Conceptual Design and Analysis of a Power Generator with Integrated Thermal Energy Storage and CO$_2$ Capture

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Need for Flexible Low Carbon Energy Sources

“Firm low-carbon” resources such as thermal generators with CCS lower the cost of decarbonization by 10–62%[1]

Integration of variable renewable energy require flexible operations from thermal generators[2]

Important to design low carbon integrated clean energy systems such as thermal generators + carbon capture + energy storage

[1] Sepulveda et al., 2018
Grid Integrated Design of Hybrid Energy Systems

- Dependency of electricity prices on the available generators and their capacities
- Generator’s revenue potential depends on the future electricity prices
- **DISPATCHES** is a multi-lab and university collaboration to develop an open-source platform for design, optimization, and analysis of hybrid energy systems
- Identify optimal designs by incorporating market interactions and demonstrate using case studies

Tightly coupled hybrid energy systems interconnecting grid with multiple generators\(^3\)

Design hybrid energy systems considering interactions with the grid

\(^3\)Arent et al. Joule, 5, 47-58, 2021
DISPATCHES Workflows

1. Price-taker
- Historical ISO Data
- Locational Marginal Price (LMP) signals
- Advanced Data Analytics
  - Stochastic realizations of LMPs
  - Representative days

2. Double-loop simulation
- Optimization Model (IDAES & Pyomo)
- Optimal Hybrid Energy System

3. Design with market surrogates
- Inputs
  - PRESIENT
  - Input-output data
- Market Surrogates (IDAES Surrogates)
1. Price-taker

Historical ISO Data

Locational Marginal Price (LMP) signals

Advanced Data Analytics

Stochastic realizations of LMPs

Representative days

Optimization Model (IDAES & Pyomo)

Optimal Hybrid Energy System

“Double loop” simulation

Market Surrogates (IDAES Surrogates)

Input-output data

PRESIENT

Inputs

Market Interaction

Price-taker
Price-taker for Thermal Energy System Design

1. Historical Electricity Prices from an ISO

2. Integrated Energy System Design

3. Optimization Model

\[
\begin{align*}
\text{Revenue} & = \sum_{d,u} \pi_t \delta_t \\
\text{Cost} & = C(d, u_t, \delta_t) \\
\text{Operating Vars} & \leq 0 \\
\text{Design Vars} & = 0 \\
\text{Operating Constraints} & \leq 0 \\
\text{Process Models} & \leq 0
\end{align*}
\]

Challenges

- Rigorous process models and property packages are non-linear and non-convex
- Multi-period superstructure-based design models difficult to solve
- Problem size increases significantly with the length of time horizon

Simplification approaches are needed to solve this problem
2-step Approach for Thermal Energy System Design

- **Step – 1:** Solve the superstructure-based process design model
  - Ultra-supercritical Power Plant + Thermal Energy Storage + CO₂ Capture System
  - Steady state, first-principles using IDAES unit model library
  - Property packages for steam/water, molten salts, & thermal oil
  - IDAES costing library for capital costs
  - CCS with 95% capture using advanced solvent technology

- **Step – 2:** Operational scheduling considering electricity prices
  - Solve a multi-period scheduling problem with the optimal design
  - Given LMP determine optimal operational schedule
  - Determine resource utilization

LMP = Locational Marginal Prices
Design decisions
✓ Choice of Storage Fluid
  • Solar Salt
  • Hitec Salt
  • Thermal Oil
✓ Steam Source
  • V High Pressure
  • High Pressure
✓ Condensate Return
  • Feedwater heaters 6, 7, 8, and 9
  • Boiler
✓ Cooler
  • Cooler after storage
  • No cooler after storage
Superstructure-based process design: Discharge Cycle

Design decisions
- Source of condensate
  - Condensate pump
  - Feed water heater 4
  - Booster Pump
  - Before feed water pump
  - Feed water heater 9
- Source for CCS reboiler heat
  - Steam from IP-LP turbines
  - Steam from discharge heat exchanger
Mathematical Formulation (step 1): Design Problem

- Incorporate all design decisions in the model
  - A superstructure flowsheet
  - Objective include annualized capital cost, operating cost, and a price for carbon emission

- Model design decisions as disjunctions
  - Formulate a Generalized Disjunctive Programming model

- GDPopt solver in IDAES
  - Logic-based Outer Approximation
  - Big-M reformulation
  - MIP solver: Gurobi, NLP solver: IPOPT

