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SAND2022-15510C

IDAES Institute for the Design of Advanced Energy Systems

DISPATCHES Design Integration and Synthesis Platform to Advance Tightly Coupled Hybrid Energy Systems

Multiperiod Generalized Disjunctive Programming Optimization in IDAES: Simultaneous Operation and Design of an Integrated Energy System

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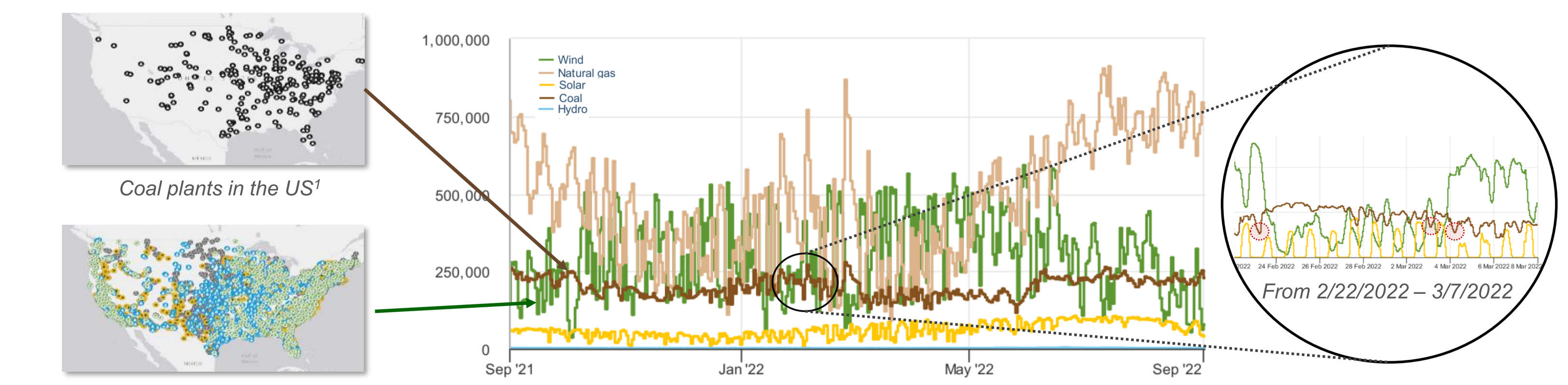
Motivation

- Integration of variable renewable energy requires more flexible fossil generators
- Thermal energy storage (TES) systems allow generators to reduce frequent cycling and operate at higher efficiencies



Coal plants in the US[1]

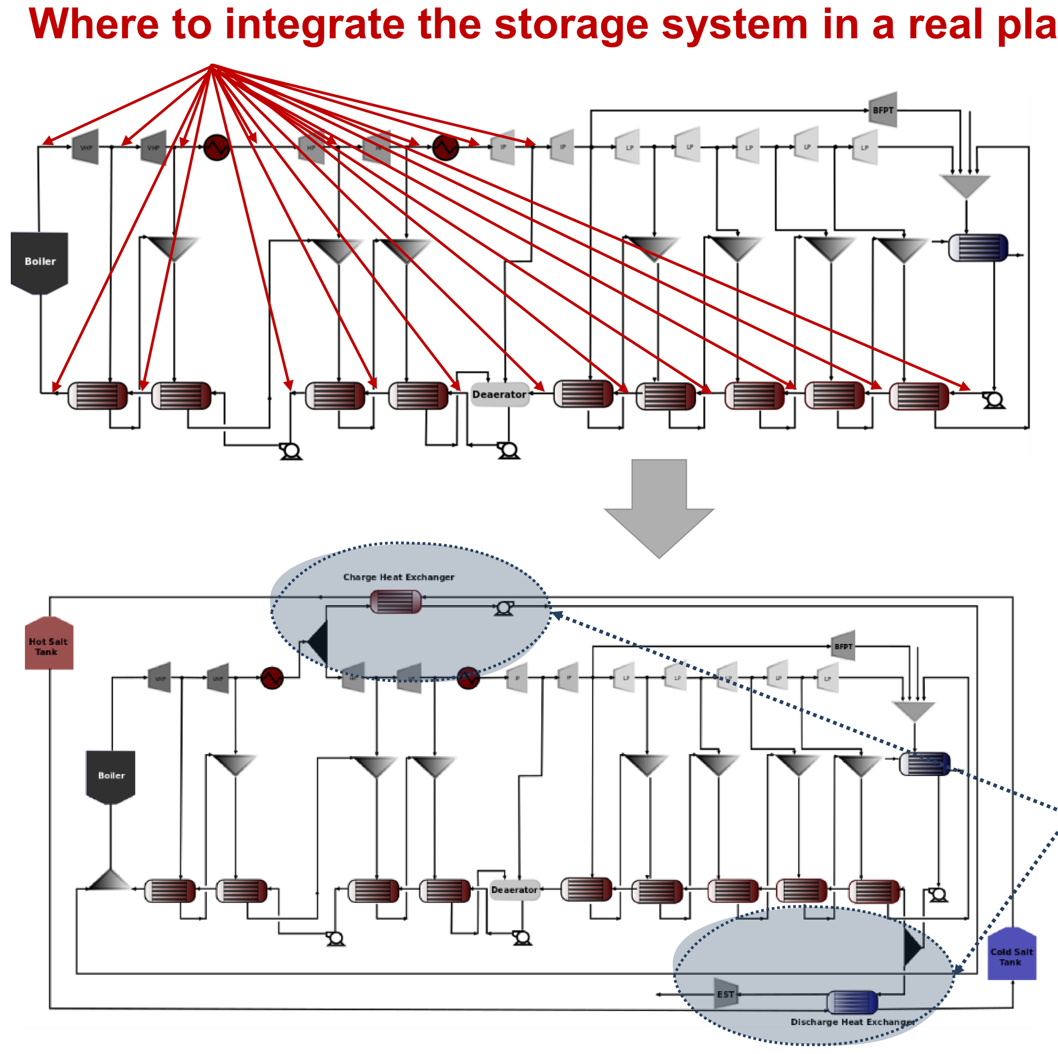
Natural gas, solar, and wind plants in the US[1]

