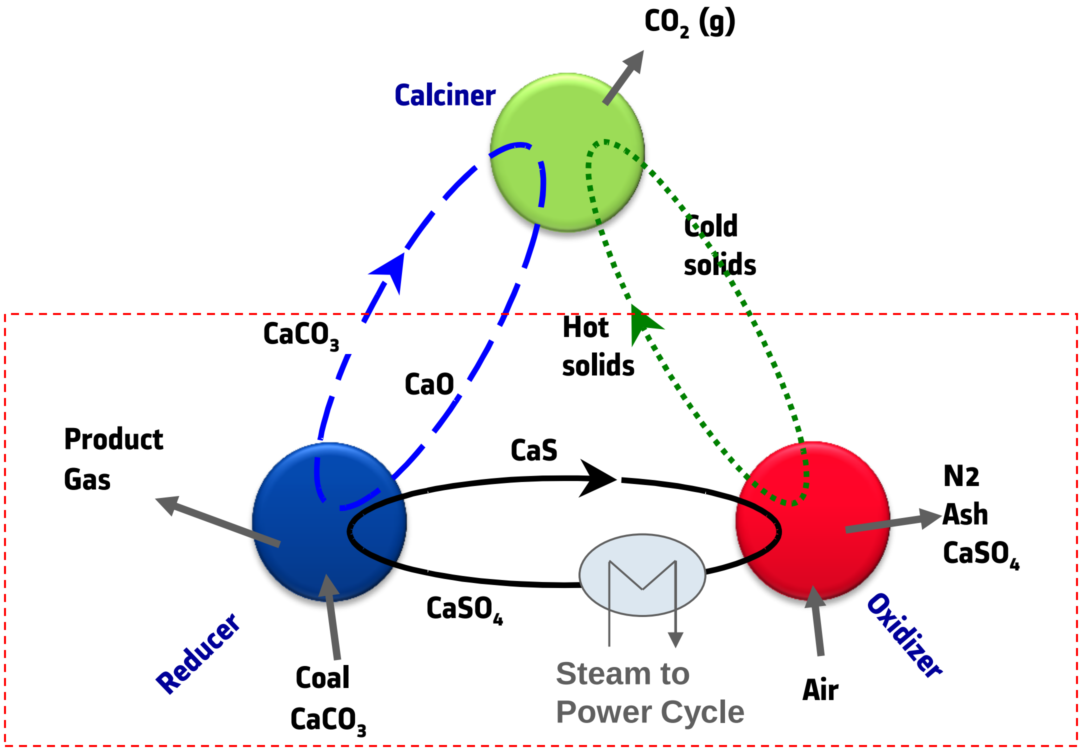
ALSTOM

# Limestone Chemical Looping Concept

**Option 1** – Chemical looping combustion
- Excess air to fuel
- Product gas is $CO_2$
- Heat produces steam for power

**Option 2** – Chemical looping gasification
- Excess fuel to air
- Product gas is Syngas
- No inherent $CO_2$ capture
- High efficiency, low cost IGCC

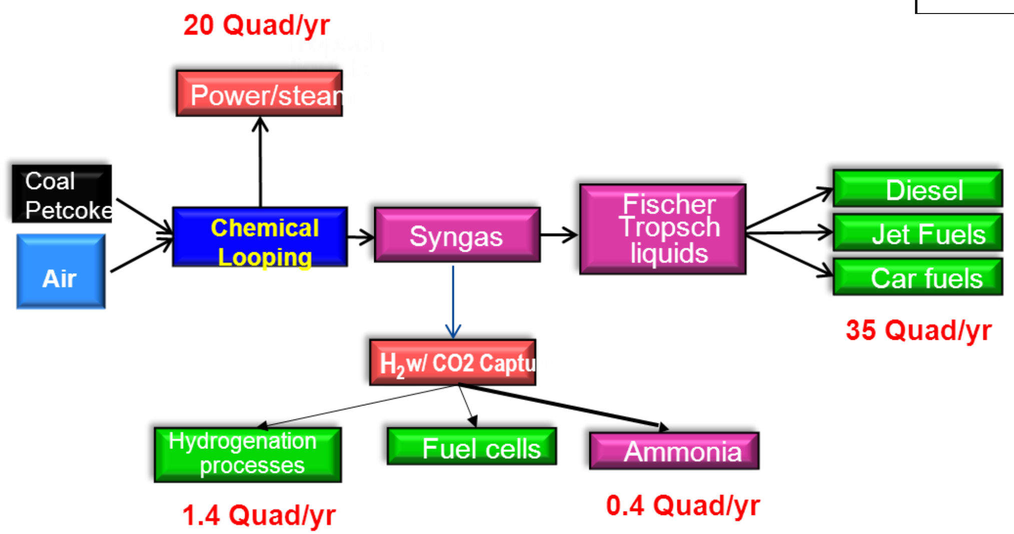
**Option 3** – Hydrogen production
- Add CaO-$CaCO_3$ loop to option 2
- Add calciner
- Product gas is low cost $H_2$
- Calciner off-gas is $CO_2$

