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

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Introduction

➞ The Evolution of the Energy Sector

- **International climate goals**[1] and **increasing penetration** of **renewable sources** indicate a shift towards an **energy market** defined by **fluctuating electricity demand** and **prices**[2,3,4,5,6]
- An **opportunity** exists for alternative generation sources, which must operate **flexibly** to accommodate the market's variability and be close to **carbon neutral**[3,4,5,6,7]
- **Natural gas combined cycle** (NGCC) power plants, equipped with **carbon capture** (CC) technology, have been predicted to play a significant role in future grids[2,7,8,9]
- While CC technology has demonstrated CO_2 capture rates larger than 90%,[10] it still faces critical **challenges** preventing its commercial deployment, including:
  - **Large capital investment** and operation costs[11,12]
  - **Flexibility limitations**[4,13]
  - A **parasitic load** imposed by CC on the host system for solvent regeneration[4,7,11,14]

→ Coupling Thermal Energy Storage

- Various **solutions** have been proposed to overcome the limitations of CC and achieve profitability:
  - Coupling CC with **external energy storage**[7,12]
  - **Storing CO_2-rich solvent** to limit CC's parasitic load at peak electricity prices[4,6]
  - **Venting** the CO_2 when more profitable than using CC[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**[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[18]

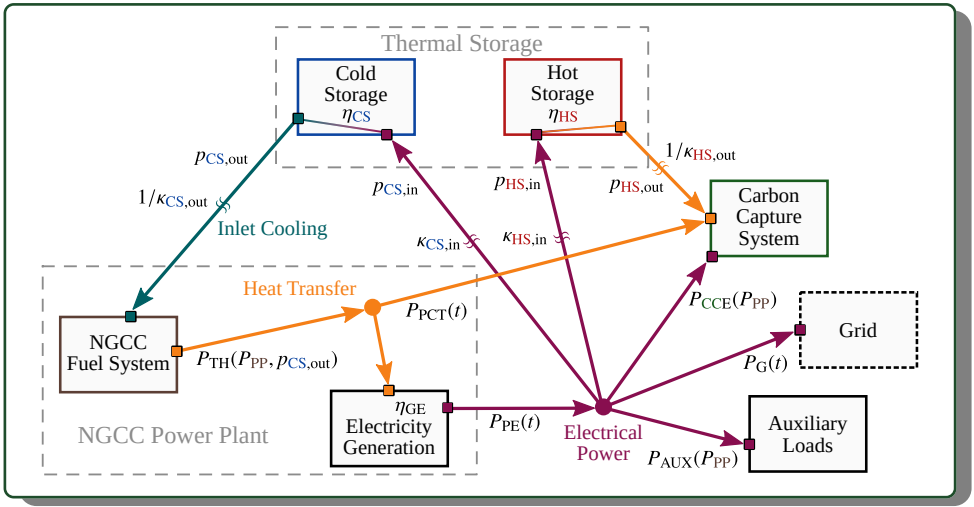
→ Control Co-design Optimization (continued)

- 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**

②

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:

$$\underset{\boldsymbol{p},\boldsymbol{u},\boldsymbol{\xi}}{\text{maximize}} \quad NPV(t, T_0, \boldsymbol{u}, \boldsymbol{\xi}, \boldsymbol{p}) \tag{1}$$

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

$$\boldsymbol{p} = \begin{bmatrix} \Sigma_{\text{HS}} & P_{\text{HS,in}} & P_{\text{HS,out}} & \Sigma_{\text{CS}} & P_{\text{CS,in}} & P_{\text{CS,out}} \end{bmatrix}^T \tag{2a}$$

$$\boldsymbol{u}(t) = \begin{bmatrix} p_{\text{HS,in}}(t) & p_{\text{CS,in}}(t) & p_{\text{HS,out}}(t) & p_{\text{CS,out}}(t) & p_{\text{PP}}(t) \end{bmatrix}^T \tag{2b}$$

$$\boldsymbol{\xi}(t) = \begin{bmatrix} E_{\text{HS}}(t) & E_{\text{CS}}(t) & P_{\text{PP}}(t) \end{bmatrix}^T \tag{2c}$$