Electric Reliability Council of Texas, Inc. (ERCO) electricity generation by energy source 9/1/2021 – 9/1/2022, Eastern Time[2]

[1] Source: U.S. Energy Information Administration. U.S. Energy Mapping System, https://www.eia.gov/state/maps.php. Accessed July 2, 2021. [2] Source: U.S. Energy Information Administration. Hourly Electric Grid Monitor, https://www.eia.gov/electricity/gridmonitor/expanded-view/custom/pending/GenerationByEnergySource-4/edit, Accessed September, 2022

Problem Statement

Where to integrate the storage system in a real plant?



To include the TES, decide:

- What **storage material** is the best and cheapest?
- What is the best **design** for the **storage** system?
- Where is the **optimal integration point** of the TES?

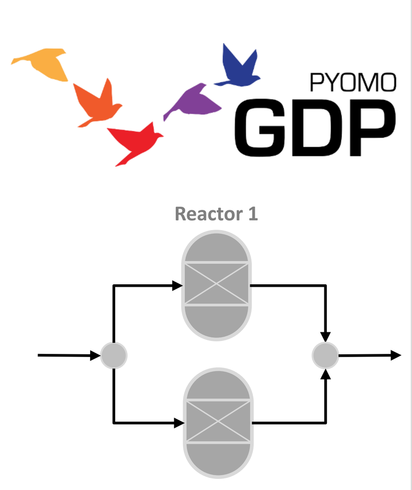
Once TES is integrated:

- **When** and **how** to deploy storage to maximize profit?

Methodology

Conceptual Design using IDAES

- Use IDAES unit models and interconnections to create rigorous superstructures
- Use **Generalized Disjunctive Programming** (GDP) to incorporate discrete design decisions as disjunctions
- Use of advanced solver **GDPopt**, to explore entire design space within **IDAES**



$$\begin{bmatrix} z_1 \\ h_1(x) = 0 \\ g_1(x) \leq 0 \end{bmatrix} \vee \begin{bmatrix} z_2 \\ h_2(x) = 0 \\ g_2(x) \leq 0 \end{bmatrix}$$

Multi-period Approach

- Pricetaker assumption to determine optimal schedule and design of storage operating cycles
- Two formulations for determining optimal schedule: Nonlinear programming (NLP) and GDP

It can be applied for designing storage systems for fossil, nuclear and geothermal energy systems

Conceptual Design of Energy Systems

- Build two superstructures to identify optimal points of integration of storage system with thermal generator
- Rigorous flowsheet using first-principle models for steam cycle and TES with accurate properties for steam/water using **IAPWS95**

