Control Co-Design Optimization of Natural Gas Power Plants with Carbon Capture and Thermal Storage

DETC2022-90021

Roberto Vercellino¹, Ethan Markey, Braden J. Limb, Maxwell Pisciotta, Joseph Huyett, Shane Garland, Todd Bandhauer, Jason C. Quinn, Peter Psarras, Daniel R. Herber²

¹Graduate Research Assistant (presenting author)
✉ verce97@colostate.edu
.reducer Colorado State University, Department of Mechanical Engineering

²Assistant Professor (corresponding author)
✉ daniel.herber@colostate.edu
.reducer Colorado State University, Department of Systems Engineering

August 14–17, 2022
Introduction
The Evolution of the Energy Sector

- **International climate goals** and increasing penetration of renewable sources indicate a shift towards an energy market defined by fluctuating electricity demand and prices.

- An opportunity exists for alternative generation sources, which must operate flexibly to accommodate the market’s variability and be close to carbon neutral.

- Natural gas combined cycle (NGCC) power plants, equipped with carbon capture (CC) technology, have been predicted to play a significant role in future grids.

- While CC technology has demonstrated CO₂ capture rates larger than 90%, it still faces critical challenges preventing its commercial deployment, including:
  - Large capital investment and operation costs
  - Flexibility limitations
  - A parasitic load imposed by CC on the host system for solvent regeneration.
→ Coupling Thermal Energy Storage

- Various solutions have been proposed to overcome the limitations of CC and achieve profitability:
  - Coupling CC with external energy storage\textsuperscript{7,12}
  - Storing CO\textsubscript{2}-rich solvent to limit CC’s parasitic load at peak electricity prices\textsuperscript{4,6}
  - Venting the CO\textsubscript{2} when more profitable than using CC\textsuperscript{15}
- A slightly different proposed solution consists in integrating NGCC and CC with hot thermal energy storage (HS) and cold thermal energy storage (CS) units:
  - Energy can then be extracted from the NGCC or directly from the grid at low electricity prices and stored in both thermal energy storage (TES) units
  - It can be discharged at peak prices from the HS to provide the heat required for CC and from the CS to chill the inlet air to the NGCC and increase the plant’s net power output

The implementation of TES technology would retain the output flexibility of NGCC power plants while allowing CC to operate at steady-state; it would deconstrain the NGCC plant beyond nominal operation output during peak price periods by utilizing stored energy from the TES for solvent regeneration and air pre-chilling\textsuperscript{16,17}
Control Co-design Optimization

- Although a **promising concept**, the **complexities** of an NGCC power plant coupled with CC, HS, and CS pose great **design** and **control challenges**:
  - For profitable implementation, each of the aforementioned subsystems (NGCC, CC, HS, CS) needs to **simultaneously operate** in response to time-varying external signals
  - In addition, **sizing decisions** accompanying the realization of such systems are strictly dependent on their day-to-day operation

- A **control co-design** (CCD) optimization approach can effectively be leveraged to simultaneously **optimize** the **physical design** and **control strategy** of this system.
Control Co-design Optimization (continued)

- Here we present an **CCD optimization model** tailored to **maximize** the **net present value (NPV)** of a **NGCC power plant** coupled with **CC, HS, and CS units** in different scenarios.

- The model has been used to assess **17 different TES configurations** with various **CC technologies** in hundreds of **electricity market scenarios**, as well as different **geographical locations** defined by their unique temperature profiles.\(^{16,17}\)

- The **optimization problem** can be posed as a **simultaneous CCD linear program** when assuming perfect foresight of the provided techno-economics signals.

