Techno-Economic Optimization of Advanced Energy Plants with Integrated Thermal, Mechanical, and Electro-Chemical Storage

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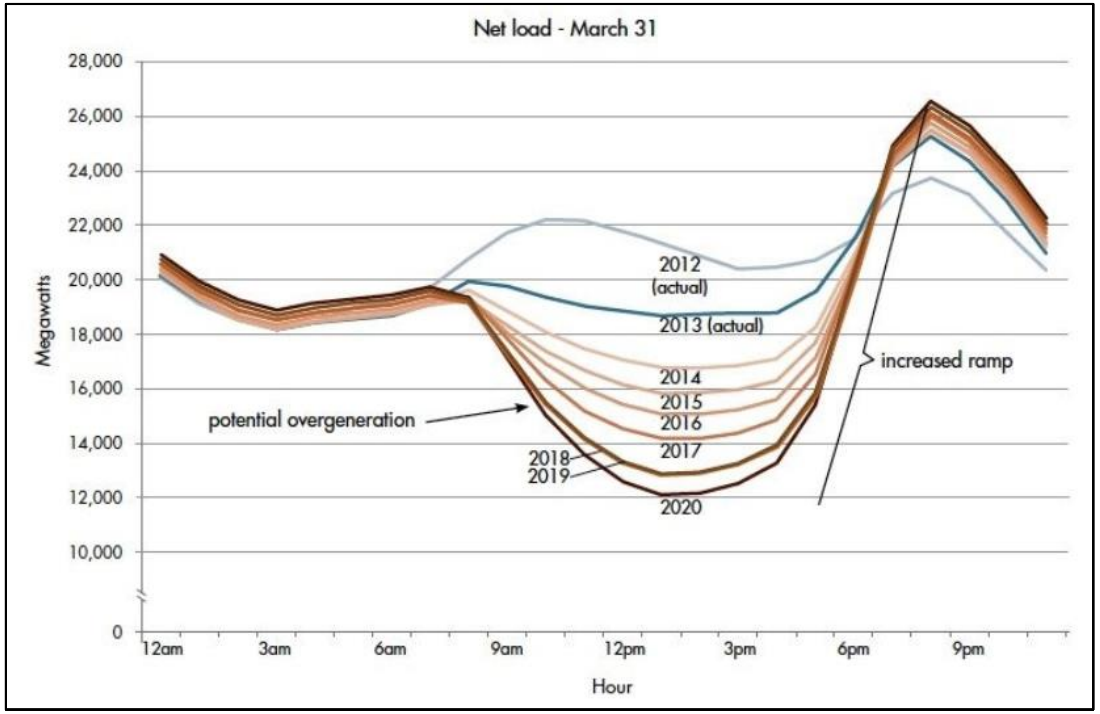
Outline

- **Motivation**
- **Opportunities of Proposed Decentralized Storage**
- **Challenges of Decentralized Storage**
- **Energy Storage Alternatives**
- **Optimal Synthesis and Suggested Case Studies**
- **Preliminary Results**
- **Project Schedule: Milestones**

Motivation

- **Increasing renewable energy penetration into the grid is resulting in increasing cycling operation of conventional generating units**
- **Increasing cycling leads to efficiency loss, higher emissions, and adverse effect on plant health**
- **Incorporating energy storage can lower power plant ramp rates while providing necessary power**
- **Information available in the current open literature shows that storage integration at grid level (centralized storage) is being mainly considered: large capacity and costs**
- **When power plant level storage(decentralized storage) is considered, synergy with the power plant operation is not exploited**
- **Here we propose storage integration at power plant level (decentralized storage) exploiting the synergy with the host plant**

CAISO Duck Curve[1]



Net demand = Grid Demand – Renewable energy production

Source: www.caiso.com.

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Opportunities of Proposed Decentralized Storage

- Greatly improves the number of potential storage options

- Reduce costs and utilize existing equipment items in host power plants
  - Since all storage options should finally produce electricity, existing equipment items from power plants can be utilized rather than purchasing new equipment items for centralized options

  - Decentralized storage is also likely to reduce the O&M cost including personnel cost

- Decentralized thermal storage can be easily achieved at various exergy levels thus providing high flexibility and efficiency

- Exploit synergy with the host power plant
  - For example, the hot air from battery cooling can be added to the combustion air of a power plant

- Lower investment
  - Much lower capital investment than centralized storage customized on the desired load-following capability of the host plant
  - Future power plants with integrated storage option may have lower nominal rating thus reducing capital investment

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Challenges of Decentralized Storage

- **Maximum ramp rate, achievable lowest load, and penalty (efficiency, emission, health) of various types of power plants are vastly different.**
  - **For optimal synthesis of the energy storage technologies and their ratings, dynamics of the host plant need to be considered along with the dynamics of the storage technology.**
  - **Impact of the cycling operation of the auxiliary equipment items provided for storage on their efficiency and health needs to be considered in the cost function.**

Therefore the optimization problem for storage synthesis is dynamic optimization and can be considerably large and expensive.

- **Decentralized storage option should align with the business strategy of the host plant.**
  - **For example, storing energy as a chemical to be sold may not align well with the business model of the power plants**

- **Should have admissible impact on power plant operation and configuration**

- **Storage technologies vary widely based on the maturity of technologies, their costs, capacity, life, availability, efficiency, footprint, dynamics, safety and environmental hazards. These aspects need to be considered in optimal selection of technology/technologies for a host power plant.**