Charge Cycle

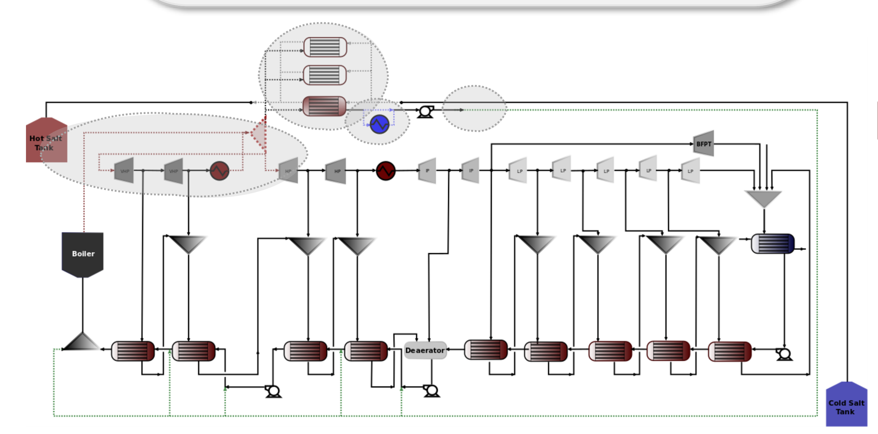
Discrete decisions:

1. **Steam source** to heat up storage material
2. **Condensed steam** return
3. **Storage material**: Solar, Hitec, Thermal oil
4. Use of a **cooler** after TES

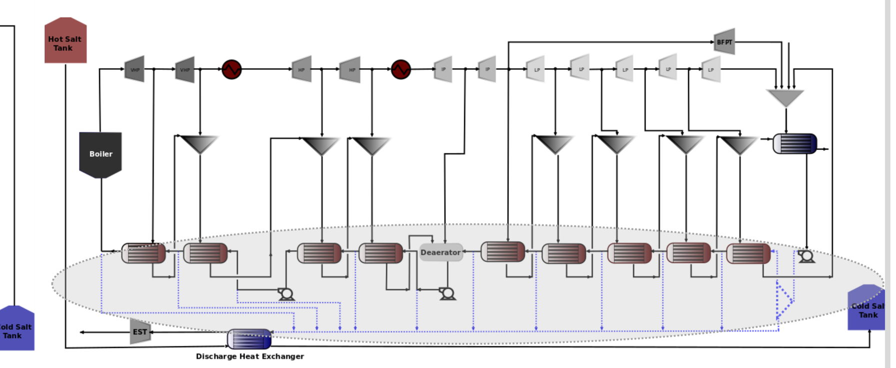
Discharge Cycle

Discrete decision:

1. **Condensed steam source** using stored energy in storage material
- Dedicated turbine connected to the discharge system



60 process configurations



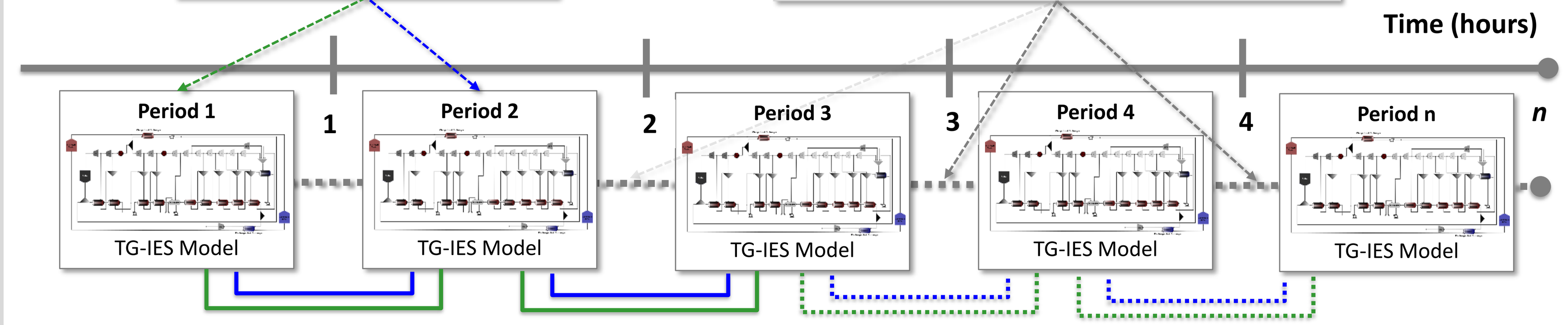
11 process configurations

Multi-period Storage Schedule and Design

- **Optimal design and operation** of the thermal generator and storage system in a given time horizon
- Optimal points of integration of TES with thermal generator obtained during GDP conceptual design
- **NLP** and **GDP** models to determine the optimal hourly operating design and schedule of the thermal energy storage system