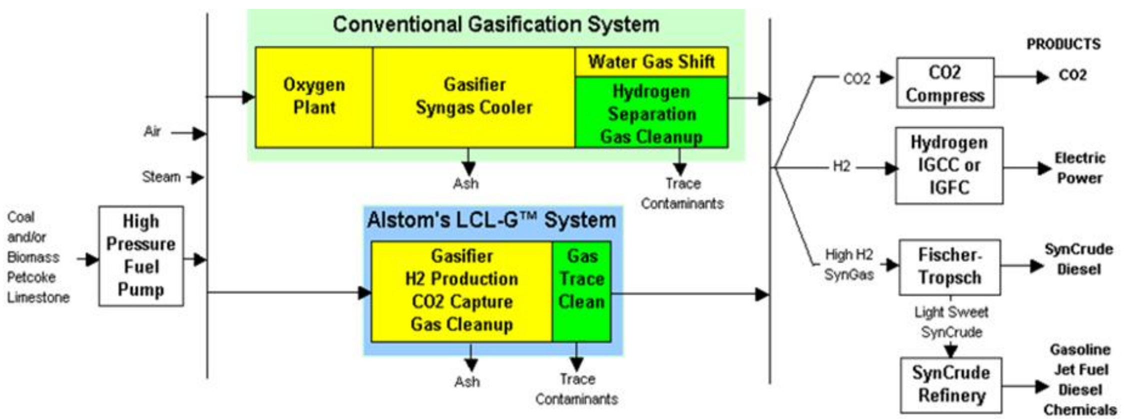



Current prototype setup

Oxygen Carrier:
- Limestone-based : Alstom – US (3 MWt, Alstom PPL, Windsor, CT)
- Metal oxide based: Alstom – Europe (1 MWt, Darmstadt University)