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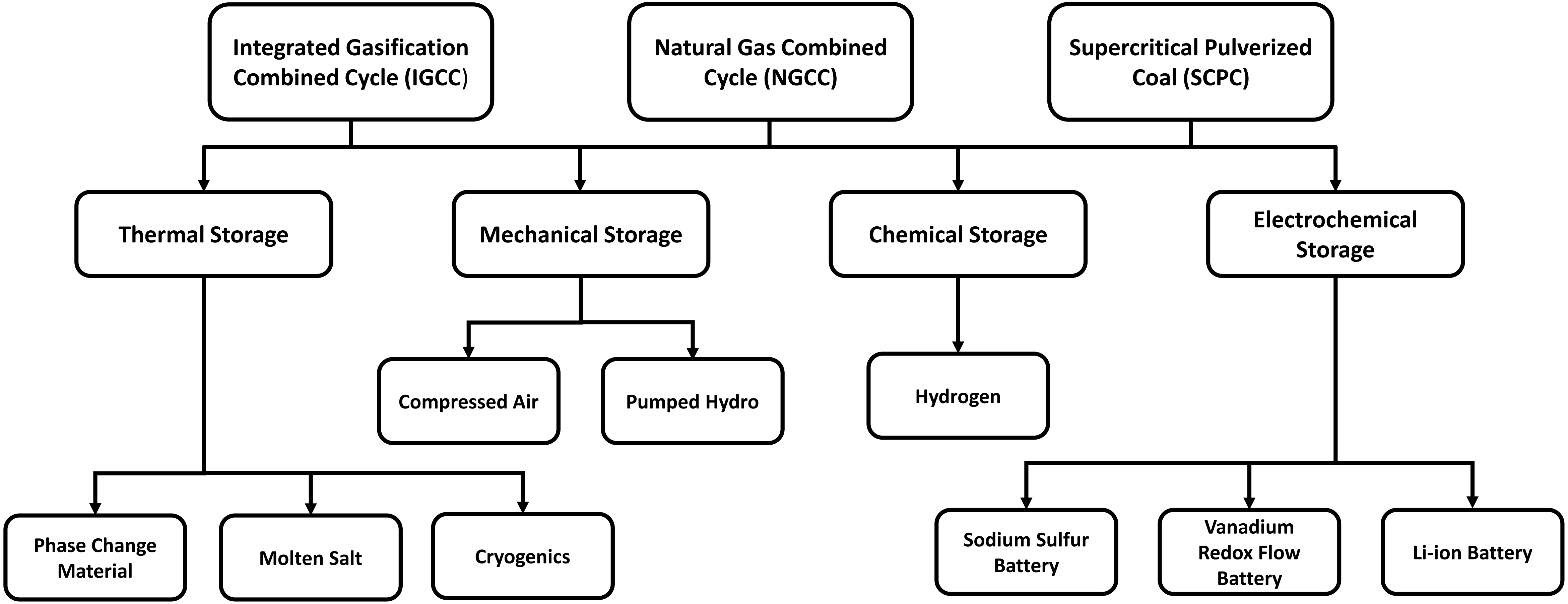
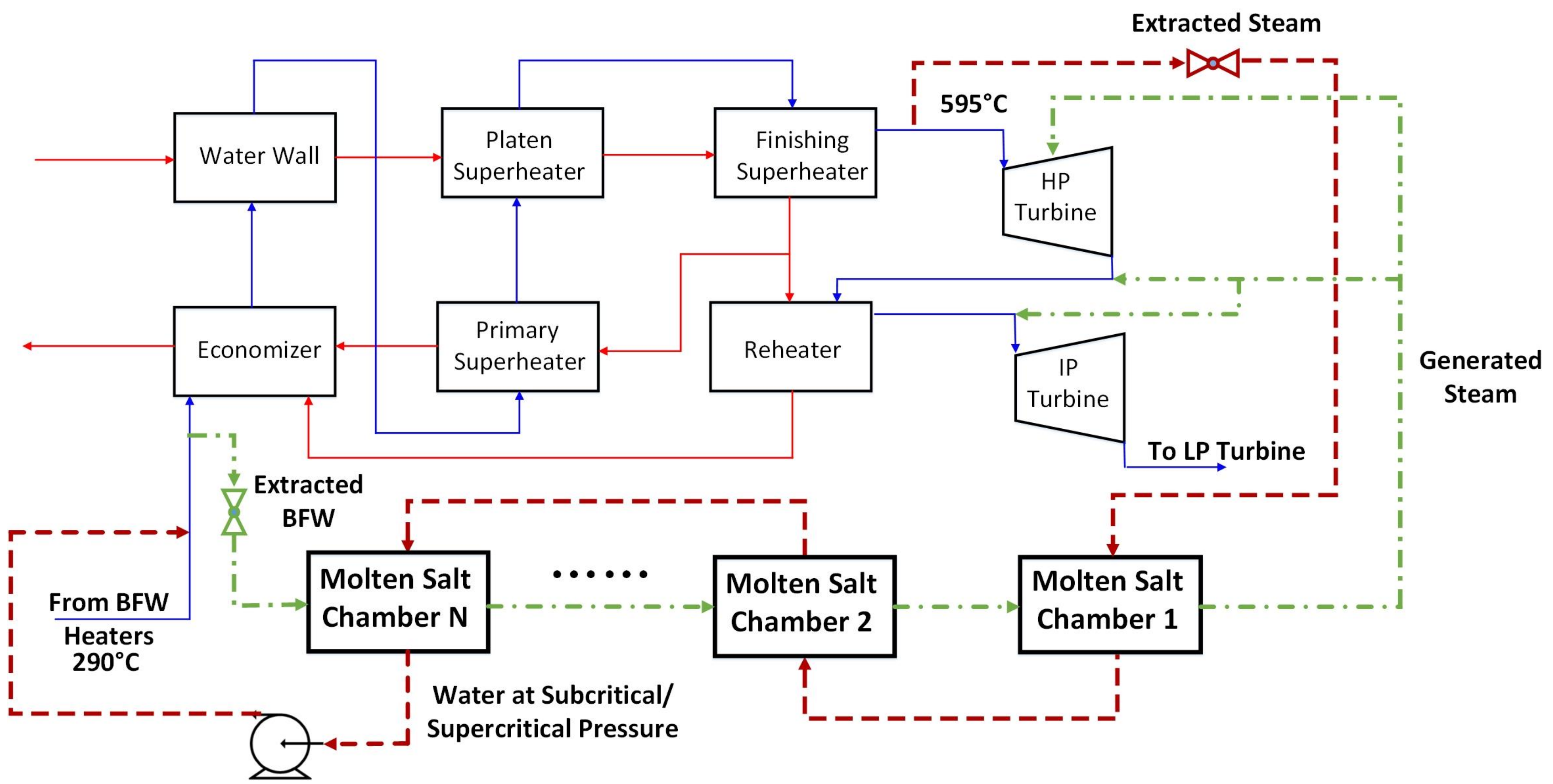
Energy Storage Alternatives