<table>
<thead>
<tr>
<th>min $f(x)$</th>
<th>Total Annualized Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>s.t. $h(x) = 0$</td>
<td>Process model equations</td>
</tr>
<tr>
<td>$g(x) \leq 0$</td>
<td>Operating constraints</td>
</tr>
<tr>
<td>$\forall i \in D_k \left[ \frac{z_{i,k}}{r_{i,k}(x)} \right] \leq 0 \quad \forall k \in K$</td>
<td>Discrete decisions</td>
</tr>
<tr>
<td>$\Omega(Z) = True$</td>
<td>Logical constraints</td>
</tr>
<tr>
<td>$Z \in {True, False}$</td>
<td>Boolean variables</td>
</tr>
<tr>
<td>$x \in X \subseteq \mathbb{R}^n$</td>
<td></td>
</tr>
</tbody>
</table>

March 24, 2023
Mathematical Formulation (Step 2): Multi-period Scheduling Problem

Multi-period Model

1. **Period 1** USCP ES Model
2. **Period 2** USCP ES Model
3. **Period 3** USCP ES Model
4. **Period n** USCP ES Model

**Coupling variables:**

- **Net power**
- **Salt tank level**
- **Global constraints and bounds**

**Global constraints and bounds**

- **Charge**
- **Discharge**

**Mathematical Formulation (Step 2):**

\[
\text{max} \sum_{t \in \mathbb{N}} (\text{revenue}_t - \text{operating costs}_t) - \text{capital costs}_t
\]

**s.t.**

- **Power plant model equations**
- **Power dispatch constraints**

\[
\begin{align*}
P_{t \text{total}} &= P_{t \text{plant}} + P_{t \text{storage}} \\
P_{t \text{total}} - \text{ramping} &\leq P_{t \text{total}} \\
P_{t \text{total}} + \text{ramping} &\geq P_{t \text{total}}
\end{align*}
\]

**Salt inventory balance**

\[
\begin{align*}
I_{t \text{hot}} &= I_{t-1 \text{hot}} + 3600(F_{t \text{salt,charge}} - F_{t \text{salt,dischage}}) \\
I_{t \text{total}} &= I_{t \text{hot}} + I_{t \text{cold}}
\end{align*}
\]

**Optimal design**

\[
A_{\text{charge/dischage}} = A_{\text{GDP charge/GDP discharge}}
\]

\[
\begin{align*}
T_{t \text{salt,charge}} &= T_{t \text{salt, in/out}}^{\text{min/max}} \\
T_{t \text{salt,dischage}} &= T_{t \text{salt, in/out}}^{\text{max/min}}
\end{align*}
\]

**Costs and bounds**
Results: Optimal Design of Integrated System

Design decisions

✓ Optimal design in an integrated ultra-supercritical power plant solution
  • Charge storage system: Solar salt, HP steam
  • Discharge storage system: FWH 9
  • Capture during discharge from HXD

✓ Optimal operational decisions
  • Storage inventory, steam and salt flows, plant power

✓ Fixed storage capacity and electricity prices not considered
Results: Optimal Scheduling with 24 hours Price Signal

Storage capacity Utilization < 50%

Charge Heat Exchanger Capacity Utilization ≈ 30%
Results: Optimal Scheduling with Alternate Price Signal

Storage Capacity Utilization > 90%

Charge Heat Exchanger Capacity Utilization > 45%
Concluding Remarks & Ongoing Work

- A simplified 2-step workflow for design and operation of integrated thermal system developed and demonstrated
  - Insights from the price taker analysis can be used to refine the design problem
  - Storage design depends on the forecasted electricity prices and the horizon considered
  - Optimal storage size can be determined through the proposed approach

- Scheduling results highlight the need for incorporating market interactions during the design stage

- Models, documentation, notebooks available on GitHub’s DISPATCHES repository
  - https://github.com/gmlc-dispatches/dispatches

- Ongoing study
  - Extending the analysis to incorporate market surrogates for a implementing a simultaneous design and operations problem
Thank you!

Acknowledging support from the Grid Modernization Laboratory Consortium through FE, NE, & EERE

National Energy Technology Laboratory: David Miller, Andrew Lee, Jaffer Ghouse, Naresh Susarla, Radhakrishna Gooty, Andres Calderon

Sandia National Laboratories: John Siirola, Michael Bynum, Edna Soraya Rawlings, Jordan Jalving

Idaho National Laboratory: Cristian Rabiti, Andrea Alfonsi, Konor Frick, Jason Hansen

National Renewable Energy Laboratory: Wes Jones, Darice Guittet, Ben Knueven, Ignas Satkauskas

Lawrence Berkeley National Laboratory: Dan Gunter, Keith Beattie, Ludovico Bianchi

University of Notre Dame: Alexander Dowling, Xian Gao, Xinhe Chen
Disclaimer

- This project was funded by the Department of Energy, National Energy Technology Laboratory an agency of the United States Government, through a support contract. Neither the United States Government nor any agency thereof, nor any of its employees, nor the support contractor, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. Team KeyLogic’s contributions to this work were funded by the National Energy Technology Laboratory under the Mission Execution and Strategic Analysis contract (DE-FE0025912) for support services.

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Questions / Comments

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