➞ 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:

$$NPV = V_{\text{income}} - C_{\text{cap}} \tag{3}$$

- V_{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($t \in [0, T_{\text{year}}]$):

$$V_{\text{income}} = \int_0^{T_{\text{year}}} \sum_{y=1}^{L_t} \begin{bmatrix} v_{\text{rev}}(t) & -v_{\text{fuel}}(t) & -v_{\text{op}}(t) \end{bmatrix} \begin{bmatrix} r_e^{y-1} \\ r_f^{y-1} \\ r_d^{y-1} \end{bmatrix} \mathrm{d}t \tag{4}$$

where: $r_e = \dfrac{1+i_e}{1+IRR} \quad r_f = \dfrac{1+i_f}{1+IRR} \quad r_d = \dfrac{1}{1+IRR}$

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:

$$C_{\text{cap}}(\boldsymbol{p}) = C_{\text{PP}} + C_{\text{CC}} + C_{\text{HS}}(\boldsymbol{p}) + C_{\text{CS}}(\boldsymbol{p}) \tag{5}$$

  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 $\boldsymbol{p}$:

$$C_{\text{HS}}(\boldsymbol{p}) = c_{\text{HS,in}} \cdot P_{\text{HS,in}} + c_{\text{HS,out}} \cdot P_{\text{HS,out}} + c_{\text{HS,TES}} \cdot \Sigma_{\text{HS}} \tag{6a}$$

$$C_{\text{CS}}(\boldsymbol{p}) = c_{\text{CS,in}} \cdot P_{\text{CS,in}} + c_{\text{CS,out}} \cdot P_{\text{CS,out}} + c_{\text{CS,TES}} \cdot \Sigma_{\text{CS}} \tag{6b}$$

- After some mathematical derivation, the NPV of the system can be written in **closed-form** as:

$$NPV = -C_{\text{cap}} + \int_0^{T_{\text{year}}} \begin{bmatrix} v_{\text{rev}}(t) & -v_{\text{fuel}}(t) & -v_{\text{op}}(t) \end{bmatrix} \begin{bmatrix} R_e \\ R_f \\ R_d \end{bmatrix} \mathrm{d}t \tag{7}$$

where: $R_e = \dfrac{1 - r_e^{L_t}}{1 - r_e}$ $R_f = \dfrac{1 - r_f^{L_t}}{1 - r_f}$ $R_d = \dfrac{1 - r_d^{L_t}}{1 - r_d}$

State Dynamic Equations

- **Thermal Energy Storage Units:**

$$\dot{E}_{\mathrm{HS}} = \kappa_{\mathrm{HS,in}} \cdot p_{\mathrm{HS,in}}(t) - \kappa_{\mathrm{HS,out}} \cdot p_{\mathrm{HS,out}}(t) \tag{8a}$$

$$\dot{E}_{\mathrm{CS}} = \kappa_{\mathrm{CS,in}} \cdot p_{\mathrm{CS,in}}(t) - \kappa_{\mathrm{CS,out}} \cdot p_{\mathrm{CS,out}}(t) \tag{8b}$$

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

- **Power Plant:**

$$\dot{P}_{\mathrm{PP}}(t) = \frac{1}{\tau_{\mathrm{PP}}}\Big(- P_{\mathrm{PP}}(t) + p_{\mathrm{PP}}(t)\Big) \tag{9}$$

where (τ_{PP}) is the **ramp rate** of the PP

➞ Inequality Constraints

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

$$0 \leq p_{\mathrm{HS,in}}(t) \leq \quad \mu_{\mathrm{HS,in}}(T_0) \quad \cdot \quad P_{\mathrm{HS,in}} \tag{10a}$$

$$0 \leq p_{\mathrm{CS,in}}(t) \leq \quad \mu_{\mathrm{CS,in}}(T_0) \quad \cdot \quad P_{\mathrm{CS,in}} \tag{10b}$$

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

  and $(P_{\mathrm{HS,in}}, P_{\mathrm{CS,in}})$ 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 ($u_{\mathrm{CS,out}}$):