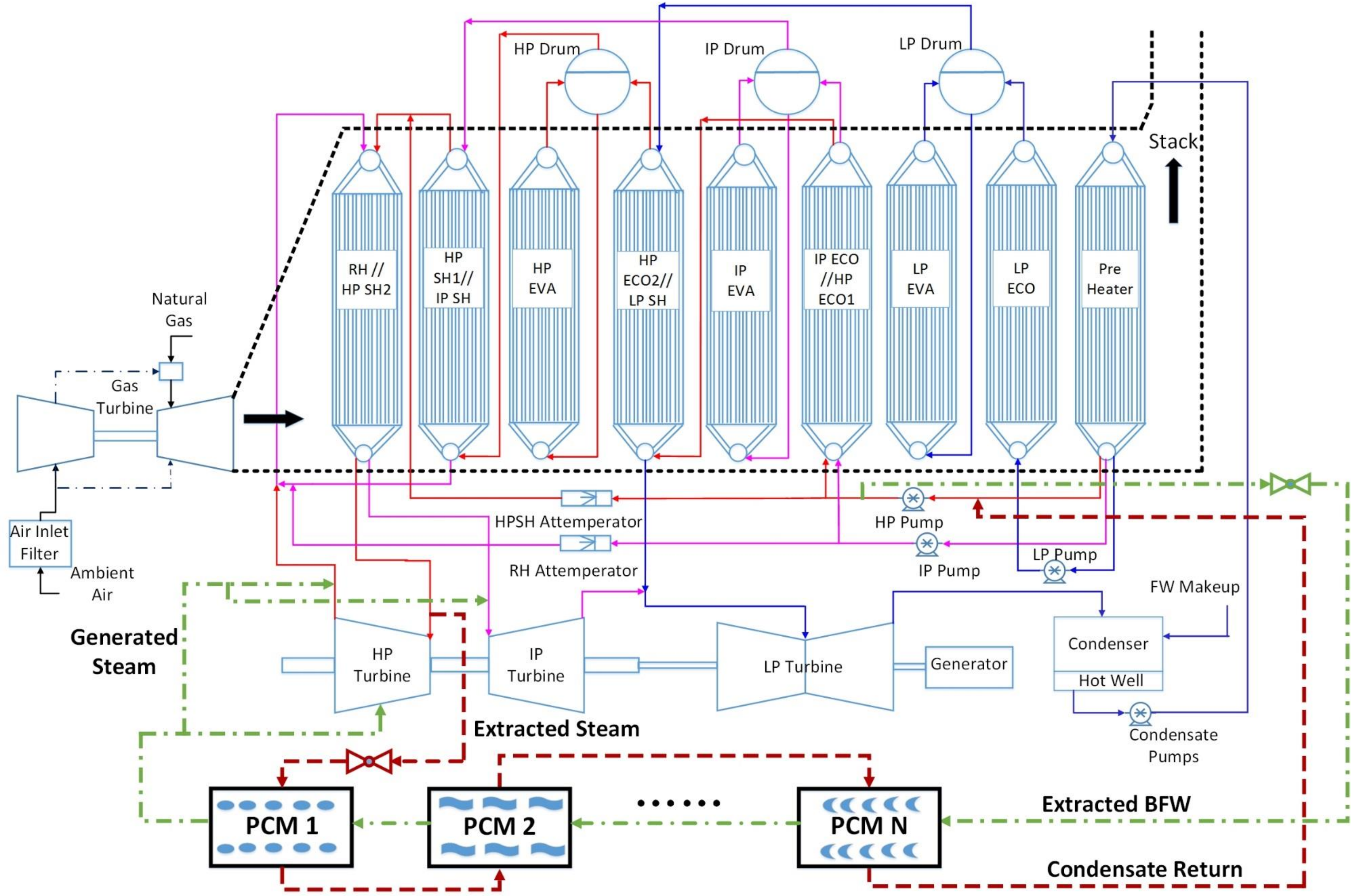


- **Note**: Not necessarily each type of storage will be considered for each type of power plant

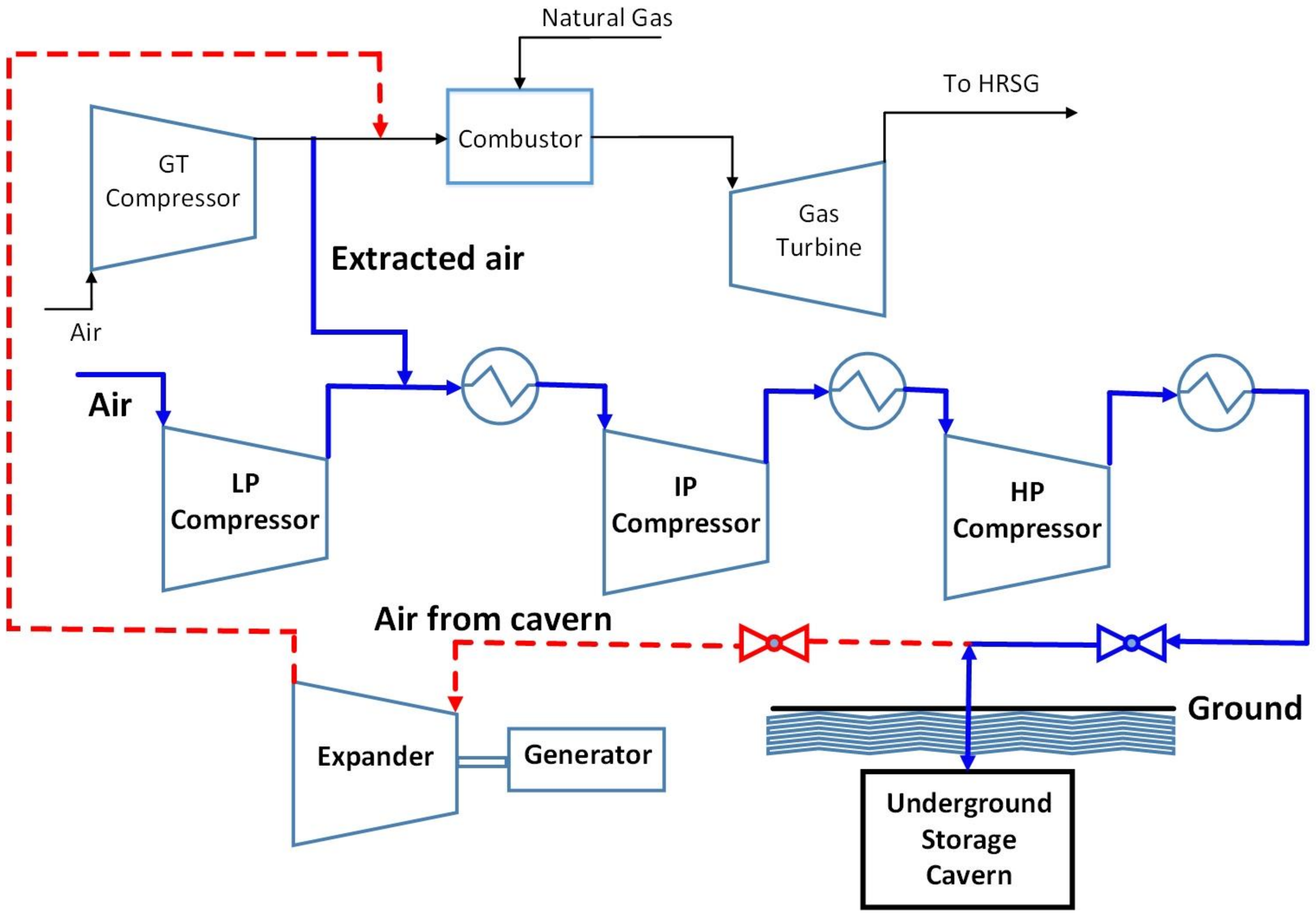
Synergistic Thermal Storage in an SCPC Plant Using Molten Salt