- When **limited information** on the signals is imposed to resemble more realistic market conditions, a **nested CCD strategy** is chosen, and the overall problem is solved with a sequence of **linear optimal control subproblems**.
Optimization Problem Formulation & Strategy
Optimization Problem Formulation & Strategy
Problem Formulation Overview

- Many of the problem variables depend on time $t$. In addition, some of the variables also depend on ambient temperature, provided as a time-dependent signal $T_0(t)$.
- The objective is to maximize the net present value (NPV) of the system:

$$\text{maximize } \mathrm{NPV}(t, T_0, u, \xi, p)$$

(1)

where $p$ are the plant-design variables, $u(t)$ are the control decision variables and $\xi(t)$ are the state variables:

$$p = \begin{bmatrix} \Sigma_{HS} & P_{HS,in} & P_{HS,out} & \Sigma_{CS} & P_{CS,in} & P_{CS,out} \end{bmatrix}^T$$

(2a)

$$u(t) = \begin{bmatrix} p_{HS,in}(t) & p_{CS,in}(t) & p_{HS,out}(t) & p_{CS,out}(t) & p_{PP}(t) \end{bmatrix}^T$$

(2b)

$$\xi(t) = \begin{bmatrix} E_{HS}(t) & E_{CS}(t) & P_{PP}(t) \end{bmatrix}^T$$

(2c)
**Net Present Value Calculation**

- NPV is the **difference** between the present value of cash inflows and the present value of cash outflows during the **loan term** $L_t$:

  $$NPV = V_{\text{income}} - C_{\text{cap}}$$  \hspace{1cm} (3)

- $V_{\text{income}}$ is the summation of the **profit** made discounted over $L_t$ and is calculated by extending the control solution over the **first year** of operation ($t \in [0, T_{\text{year}}]$):

  $$V_{\text{income}} = \int_{0}^{T_{\text{year}}} \sum_{y=1}^{L_t} \left[ v_{\text{rev}}(t) - v_{\text{fuel}}(t) - v_{\text{op}}(t) \right] \begin{bmatrix} r_e^{y-1} \\ r_f^{y-1} \\ r_d^{y-1} \end{bmatrix} dt$$  \hspace{1cm} (4)

  where: $r_e = \frac{1 + i_e}{1 + IRR}$ \hspace{0.5cm} $r_f = \frac{1 + i_f}{1 + IRR}$ \hspace{0.5cm} $r_d = \frac{1}{1 + IRR}$

  where a **discount factor** which depends on the selected **rate of return** $IRR$ is used to convert future values into a present value.
Net Present Value Calculation (continued)

- The system’s **capital costs** $C_{cap}$ are:
  \[ C_{cap}(p) = C_{PP} + C_{CC} + C_{HS}(p) + C_{CS}(p) \]  
  \[ \text{(5)} \]
  where $(C_{PP}, C_{CC})$ are the fixed capital investment to realize the PP and the CC subsystems, while $(C_{HS}, C_{CS})$ are the costs for the TES units and depend on $p$:
  \[ C_{HS}(p) = c_{HS,\text{in}} \cdot P_{HS,\text{in}} + \sum c_{HS,\text{out}} \cdot P_{HS,\text{out}} + c_{HS,\text{TES}} \cdot \sum_{HS} \]  
  \[ \text{(6a)} \]
  \[ C_{CS}(p) = c_{CS,\text{in}} \cdot P_{CS,\text{in}} + \sum c_{CS,\text{out}} \cdot P_{CS,\text{out}} + c_{CS,\text{TES}} \cdot \sum_{CS} \]  
  \[ \text{(6b)} \]
- After some mathematical derivation, the NPV of the system can be written in **closed-form** as:
  \[ NPV = -C_{cap} + \int_{0}^{T_{\text{year}}} \begin{bmatrix} v_{\text{rev}}(t) & -v_{\text{fuel}}(t) & -v_{\text{op}}(t) \end{bmatrix} \begin{bmatrix} R_{e} \\ R_{f} \\ R_{d} \end{bmatrix} dt \]  
  \[ \text{(7)} \]
  where:
  \[ R_{e} = \frac{1 - r^{L_{t}}_{e}}{1 - r_{e}} \]
  \[ R_{f} = \frac{1 - r^{L_{t}}_{f}}{1 - r_{f}} \]
  \[ R_{d} = \frac{1 - r^{L_{t}}_{d}}{1 - r_{d}} \]
State Dynamic Equations