# Syngas Option – LCL-G™
## Syngas for Petrochemical/Power




Another route to chemical looping demonstration

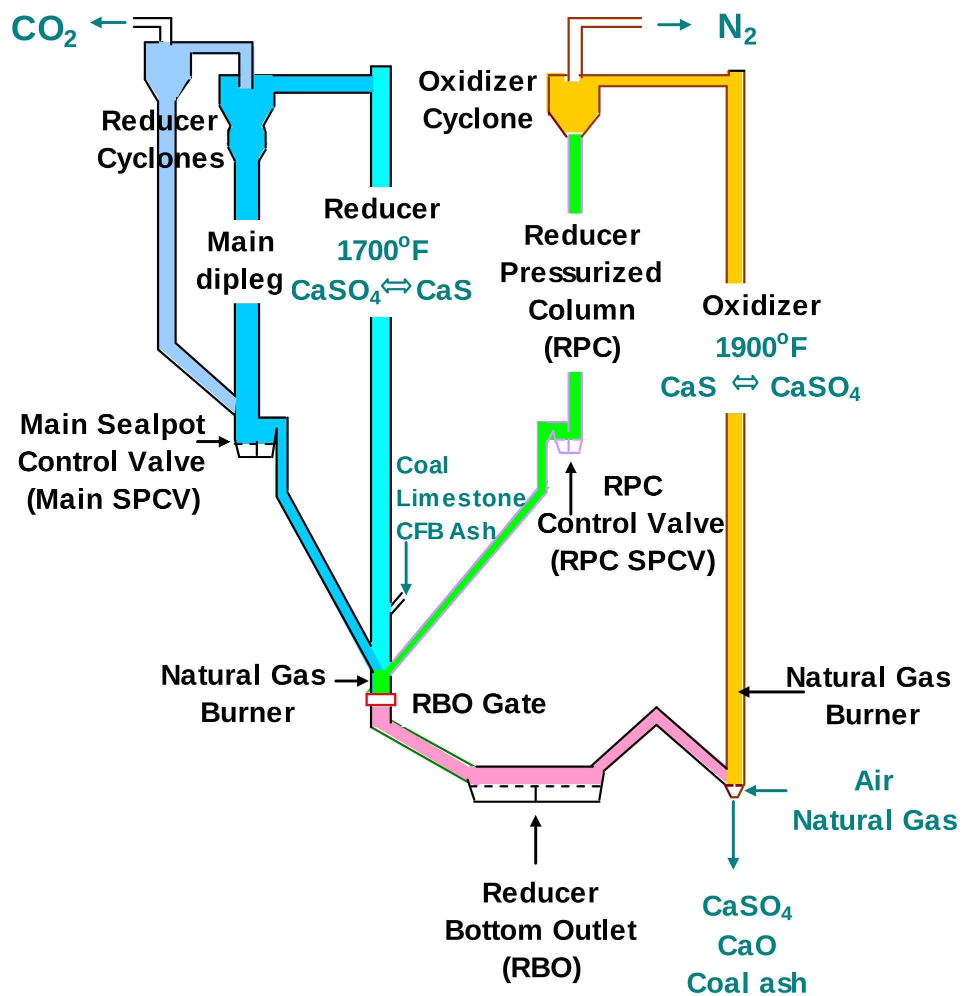




ALSTOM

# Limestone Chemical Looping (LCL-G™) Development

## 3 MWt LCL™ Prototype



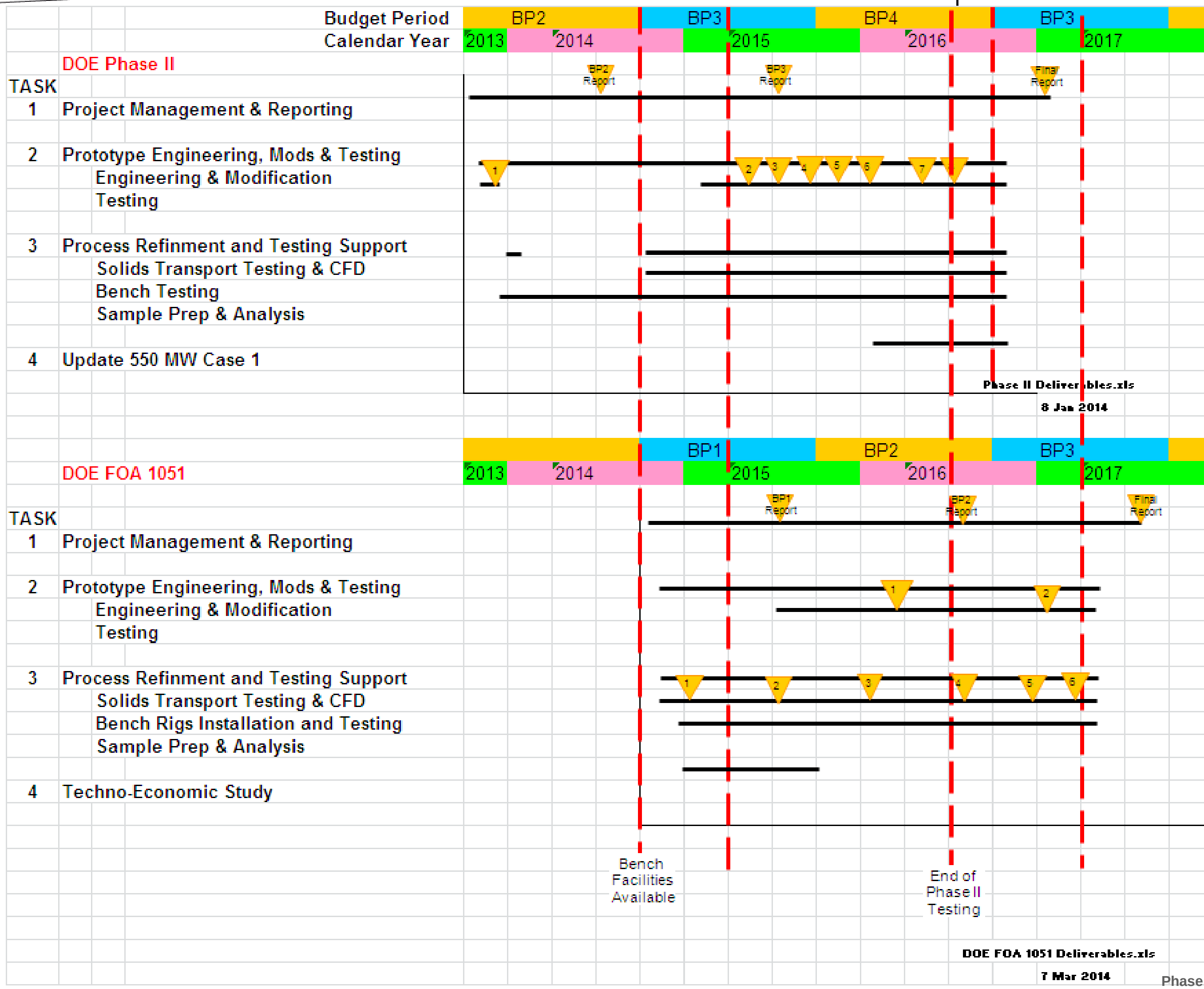





ALSTOM

# Limestone Chemical Looping - Gasification

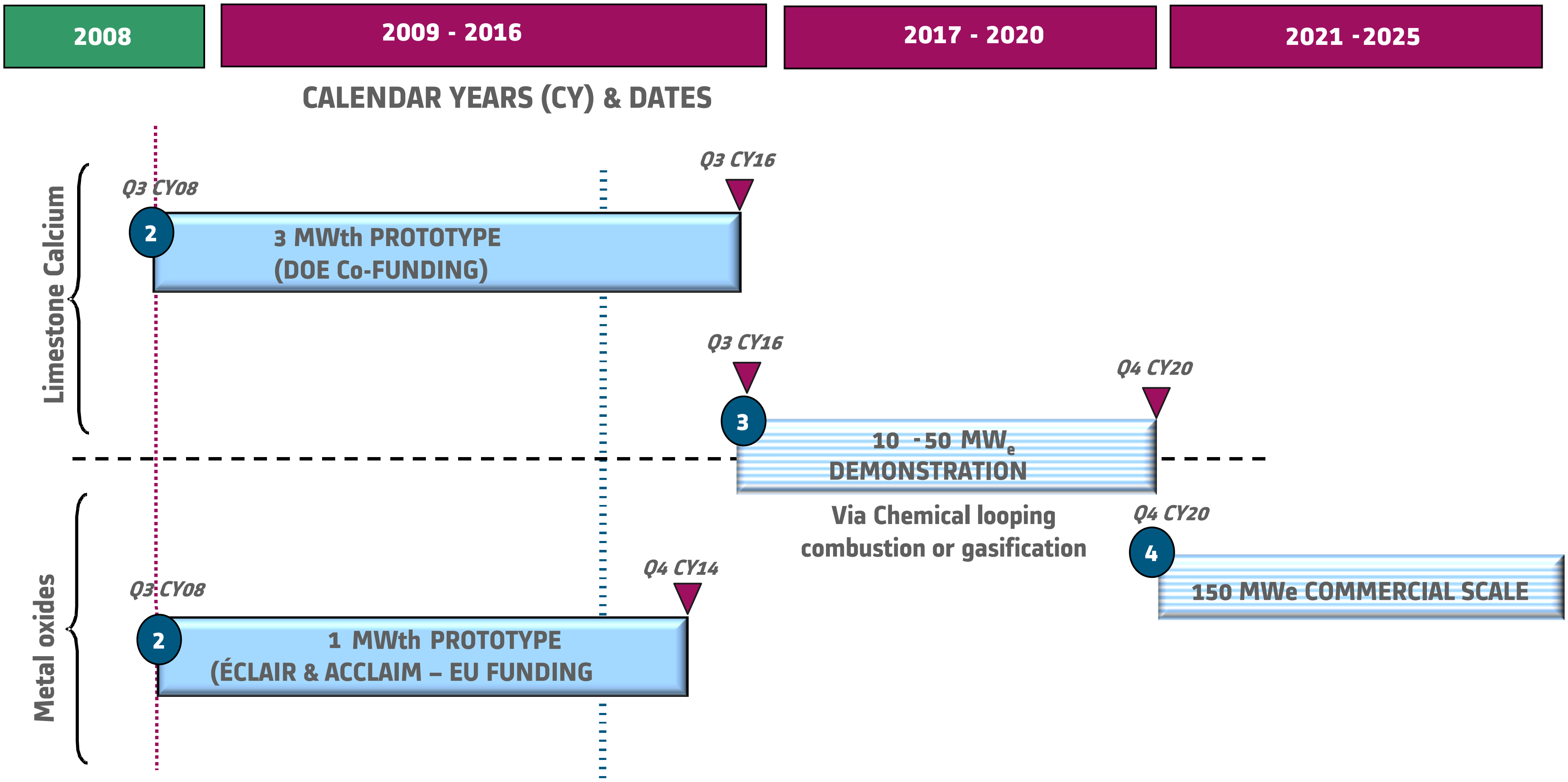
## Project Workscope & Schedule




Phase II Deliverables.xls 1 Nov 2013

# Overview

# Chemical Looping Combustion Technology
## Development Roadmap








ALSTOM

# Chemical Looping Technology
# Conclusions

- CLC technology:
  - Potential for high efficiency, low cost power and low cost $CO_2$ capture
- CLC flexiblity:
  - New or retrofit application
  - Syngas, hydrogen or power
- CLC appears feasible for limestone and  MeOx
- Next steps - field demonstration:
  - power or refinery
  - 10-50 MWe scale