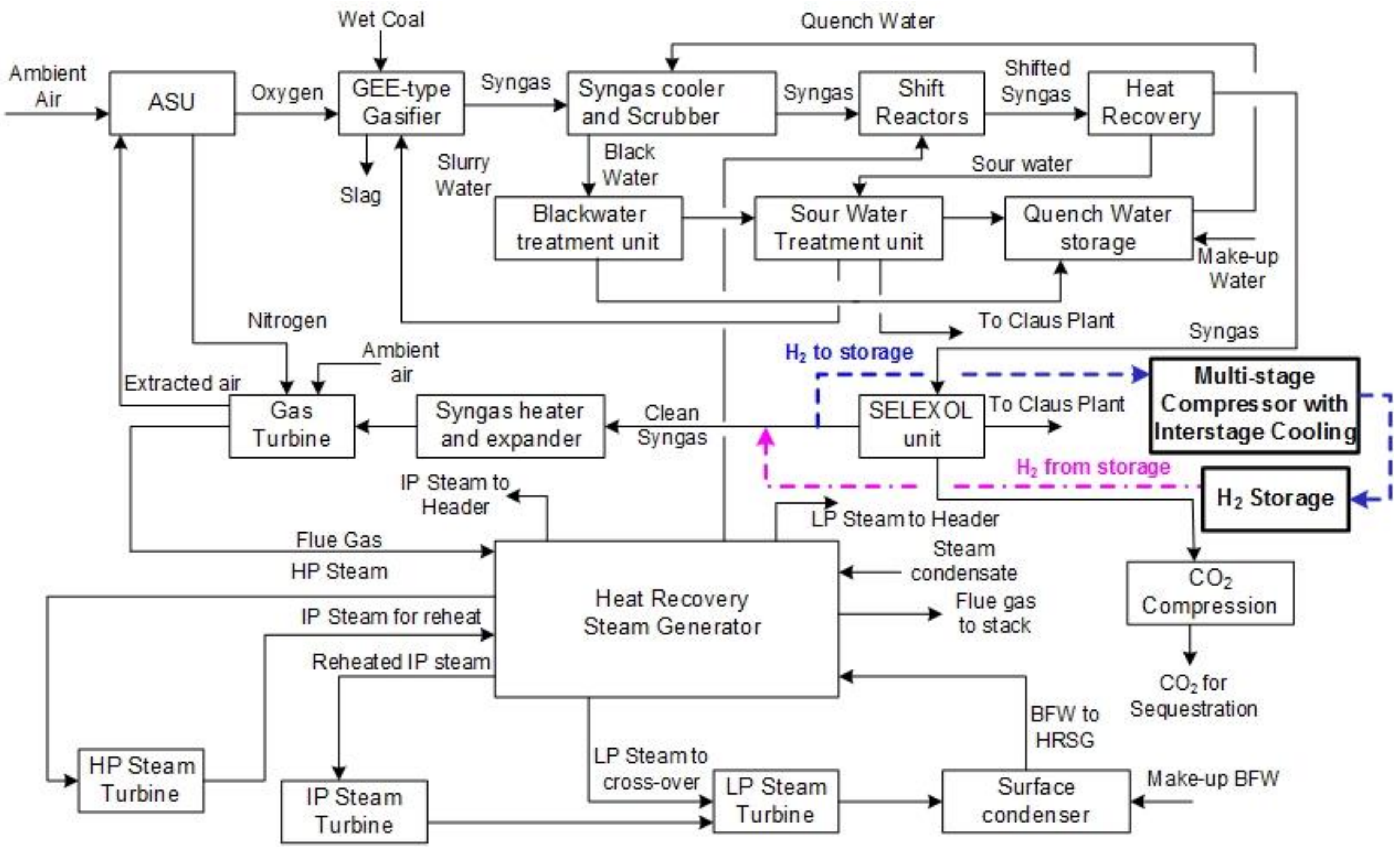
Synergistic Thermal Storage in an NGCC Plant Using Phase Change Materials (PCMs)



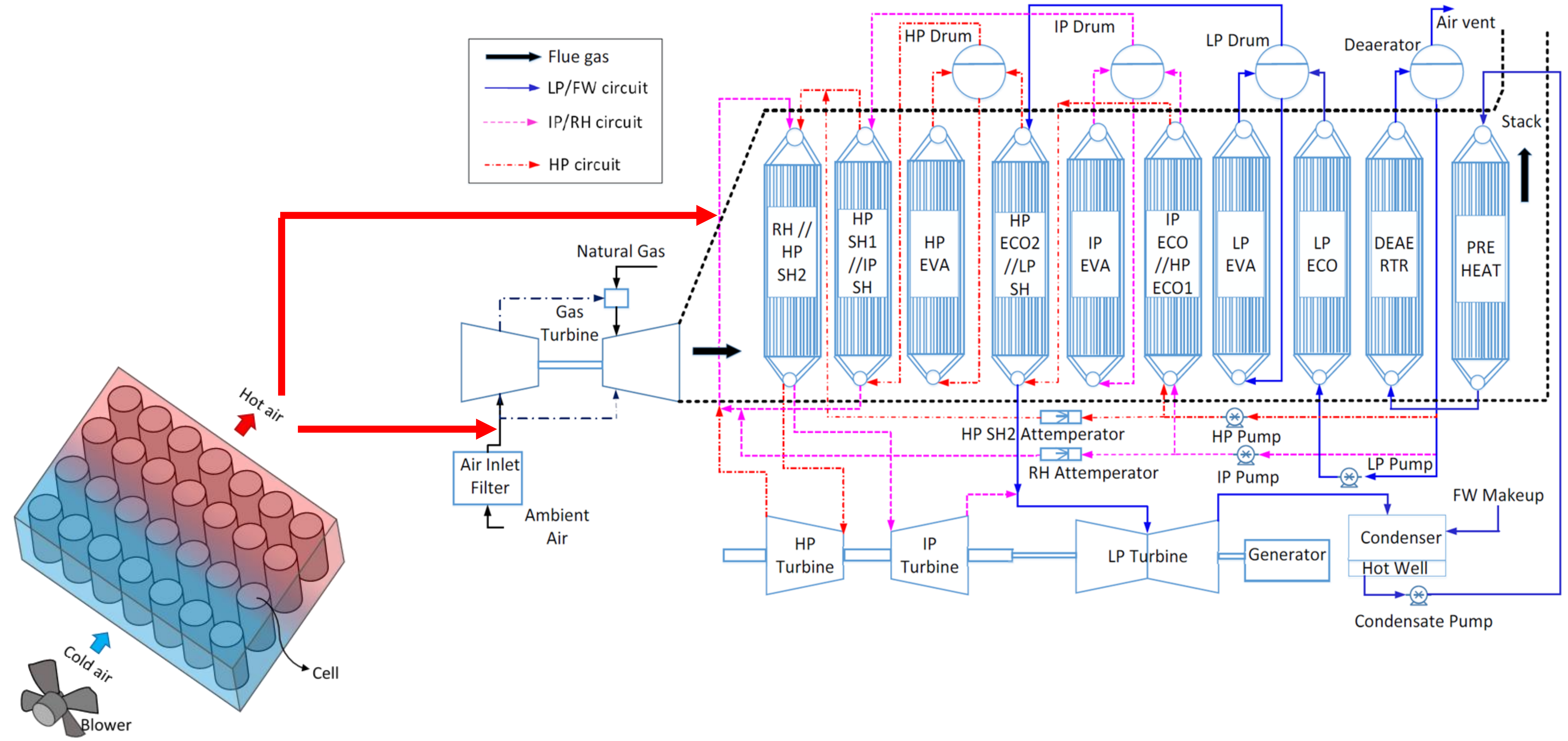
Synergistic Mechanical Storage in an NGCC Plant Using Compressed Air



