Design and Optimization of Coal Plants of the Future

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Outline

• **Why** do this?
  • Getting from existing fleet to next-generation

• **What** are the objectives?
  • Desired characteristics for the next-generation of coal plants
  • Status quo of existing PSE tools to solve this problem

• **How** do we solve the problem?
  • The need for advanced modeling and optimization tools
  • How the IDAES project fits here?
Why do this?

- **Fossil Energy Objectives**
  - **Cost of Energy and CO$_2$ Capture from Advanced Power Systems** – Develop cost-effective, efficient, and reliable CO$_2$ separation technologies and energy conversion technologies that inherently capture CO$_2$, for both new and existing coal-fired power plants.
  - **Power Plant Efficiency Improvements** – Develop cost-effective, reliable technologies to improve the efficiency of new and existing coal-fired power plants.

What should be the characteristics of the next-generation of coal plants to provide secure, stable, and reliable power?
What are the desired characteristics?

- **F**lexible operations to meet the needs of the modern grid
  - High ramp rates and minimum load operation (renewable targets 2050)
- **I**nnovative solutions to improve efficiency and reduce emissions
  - > 40% HHV efficiency, near zero emissions, low water consumption
- **R**esilient capability to provide power to United States
  - Minimize forced outages with enhanced monitoring and diagnostics
- **S**mall scale compared to conventional utility-scale coal power plants
  - 50-350 MW, minimize field construction costs
- **T**ransformative of how coal technologies are designed and deployed
  - Coupled with energy storage, integrate with coal upgrading
Designing Coal FIRST Power Plants

Project Inception: 2019
Flexible, Innovative, Resilient, Small and Transformational

- Develop robust conceptual design tools to identify the flexible design (< 350 MW)
- Develop reliable cost-estimating methodologies for new and existing candidate technologies
- Create advanced models for transformational technologies that enable optimal design and analysis
- Develop design targets that best integrate with the evolving needs of the electric grid
- Identify innovative materials using optimization that might help meet high performance metrics
Process Design Studies – Status Quo

Techno-economic Studies
• Detailed steady-state models ✓
• Reasonable cost estimates ✓
• Not extensive, case by case analysis ×
• Difficult to realize synergistic advantages ×
• More a sensitivity study ×

Conceptual Design Studies
• Extensive search space ✓
• Realize synergies between processes ✓
• Simple input/output models ×
• Performance prediction maybe erroneous ×
• No commercial tool; mostly academic ×
The IDAES Approach

Effectiveness for optimization

Time required to develop

Equation Oriented platforms

Sequential Modular platforms

AML platforms

Miller et al (2018), Computer Aided Chemical Engineering
Superstructure for Coal FIRST (Power Generation)

Combustion Source

- Coal
- Air
- Super-critical PC
- Direct fired S-CO₂
- Indirect fired S-CO₂

Heat Transfer & Power Generation

- Heat recovery to working fluid
- Power generation turbine train

Energy Storage Options

- Thermal Storage
- Methanol Synthesis
- Ammonia Synthesis

Energy Storage

- Carbon capture systems
- Electrification

Pollution Control

- SCR/ESP/FGD
- Pollution control

During peak demand

- Electricity
- CH₃OH
- NH₃
- O₂+CO₂

During low demand

- Heat
- Chemical
- Electricity
- Working Fluid
Conceptual Design Tools in IDAES
PyoSyn Framework in IDAES

- Generalized Disjunctive Programming
- Automatically implement either-or logic
  - Less human **pre-processing**, fewer **modeling errors**

9 disjunctions, 18 binary variables $\rightarrow$ 315 choices

\[
\begin{align*}
\text{Process 1} & \quad \text{Process Equations} \\
& \quad \text{Costing correlation} \\
& \quad + \text{Binary variable } \{0, 1\}
\end{align*}
\]

or

\[
\begin{align*}
\text{Process 2} & \quad \text{Process Equations} \\
& \quad \text{Costing correlation} \\
& \quad + \text{Binary variable } \{0, 1\}
\end{align*}
\]
Implementation in IDAES – A Simple Example

Isentropic Compression of an Ideal Gas

Goal: minimize operating cost

\[ 300 \text{ K} \quad \text{1 atm} \quad 10 \text{ atm} \]

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\text{fs.feed.pressure}.\text{fix}(0.101325)
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\text{fs.feed.temperature}.\text{fix}(3)
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\[
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\]
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\text{product.pressure}[0.0].\text{fix}(1.01325)
\]