Carbon Capture System

- The CC **subsystem** is implemented such that it is always operating when the PP is operating
- The total $\mathrm{CO_2}$ **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 $u_{\mathrm{CS,out}}$
- 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_{rev} is the **revenue** gained by outputting power to the grid P_{G} at the **current electricity price** c_{elec}:

$$v_{\mathrm{rev}}(t) = c_{\mathrm{elec}}(t) \cdot P_{\mathrm{G}}(t) \tag{11}$$

- v_{exp} represents the **expenses** of the system, which are divided in **cost of fuel** v_{fuel} and other **operation costs** v_{op}:

$$v_{\mathrm{exp}}(t) = v_{\mathrm{fuel}}(t) + v_{\mathrm{op}}(t) \tag{12a}$$

(12b)

➞ Summary

- The six total **plant design optimization variables** are:

$$\boldsymbol{p} = \begin{bmatrix} \Sigma_{\mathrm{HS}} & P_{\mathrm{HS,in}} & P_{\mathrm{HS,out}} & \Sigma_{\mathrm{CS}} & P_{\mathrm{CS,in}} & P_{\mathrm{CS,out}} \end{bmatrix}^T \tag{13}$$

- Additionally, there are four **control variables**:

$$\boldsymbol{u}(t) = \begin{bmatrix} p_{\mathrm{HS,in}}(t) & p_{\mathrm{CS,in}}(t) & p_{\mathrm{HS,out}}(t) & p_{\mathrm{CS,out}}(t) & p_{\mathrm{PP}}(t) \end{bmatrix}^T \tag{14}$$

- Finally, there are three **state variables**:

$$\boldsymbol{\xi}(t) = \begin{bmatrix} E_{\mathrm{HS}}(t) & E_{\mathrm{CS}}(t) & P_{\mathrm{PP}}(t) \end{bmatrix}^T \tag{15}$$

- There a several **linear inequality constraints** (both path and boundary types)
- The **linear objective function** of the problem is to maximize NPV of the system:

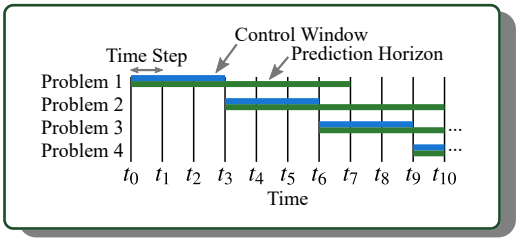
$$\underset{\boldsymbol{u},\boldsymbol{\xi},\boldsymbol{p}}{\text{maximize}} \;\; NPV(t, T_0, \boldsymbol{u}, \boldsymbol{\xi}, \boldsymbol{p}) \tag{16}$$

➞ Optimization Strategy Considerations

- To solve the dynamic optimization problem, **direct transcription** (DT) is used,[19,20,21] resulting in a finite-dimensional large, sparse **linear optimization program** that is constructed using the open-source MATLAB-based software DTQP[22]
- MATLAB's `linprog` solver using the interior-point method was found to be quite effective at solving the resulting linear program[23]
- 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**[21]
- 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]



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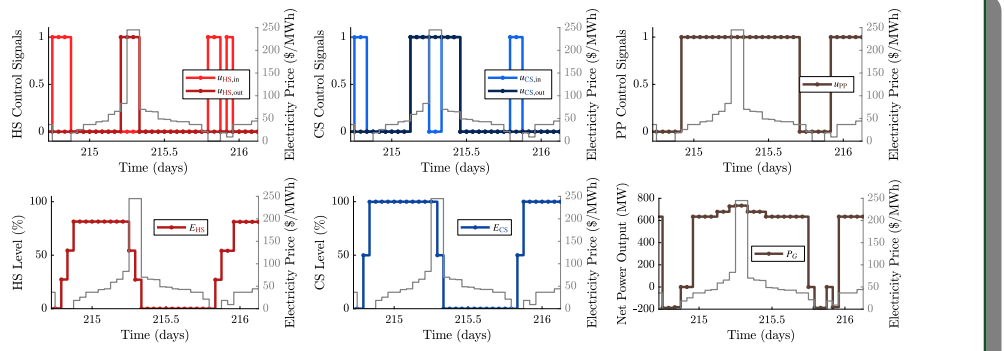
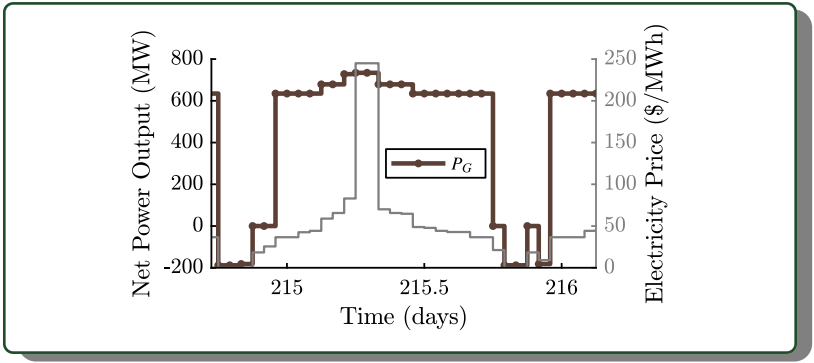
Results & Discussion