Synergistic Chemical Storage in an IGCC Plant Using Hydrogen



Synergistic Electro-Chemical Storage in an NGCC Plant Using Sodium Sulfur Battery



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West Virginia University

Optimal Synthesis of Storage Technologies

- **Trade-offs between capital costs and efficiency for technologies**
- **Discrete decisions for selection of storage technologies: Mixed Integer Nonlinear Programming (MINLP) problem**
- **Integrated system must be able to follow a time-varying grid demand**
- **Need for dynamic models of storage and power plants**
- **Including system dynamics in the optimization framework results in Mixed-Integer, Nonlinear and Ordinary Differential Equation (MINODE) models**

$$\min_{y_i, x_i, \epsilon_i(t)} \quad C_i^{f/c}\, y_i + C_i^{i/c} \left(\frac{x_i}{x_i^o}\right)^n + y_i \left[\sum_{t=1}^{NT} C_i^{o/p}(t)\, dt\right] + y_i\, C_i^{m/c}$$

Minimizing total costs

s.t.

$$\bigvee_{i \in I} \begin{bmatrix} y_i, \\ \dot{g}_i(x_i, \epsilon_i(t)) \leq 0, \\ \dot{h}_i(x_i, \epsilon_i(t)) = 0, \\ \epsilon_i(t_0) = \epsilon_{i,0}, \\ g_i^{ss}(x_i) \leq 0, \\ h_i^{ss}(x_i) = 0, \\ x_i \in [x_i^L, x_i^U], \end{bmatrix}$$

ODEs for storage technology i

Steady state equations as a function of storage capacity x_i

Bounds on storage capacity x_i

$$\sum_{i=1}^{I} \epsilon_i(t)\, y_i - D(t) = 0,$$

Sum of electricity dispatch ϵ_i from each storage technology to meet demand

$y_i \in \{0, 1\}, x_i \in R, \epsilon_i(t) \in R.$

y_i : Binary variable for selection of storage technology i

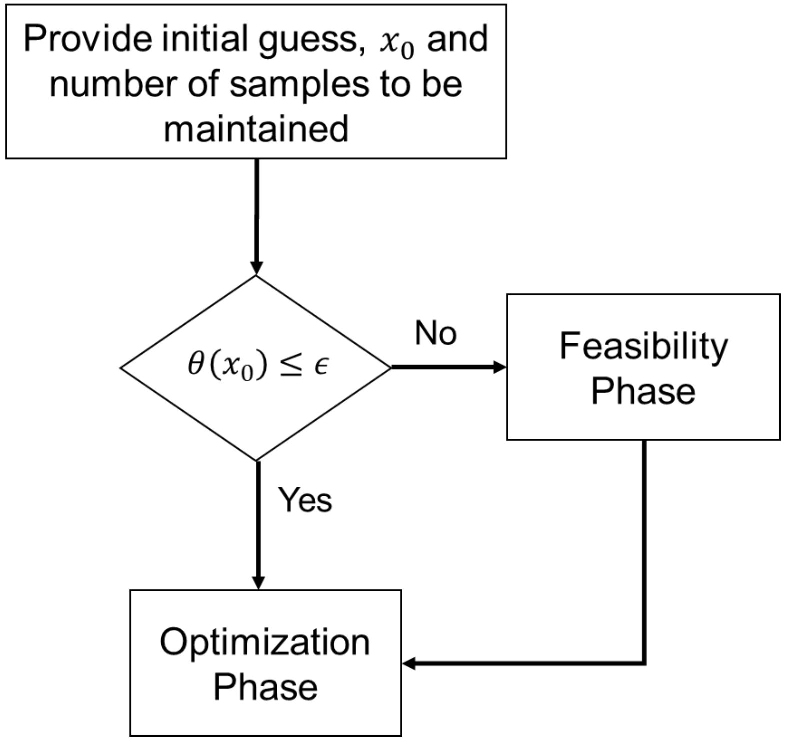
x_i : Maximum capacity of storage technology i

$\epsilon_i(t)$: Electricity storage/dispatch variable of storage technology i at time t

Decision variables

Solution Strategy

- **Data-Driven Black-Box Optimization used**
- **Consists of Feasibility and Optimization phases**
- **Both phases based on trust-region framework**
- **Utilize input-output simulation data for constructing surrogate models**
- **Can handle infeasible initial points**
- **General form:**



P1

$$\begin{aligned} \min_x \; & f(x) \\ s.t. \; & g_k(x) \leq 0, && \forall\, k = 1, \ldots, K \\ & g_u(x) \leq 0, && \forall\, u = 1, \ldots, U \\ & x_i \in \left[x_i^L, x_i^U\right] && \forall\, i = 1, \ldots, n \end{aligned}$$