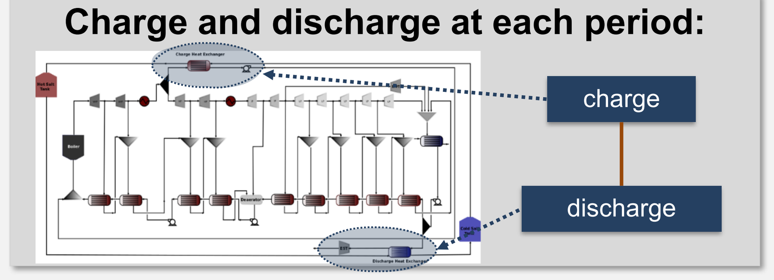
Coupling variables:
Net power
Salt tank levels

Non-anticipativity constraints:
Area of storage heat exchangers
Temperature of hot storage material



NLP Model

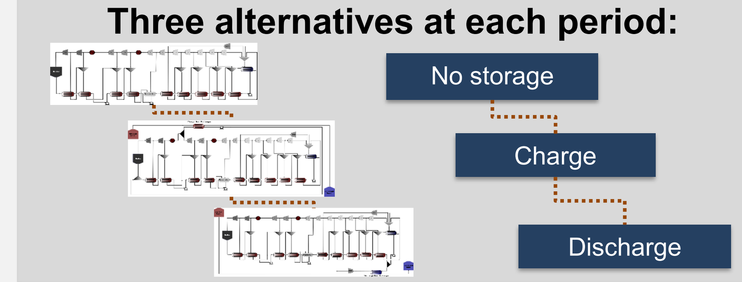
Charge and discharge at each period:



- Minimum flow requirement for the storage operating cycles
- Simplified scheduling analysis to determine when to use storage

GDP Model

Three alternatives at each period:



- Disjunction for the selection of operation mode
- Problem size from **millions** to **quadrillions: 3^n alternatives**

Results

Conceptual design of storage superstructures

- Optimal design for **charge superstructure**: Solar salt as storage material, a high pressure steam, condensed steam to return to the boiler, and no cooler
- Optimal design for **discharge superstructure**: Condensed steam source after condenser

Multi-period Analysis for Storage Schedule and Design

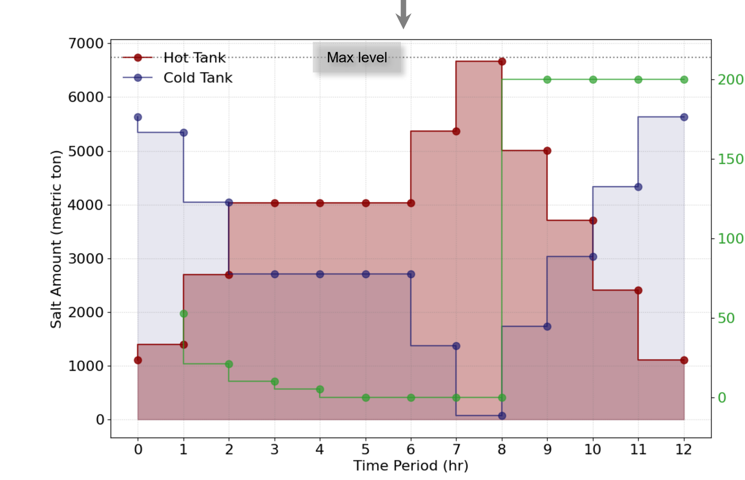
- Determine heat exchanger areas and operating temperatures
- Optimal schedule varies based on electricity prices
- GDP multi-period allows for the search when 3^{12} **alternatives** are available

