Optimization of CCS-Enabled Coal-Gas-Solar Power Generation

Philip G. Brodrick, Charles A. Kang, Adam R. Brandt, Louis J. Durlofsky
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Outline

- Problem Design
- System Model
- Optimization Methodology
- Input Data
- Optimization Results
Auxiliary Heat Source

Coal Plant

Gas Fired Subsystem

Carbon Capture Subsystem

Compressed CO₂

Scrubbed Flue Gas

Steam

Electricity Produced ☀
Electricity Consumed ☢
Design Decision Variable ★
Auxiliary Heat Source

Gas Fired Subsystem

Solar Thermal Subsystem

Steam

Coal Plant

Flue Gas

Compressed CO₂

Scrubbed Flue Gas

Electricity Produced

Electricity Consumed

Design Decision Variable
Problem Setup

- Coal plant in New Mexico, exporting power to Southern California

- System and component emissions cap at 500 kg / MWh, based on California Law SB 1368
Problem Setup

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Source: Visualizing the US Electricity Grid, by NPR
Process Flow Model

Gas-fired Subsystem (CCGT)

Gas Turbine

Steam

Heat Recovery Steam Gen. (HRSG)

Steam Turbine

Condenser

Capture Subsystem

Compressor

Storage

Regeneration Column

Absorption Column

Solar Thermal Subsystem

Concentrating Parabolic Troughs

Steam Turbine

Saturated Steam

Coal Plant

Flue Gas

Condensate Return

Steam for Regenerator

Operational Decision Variable

Electricity Produced

Design Decision Variable

Electricity Consumed

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Solar Thermal Subsystem

- Based on the GlassPoint system
- Designed to produce process heat for enhanced oil recovery
- Relatively low capital cost
- Mid-level temperature

GlassPoint Troughs

GlassPoint Installation, Oman – 7 MW
Solar Thermal Subsystem

Design Decision Variables

\( (x_{\text{Size,Sol}}) \) Size of concentrating parabolic troughs

\( (x_{\text{Size,Sol-ST}}) \) Size of steam turbine

Operational Decision Variables

\( (u_{\text{Sol}}) \) Percent of steam output to utilize

\( (u_{\text{Sol-ST}}) \) Percent of steam to run through steam turbine
Capture Subsystem

- Amine-based temperature swing absorption system

- Thermodynamic and cost data comes from Carnegie Mellon’s Integrated Environmental Control Model (IECM) for a default amine CO₂ capture design

- Includes storage of CO₂ rich solvent to allow for regeneration when steam is available
Capture Subsystem

Design Decision Variables

$$x_{\text{Size, Abs}}$$ Size of absorber
$$x_{\text{Size, Reg}}$$ Size of regenerator
$$x_{\text{Size, Stor}}$$ Size of amine storage system

Operational Decision Variables

$$u_{\text{Cap-Stor}}$$ Percent of absorbed CO$_2$ to be stored
Optimization Methodology

- Mixed integer nonlinear optimization problem

- Two-level optimization – design and operations are optimized iteratively with joint optimization upon convergence

- Constrained by CO$_2$ emissions, and by mass and energy balances
Optimization Overview

Design Optimization

\[ x^* = \underset{x}{\text{argmax}} \ \text{NPV} \]
Subject to:
\[ h_{op} + h_{des} \leq 0 \]

Calculate
\[ \text{NPV}(C(x^k), P(x^k, u^*)) \]
and
\[ h_{des}(x^k) \]

Operations Optimization

\[ u^* = \underset{u}{\text{argmax}} \ P(x^k, u) \]
Subject to:
\[ h_{op}(x^k, u) \leq 0 \]
Data

- Solar irradiation and electricity prices on an hourly basis are needed.
- Hourly optimization is expensive, so there is a need to use a limited number of representative days.
- k-means clustering is used to cluster data based on centroid values.
- Clusters are based on a 24 element day vector – (12 irradiation, 12 electricity price)
Capture System Operations in Solar Design

54.5 USD/MWh, 30% Investment Tax Credit
Capture System Operations

Solar Thermal System Operations

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Base Case

Average Electricity Price: 54.5 USD/MWh
Natural Gas Price: 6.5 USD/GJ
Investment Tax Credit: 30%
Discount Rate: 8%

NPV (Millions of USD)