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\[ m.\text{tscd.cooler} = \text{Heater(default={"property_package": props, "has_phase_equilibrium": False})} \]
\[ m.\text{tscd.cooler.heat_duty}[0.0].\text{setub}(0) \quad \text{# it is a cooler} \]
\[ m.\text{tscd.cooler.outlet.temperature}[0.0].\text{setlb}(3) \]
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\[ m.\text{tscd.stream2} = \text{network.Arc(source=tscd.compressor1.outlet, destination=tscd.cooler.inlet)} \]
\[ m.\text{tscd.stream3} = \text{network.Arc(source=tscd.cooler.outlet, destination=tscd.compressor2.inlet)} \]
\[ m.\text{tscd.stream4} = \text{network.Arc(source=tscd.compressor2.outlet, destination=product.inlet)} \]
One Possible Design

Heat recovery to working fluid

Power generation turbine train

Pollution control SCR/ESP/FGD

MEA

Energy Storage Options

Thermal Storage

Methanol Synthesis

Electrolysis

Ammonia Synthesis

One Possible Design
Detailed Modeling

- Power generation turbine train
- Electricity
- Pollution control SCR/ESP/FGD
- Thermal Storage
- Electrolysis
- CH₃OH
- NH₃
- O₂
- N₂
- H₂
- During peak demand
- During low demand
- Heat
- Chemical
- Working Fluid
- Electricity
- Zone 1
- Zone 2
- Zone 3
- Zone 4
- Zone 5
- Zone 6
- Zone 7
- Zone 8
- Zone 9
- Zone 10
- Over-Fire Level
- Burner Level 1
- Burner Level 2
- Burner Level 3
- Burner Level 4
- Air
- Air/O₂
- Coal
- O₂+CO₂
- Sub-critical PC
- Super-critical PC
- Ultra super-critical PC
- Direct fired S-CO₂
- Indirect fired S-CO₂
Advanced Modeling in IDAES
Detailed Modeling

- Customized model library for power plant unit operations

1D-3D Boiler Model

- Hybrid boiler model

Unit Models

- Liquid-gas contactor model

CO₂ Capture Model

- MESH equations for each tray

Column Models
Grid and Infrastructure Planning
Generation Expansion Planning

- Time scale approach:
  - Multi-year, days per year, hours per day
- Region and cluster representation
  - Area represented by a few zones
  - Potential locations are the midpoint in each zone
- Clustering of generators
- Transmission representation
  - Flow in each line is determined by the energy balance between each region $r$
Project Milestones & Timeline

**Project Inception**
- 1/1/19

**Use PyoSyn with IDAES Unit Models**
- 6/30/19

**Initial Cost Database Energy Storage**

**Initial version of materials design tool**

**Use PyoSyn for energy storage subsystem**
- 12/31/19

**Use PyoSyn for COAL FIRST plant design**

**Cost framework for Coal FIRST**

**Incorporate uncertainty in expansion planning**

**Dynamic models for solid fuel reactors**
- 6/30/20

**Multi-objective & uncertainty capabilities in PyoSyn**

**Use PyoSyn for Coal FIRST with additional product routes**
- 12/31/20

**General cost breakdown methodology for Unit Model Library**
Conclusions

• Coal FIRST plant design
  • Large and complex problem
  • Multi-scale (particle level to grid interactions)
  • Explore value addition for coal plants (power + )

Developing next-generation PSE tools
• Detailed steady-state models ✓
• Reasonable cost estimates ✓
• Not extensive, case by case analysis ✗
• Difficult to realize synergistic advantages ✗
• More a sensitivity study ✗

Applying the tools to solve challenging problems
• Extensive search space ✓
• Realize synergies between processes ✓
• Simple input/output models ✗
• Performance prediction maybe erroneous ✗
• No commercial tool; mostly academic ✗
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Appendix
Modular Coal-fired Power Plants: Cost of Electricity

Costing Methodology
- Investment cost
- Operating cost
  - Fixed: labor, maintenance, others
  - Variable: utilities “coolant & steam,” waste water, others
- Net Power
- Storage Technologies

\[
COE = \frac{(Investment + Operating_{\text{fix}} + Operating_{\text{var}})}{(Net \ Power)}
\]


Product and Process Design Principles Synthesis (Seider et al., 2009) Purchase cost correlations

Modular Power Plants (250 MW to 500 MW): Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology (DOE/NETL-2013/341)

\[
SC = RC \left( \frac{SP}{RP} \right)^\alpha
\]

Based on technologies
Reference Parameters

\(\alpha, RP, RC, SP\)
- Subcritical, Supercritical, and ultra-supercritical
- Air-fired and oxy-fired
- With and without CO2 capture
- Illinois No. 6 coal, PRB and ND Lignite coals
- IGCC
- Large Data base (vendor quotes)