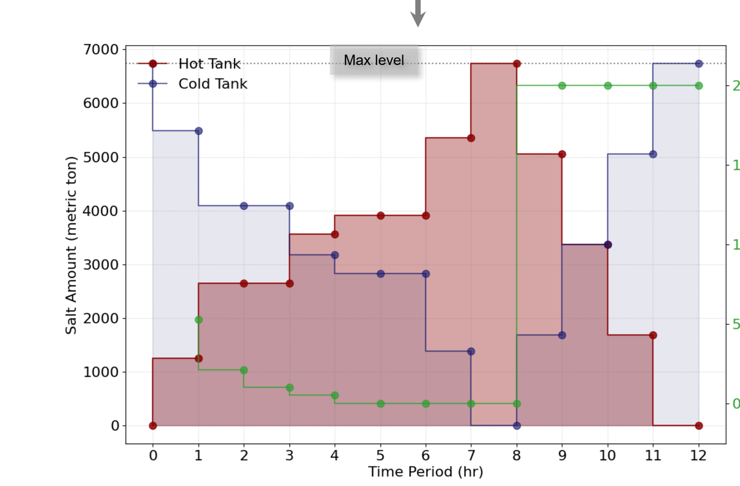
NLP multi-period approach

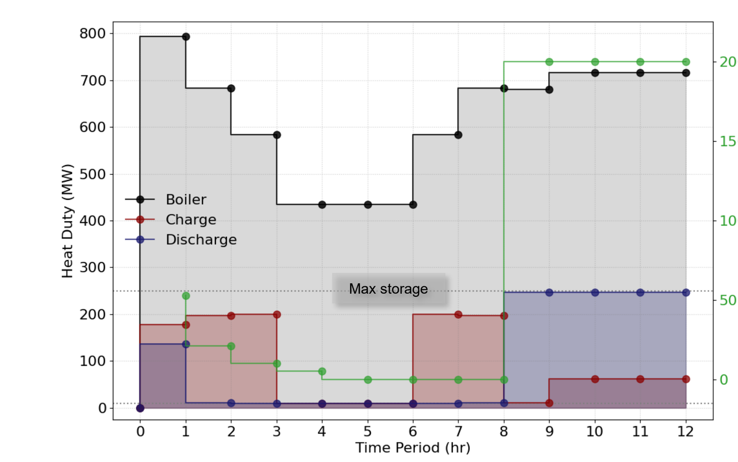
Area heat exchangers
Charge: 2987 m^2
Discharge: 3000 m^2
Profit: $311,953

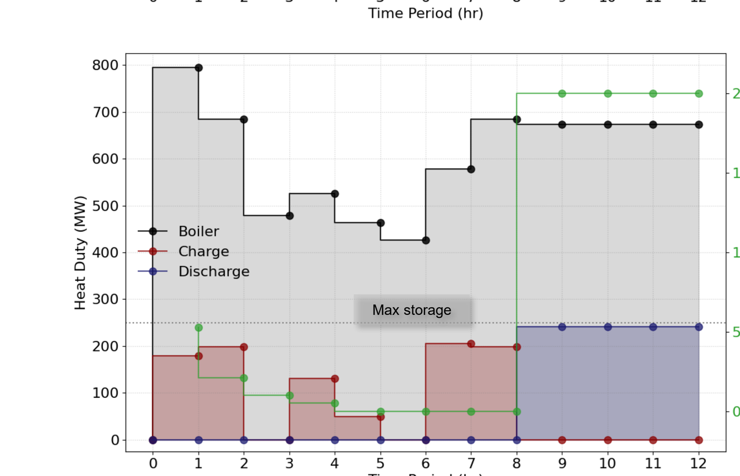
GDP multi-period approach

Area heat exchangers
Charge: 3000 m^2
Discharge: 2486 m^2
Profit: $344,947









GDP approach improve profit by 10% when comparing with NLP approach with minimum flow constraints

Future Work

- Include using discharge steam in CCS system as a potential design option
- Extend analysis of NLP and GDP multi-period models to consider electricity market surrogates, i.e. remove pricetaker assumption

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Acknowledgments This research was conducted as part of the Institute for the Design of Advanced Energy Systems (IDAES) and Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems (DISPATCHES) projects. It was supported by (1) the Simulation-Based Engineering, Crosscutting Research Program within the U.S. Department of Energy's Office of Fossil Energy and Carbon Management and (2) the Grid Modernization Initiative of the U.S. Department of Energy as part of its Grid Modernization Laboratory Consortium, a strategic partnership between DOE and the national laboratories to bring together leading experts, technologies, and resources to collaborate on the goal of modernizing the nation's grid.

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