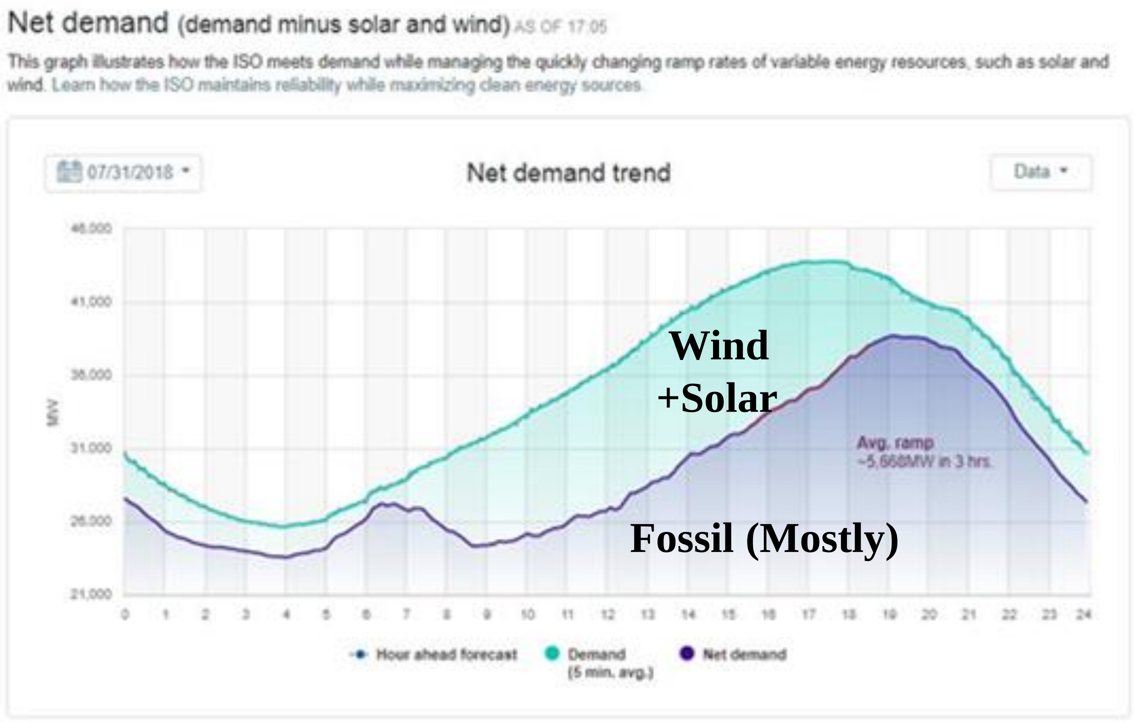
Functions with hidden expressions in a black-box simulator (g_k)

Functions with known expressions (g_u)

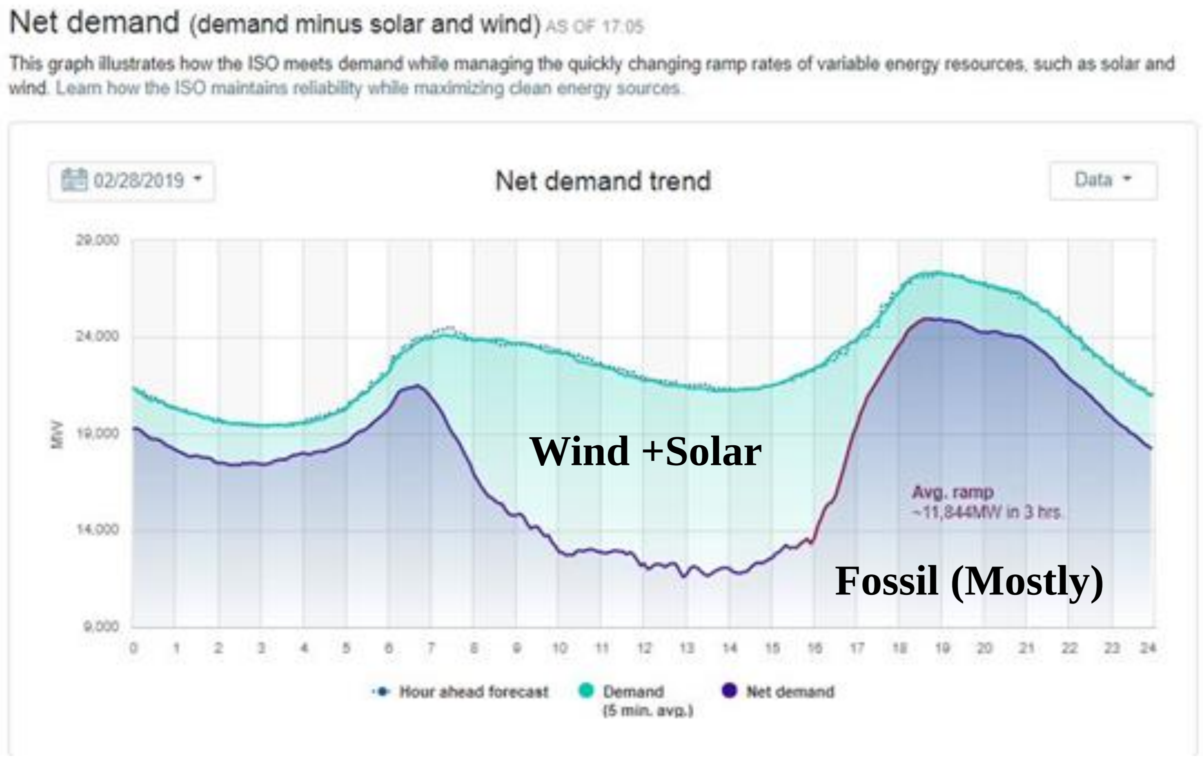
Bajaj et al. "A trust region-based two phase algorithm for constrained black-box and grey-box optimization with infeasible initial point." Computers & Chemical Engineering 116 (2018): 306-321.