- **Thermal Energy Storage Units:**

\[ \dot{E}_{HS} = \kappa_{HS,in} \cdot p_{HS,in}(t) - \kappa_{HS,out} \cdot p_{HS,out}(t) \]  \hspace{1cm} (8a)

\[ \dot{E}_{CS} = \kappa_{CS,in} \cdot p_{CS,in}(t) - \kappa_{CS,out} \cdot p_{CS,out}(t) \]  \hspace{1cm} (8b)

where \((\kappa_{HS,in}, \kappa_{CS,in}, \kappa_{HS,out}, \kappa_{CS,out})\) are conversion coefficients between electrical power and thermal energy transfer rate

- **Power Plant:**

\[ \dot{P}_{PP}(t) = \frac{1}{\tau_{PP}} \left( -P_{PP}(t) + p_{PP}(t) \right) \]  \hspace{1cm} (9)

where \((\tau_{PP})\) is the ramp rate of the PP
Inequality Constraints

- Some inequality constraints limit the power penalty for charging the TES units:

\[
0 \leq p_{HS,\text{in}}(t) \leq \mu_{HS,\text{in}}(T_0) \cdot P_{HS,\text{in}} \tag{10a}
\]

\[
0 \leq p_{CS,\text{in}}(t) \leq \mu_{CS,\text{in}}(T_0) \cdot P_{CS,\text{in}} \tag{10b}
\]

where \((\mu_{HS,\text{in}}, \mu_{CS,\text{in}})\) define the fraction of the nominal power input available at the current temperature \(T_0\)

and \((P_{HS,\text{in}}, P_{CS,\text{in}})\) establish a trade-off between performance and capital investment.

- Similar constraints are enforced on the other state and control variables and are presented in detail in the article.
Model Intermediate Parameters

Natural Gas Fuel Consumption

- The instantaneous fuel consumption of the PP is proportional to the effective power output of the PP ($P_{PP}$) and the discharging of the CS ($u_{CS,\text{out}}$):

Carbon Capture System

- The CC subsystem is implemented such that it is always operating when the PP is operating
- The total CO$_2$ captured and emitted into the atmosphere can be approximated as linear trajectories between two known points of operation and are also proportional to $P_{PP}$ and $u_{CS,\text{out}}$
- $P_{CCE}$ is the electrical power required to run the CC and is directly extracted from the PP output, while $P_{CCT}$ is the thermal power requirement which is either also extracted from the PP or is provided by the HS
Electricity Generation

- The **electricity generated** by the system \( P_G \) is the primary source of **revenue** driving the NPV objective and is calculated by subtracting from the **gross electrical output** of the plant any power that is:
  - diverted to the CC
  - sent to charge the TES units
  - required to satisfy the system’s auxiliary loads

- \( v_{\text{rev}} \) is the **revenue** gained by outputting power to the grid \( P_G \) at the **current electricity price** \( c_{\text{elec}} \):
  \[
  v_{\text{rev}}(t) = c_{\text{elec}}(t) \cdot P_G(t) \tag{11}
  \]

- \( v_{\text{exp}} \) represents the **expenses** of the system, which are divided in **cost of fuel** \( v_{\text{fuel}} \) and other **operation costs** \( v_{\text{op}} \):
  \[
  v_{\text{exp}}(t) = v_{\text{fuel}}(t) + v_{\text{op}}(t) \tag{12a}
  \]
  \[
  \tag{12b}
  \]
Summary

• The six total plant design optimization variables are:

\[ p = \left[ \sum_{\text{HS}} P_{\text{HS,in}} \quad P_{\text{HS,out}} \quad \sum_{\text{CS}} P_{\text{CS,in}} \quad P_{\text{CS,out}} \right]^T \]  \hspace{1cm} (13)

• Additionally, there are four control variables:

\[ u(t) = \left[ p_{\text{HS,in}}(t) \quad p_{\text{CS,in}}(t) \quad p_{\text{HS,out}}(t) \quad p_{\text{CS,out}}(t) \quad p_{\text{PP}}(t) \right]^T \]  \hspace{1cm} (14)

• Finally, there are three state variables:

\[ \xi(t) = \left[ E_{\text{HS}}(t) \quad E_{\text{CS}}(t) \quad P_{\text{PP}}(t) \right]^T \]  \hspace{1cm} (15)