Solar Thermal Design

Natural Gas Design
Parametric Study

Mean Electricity Clearing Price

36 USD/MWh

73 USD/MWh

NPV (Millions of USD)
Parametric Study

Mean Electricity Clearing Price

36 USD/MWh to 73 USD/MWh

Mean Electricity Clearing Price vs. NG Price

10 USD/GJ to 3 USD/GJ

NPV (Millions of USD)

-600 -400 -200 0 200 400 600 800 1000 1200 1400 1600
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Parametric Study

- Mean Electricity Clearing Price: 36 USD/MWh - 73 USD/MWh
- Power Purchase Agreement: No PPA - 150 USD/MWh
- Investment Tax Credit: 0% - 30%

Mean Electricity Clearing Price

- NG Price: 10 USD/GJ - 3 USD/GJ

NPV (Millions of USD)
Parametric Study

- Mean Electricity Clearing Price: 36 USD/MWh - 73 USD/MWh
- Power Purchase Agreement: No PPA - 150 USD/MWh
- Investment Tax Credit: 0% - 30%
- Discount Rate: 10% - 6%
- Mean Electricity Clearing Price: 36 USD/MWh - 73 USD/MWh
- NG Price: 10 USD/GJ - 3 USD/GJ
- Discount Rate: 10% - 6%

NPV (Millions of USD) from -600 to 1600
Solar / Natural Gas NPV Comparison

PPA : 100 USD/MWh
Discount Rate : 8%

Average Electricity Clearing Price (USD/MWh)

Natural Gas Price (USD/GJ)

2014

- Gas Design
- Solar Design
- Negative NPV

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Solar / Natural Gas NPV Comparison

PPA: 100 USD/MWh
Discount Rate: 8%

PPA: None
Discount Rate: 6%

Average Electricity Clearing Price (USD/MWh)

Gas Design
Solar Design
Negative NPV

Natural Gas Price (USD/GJ)

2014
Concluding Remarks

- Developed a modeling and optimization procedure for CCS-enabled fossil fuel and solar thermal systems.

- Solar thermal designs profitable with average electricity prices $\geq 54.5 \text{ USD/MWh}$ and a 30% investment tax credit, though natural gas systems are generally preferable.

- Future work may include more detailed system models, improved optimization procedures, the treatment of other locations, and additional carbon policies.
Acknowledgements

- John O’Donnell and GlassPoint Inc.
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- Stanford Center for Computational Earth and Environmental Sciences
Questions?
Problem Setup

- Coal Plant in New Mexico, exporting power to Southern California.
- System and component emissions cap at 499 kg / MWh, based on California Law SB 1368.
Optimization Problem

Design Optimization

\[
\max_{x \in X} \text{NPV}(x, u) = -C(x) + \sum_{\tau=1}^{N_{\text{years}}} \frac{P_{\tau}(x, u)}{(1-r)^\tau} \quad \text{s.t.} \quad h_{\text{des}} + h_{\text{op}} \leq 0
\]

Operations Optimization

\[
\max_{u \in U} P(x, u) = \sum_{t=1}^{N_{\text{time-steps}}} (R_t(x, u_t) - E_t(x, u_t)) \quad \text{s.t.} \quad h_{\text{op}} \leq 0
\]
Optimization Algorithms

- Design Algorithm – PSO-MADS
  - Gradient free search
  - Handles discreet and continuous variables

- Dispatch Algorithm – SNOPT
  - Gradient based search algorithm
  - Handles continuous variables
System Constraints

- \( \text{CO}_2 \) intensity – system and subsystems

- Total power production – limited to twice the coal plant capacity

- Mass balances
Paired Electricity and Irradiation Data
Accuracy vs Number of Clusters
Accuracy vs Number of Clusters

Optimal Gas Design NPV (USD)

Optimal Solar Design NPV (USD)

Number of Clusters

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Early Summer Cluster

Winter Cluster
Solar / Natural Gas NPV Comparison (8% Real DR)
Solar / Natural Gas NPV Comparison (8% Real DR)

No PPA, No Tax Credit

No PPA, 30% Tax Credit

Natural Gas Price (USD/GJ)

Average Electricity Clearing Price (USD/MWh)
Solar / Natural Gas NPV Comparison (8% Real DR)

- 100 USD/MWh PPA
- 150 USD/MWh PPA

Average Electricity Clearing Price (USD/MWh)

Natural Gas Price (USD/GJ)

- Gas Design
- Solar Design
- Negative NPV

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