Suggested Case Studies

One Summer Day Imbalance from California ISO Considered as ‘Today’



One Winter Day Imbalance from California ISO Considered as ‘Extreme’



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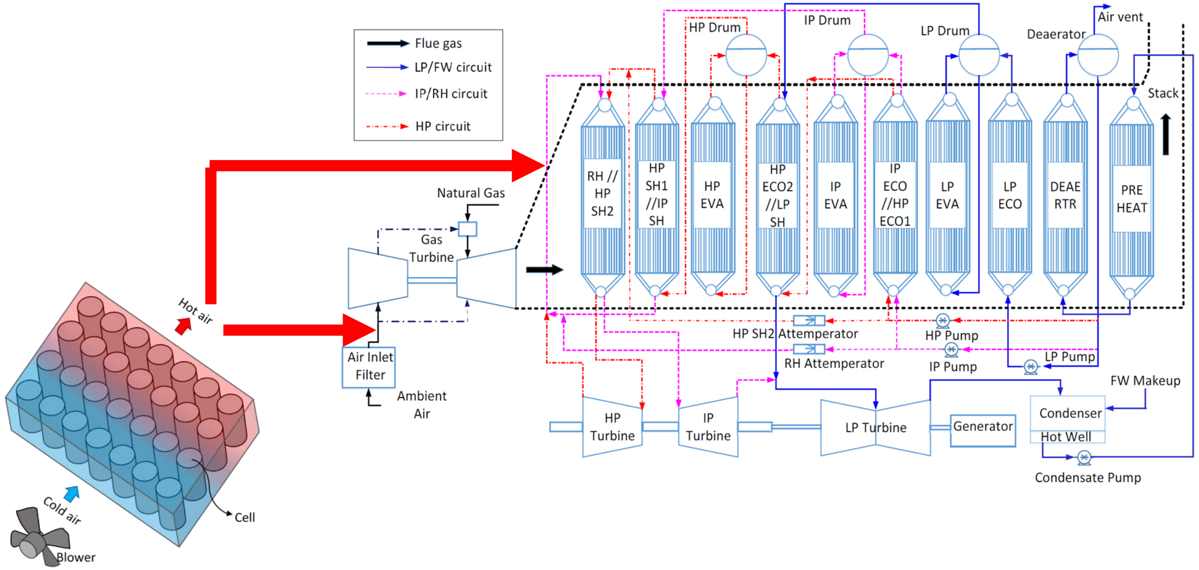
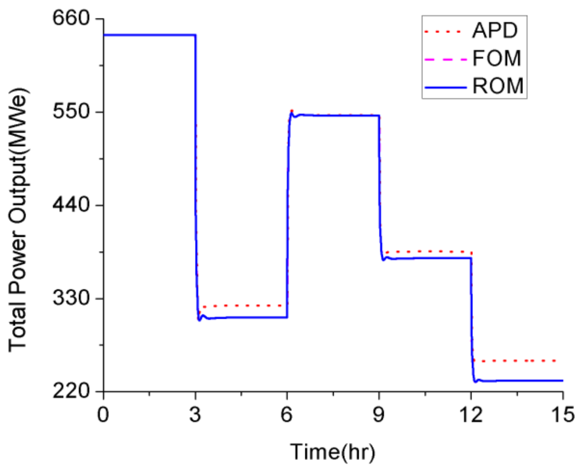
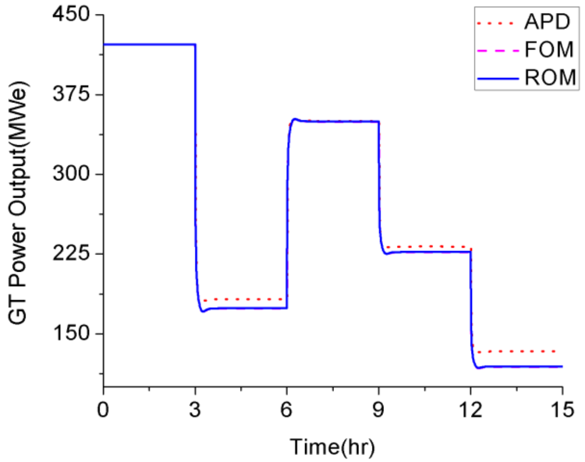
Preliminary Results: NGCC Plant with Integrated Sodium Sulfur Battery

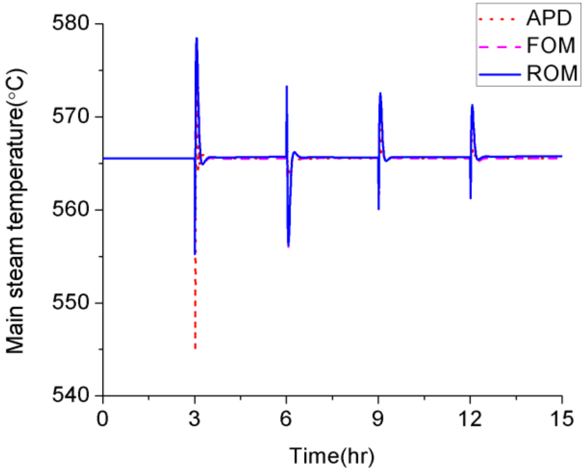
Development of reduced order model (ROM) for the NGCC plant to be used for optimal downselection:

- **Linearization of the nonlinear NGCC plant model at different load. (e.g. full load, 80% load, 60% load, etc.)**
- **Large-scale state-space model includes about 600 state variables**
- **ROM is generated using the balanced truncation method, based on Hankel singular value (HSV) decomposition**







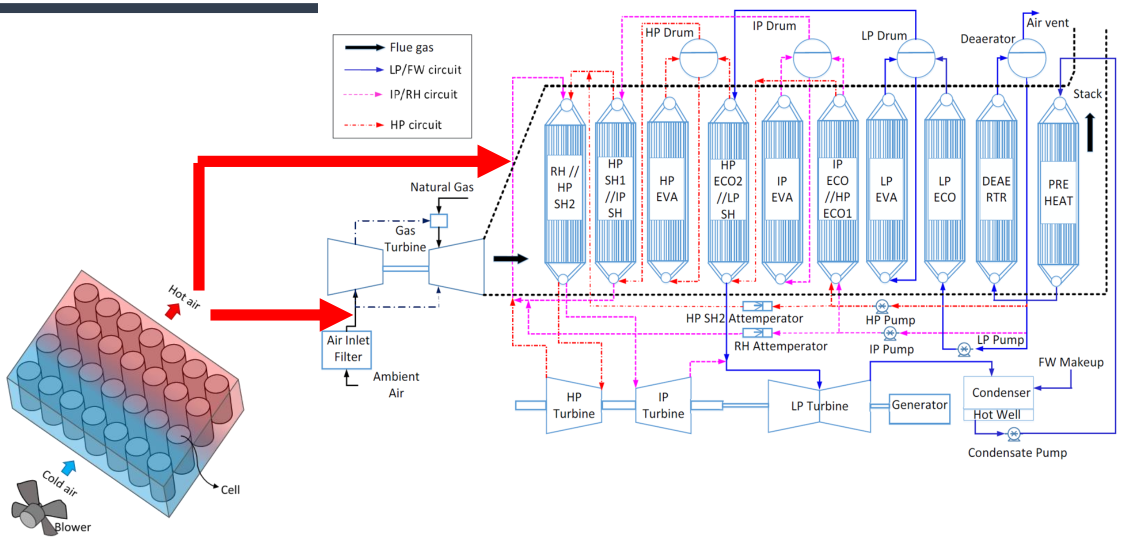


APD: High-fidelity model in Aspen plus dynamics; FOM: Full-order model linearized at full load, Size(FOM)= **582**
ROM: Reduced-order model, Size(ROM)=**35**