• There are several linear inequality constraints (both path and boundary types)

• The linear objective function of the problem is to maximize NPV of the system:

\[ \maximize_{u,\xi,p} \NPV(t, T_0, u, \xi, p) \]  \hspace{1cm} (16)
Optimization Strategy Considerations

- To solve the dynamic optimization problem, **direct transcription** (DT) is used, resulting in a finite-dimensional large, sparse **linear optimization program** that is constructed using the open-source MATLAB-based software DTQP.
- MATLAB’s `linprog` solver using the interior-point method was found to be quite effective at solving the resulting linear program.
- The time mesh is selected to be at **hourly intervals**; the control decisions over these hourly intervals are assumed to be **constant**.
- With constant controls and linear dynamics, the **zero-order hold** (ZOH) method is used to discretize the dynamic constraints since there would be **no discretization error**.
- A basic composite **Euler forward** method is chosen for **quadrature**.
- The ZOH method is particularly **efficient** to implement if matrices are **time invariant**. Because there are several locations in the formulation where time (really temperature) dependence would be useful, a specific non-intuitive formulation is chosen to keep the dynamic equations **linear time invariant** (LTI).
Moving Horizons Strategy Approach

- As currently posed, the **open-loop optimal control problem** can be solved for any time horizon, to obtain results for one year of operation and calculate NPV.
- In real markets, signals are known to utility operators with reasonable accuracy only with **limited foresight** (e.g., 24 hours of future information^{24}).
- A **moving prediction horizons approach** was utilized based on notions of model predictive control (MPC).
- This approach entails leveraging the knowledge of the future signals, despite being limited, to construct a tentative control strategy that is then updated when new information about the signals is available^{25}.

![Diagram: Time Steps and Control Windows](image-url)
Results & Discussion
The optimal control strategy of the system is as expected, as shown by control, state and output signals extracted from the solution for the whole year.
Control Strategy Results (continued)

- Hot and cold storage are being charged when prices are near zero
- NGCC turns on when prices are above break-even point
- Discharging occurs at peak prices for maximum revenue
Temperature-dependence Results

- Concerns about the effectiveness of the CS unit depending on ambient temperature can be addressed using this model.
- NPV’s for both B31B and the TES configuration noticeably decrease in warmer climates, due to the poor performance of the NGCC plant.
- The difference between the PP equipped with TES and the base plant tends to increase with average temperature, due to increasing impact of CS.
• For certain values of the prediction horizon and control window, MPHs is an effective strategy for this system.

• Marked with ‘1’ in the figure, assuming 24-hr foresight, solutions with control windows between 1–12 hours are close to the maximum NPV line.

• Even with 12-hr prediction horizon (marked with ‘2’ in the figure), any strategy with a smaller control window still performs well.
The optimization model allows for assessing a wide range of technologies without much additional work.

Here, fundamentally different TES configurations (IPTE & ER) are evaluated against the state-of-the-art (B31B).

Results show that an effective TES configuration must be inexpensive and able to charge independently from the PP, and that optimal design decisions highly depend on market scenario.
Conclusion
Conclusion

- In this work, an optimization model was constructed to help address important design and operation questions for a novel system combining natural gas power plants with carbon capture and thermal energy storage.
- The need for integrated design, control co-design in particular, is demonstrated for this system, to dynamically consider its control strategy and several fundamental design decisions.
- The proposed open-loop optimal control problem for this system is efficiently solved as a large-sparse linear program for an entire year at once or utilizes a more realistic, information-limited moving prediction horizons approach to investigate implementable operation.
- Future work will explore how to better characterize uncertainties in the economic and environmental signals and include them as part of an implementable control strategy using moving prediction horizons.
The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award # DE-AR0001306
References


References (continued)


 References (continued)


References (continued)


References (continued)

[22] DTQP project. URL: https://github.com/danielrherber/dt-qp-project


Questions?

Control Co-Design Optimization of Natural Gas Power Plants with Carbon Capture and Thermal Storage
DETC2022-90021

Roberto Vercellino
Colorado State University
verce97@colostate.edu

Daniel R. Herber
Colorado State University
daniel.herber@colostate.edu