**Chemical Looping Potential – Flexible and Low Cost**

# Acknowledgement

- **DOE / NETL** Cooperative Agreement No. DE-FE0009484

  Project Manager Dr. Briggs White

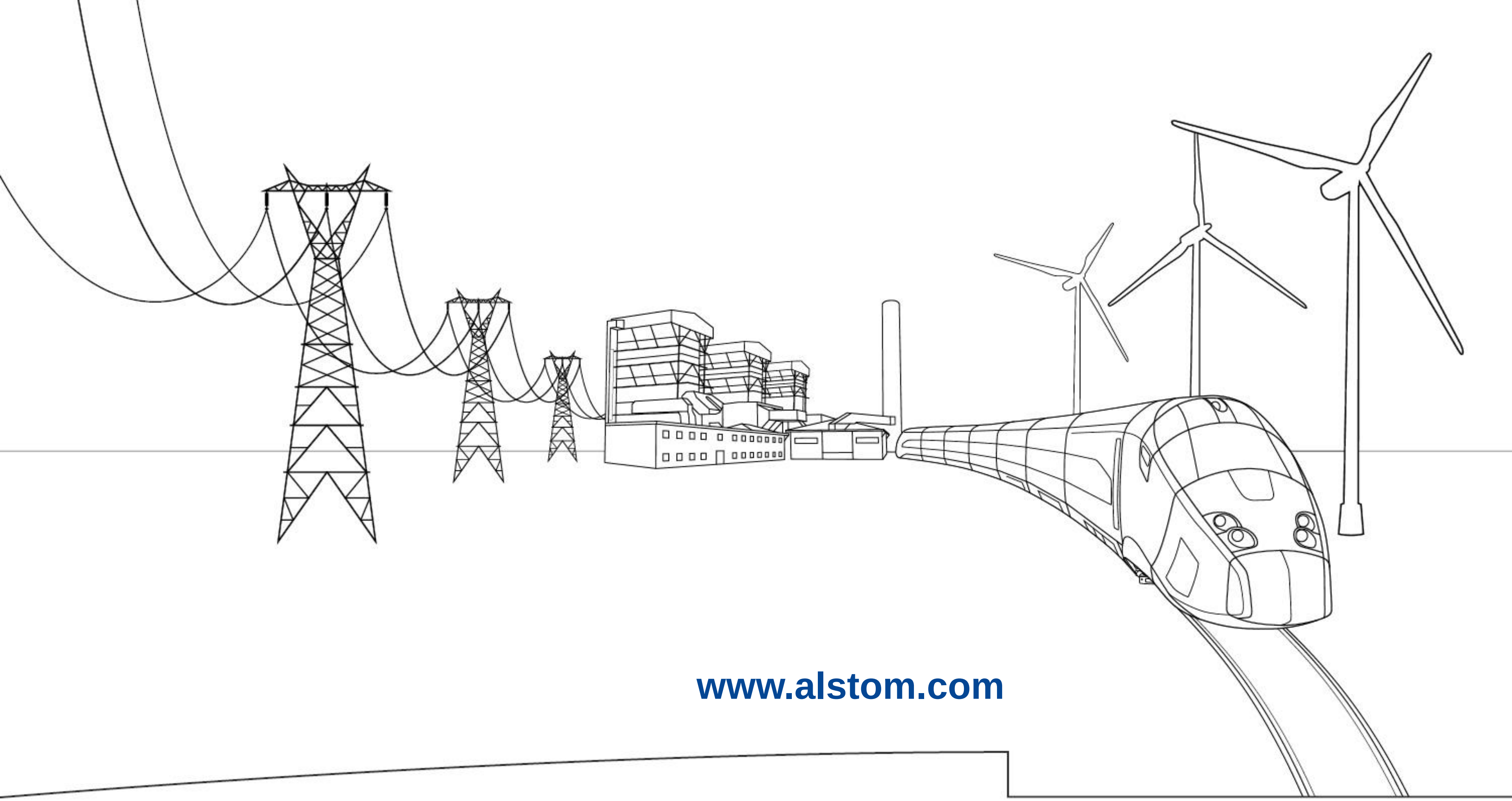
- **DOE / NETL** FOA 1051

Constructive Direction, cooperation, and support





ALSTOM



**www.alstom.com**

ALSTOM
*Shaping the future*