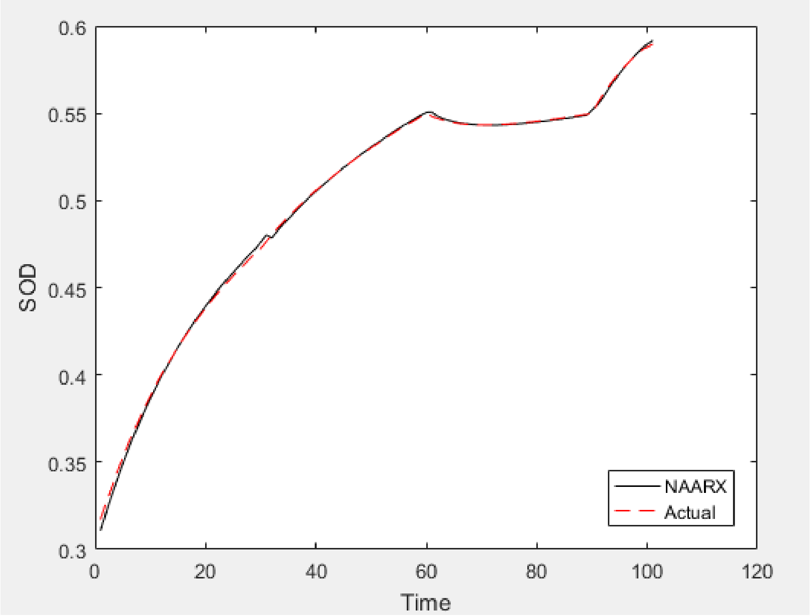
Preliminary Results: NGCC Plant with Integrated Sodium Sulfur Battery

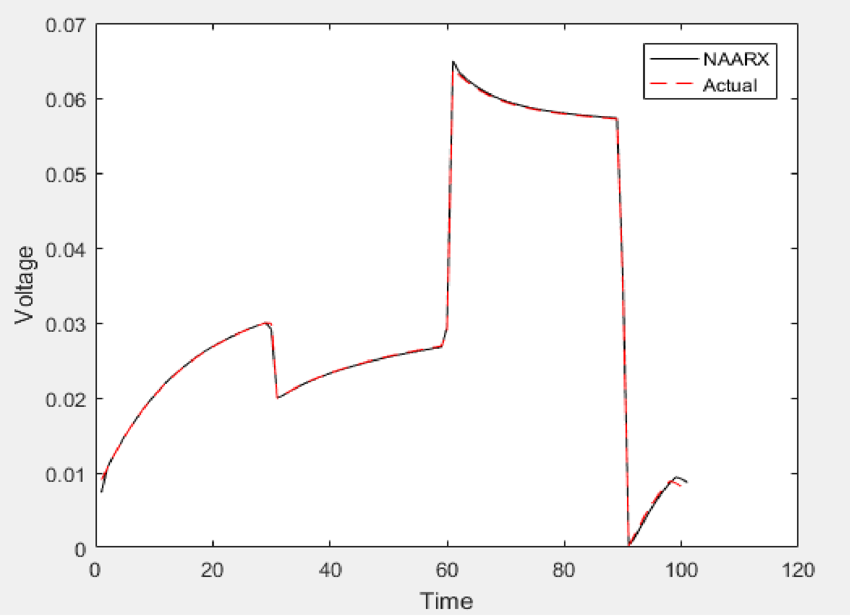
Development of reduced order model (ROM) for the Sodium-Sulfur Battery to be used for optimal downselection:

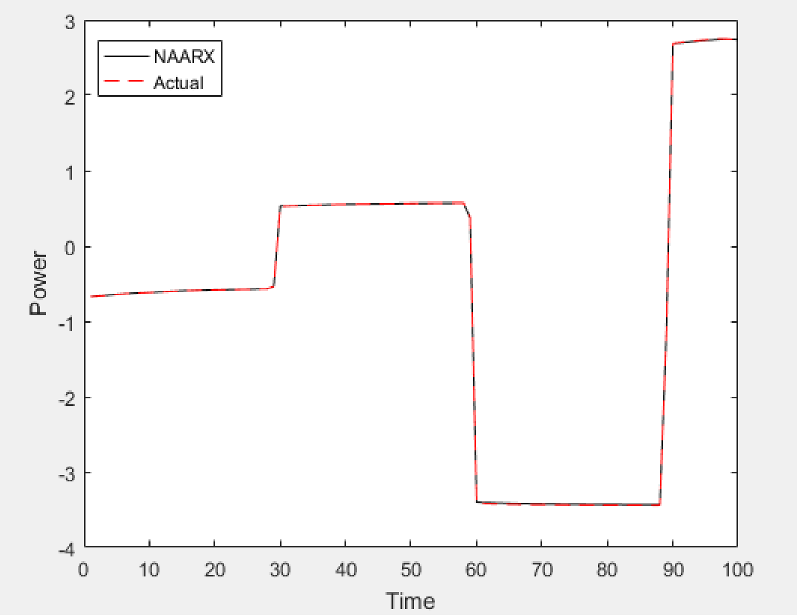
- **NAARX (Non-linear Additive Autoregressive with Exogenous Input) model**
- **Model selection using Akaike Information Criterion**



Model Validation: Discharging in 2-Phase Region







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Project Schedule: Milestones

Milestone No.	Task/Sub task	Milestone Title and Descriptions	Planned Completion Date	Verification Method
1	4.1	Complete the simplified input-output model of the proposed mechanical, chemical and electrochemical energy storage technologies	10/31/20	Root mean squared error (RMSE) is within 10% of rigorous dynamic model and time to simulate the model takes less than $1/100^{th}$ of real time so that they can be used in optimization
2	4.2	Complete the simplified input-output model of the proposed thermal energy storage technologies	10/31/20	Root mean squared error (RMSE) is within 10% of rigorous dynamic model and time to simulate the model takes less than $1/100^{th}$ of real time so that they can be used in optimization
3	5.0	Complete the energy storage technology downselection	12/31/20	MINLP algorithm successfully satisfied the convergence criteria
4	8.0	Complete the TEA of six selected system concepts	12/31/21	Energy storage technologies can satisfy the imbalance with at least 10% excess storage, which is the design margin

Acknowledgement

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- Our students: Manali Zantye (TAMU), Yifan Wang (WVU) and Sai Pushpitha Vudata (WVU)

Thank you for your attention

Questions?