➞ Control Strategy Results



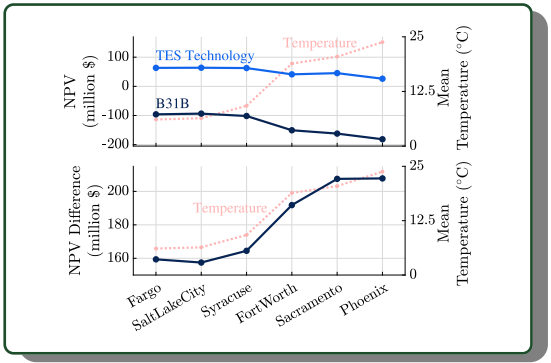
- The optimal control strategy of the system is as expected, as shown by **control**, **state** and **output signals** extracted from the **solution** for the **whole year**

➞ Control Strategy Results (continued)



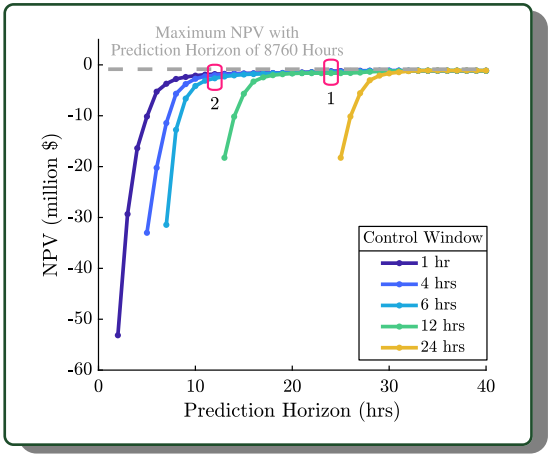
- Hot and cold storage are being **charged** when **prices** are **near zero**
- NGCC turns on when prices are **above break-even point**
- **Discharging** occurs at **peak prices** for **maximum revenue**

➞ Temperature-dependence Results



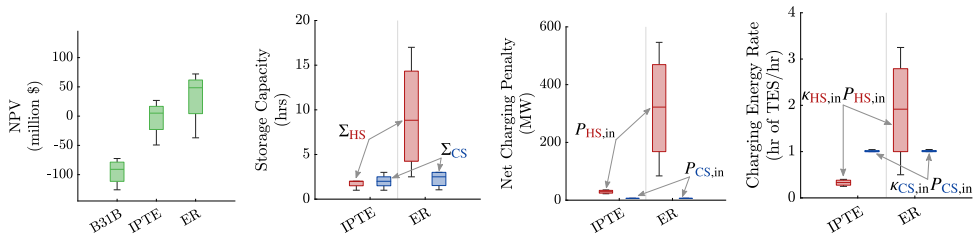
- Concerns about the **effectiveness** of the CS unit depending on **ambient temperature** can be addressed using this model
- **NPV's** for both B31B and the TES configuration noticeably **decrease** in warmer climates, due to the poor performance of the NGCC plant
- The **difference** between the PP equipped with TES and the base plant tends to **increase** with **average temperature**, due to increasing impact of CS

Moving Prediction Horizons Strategy Results



- 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

→ TES Technologies Comparison Results



- 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

④

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

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Questions?

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