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

Award#:DE-FE0031771

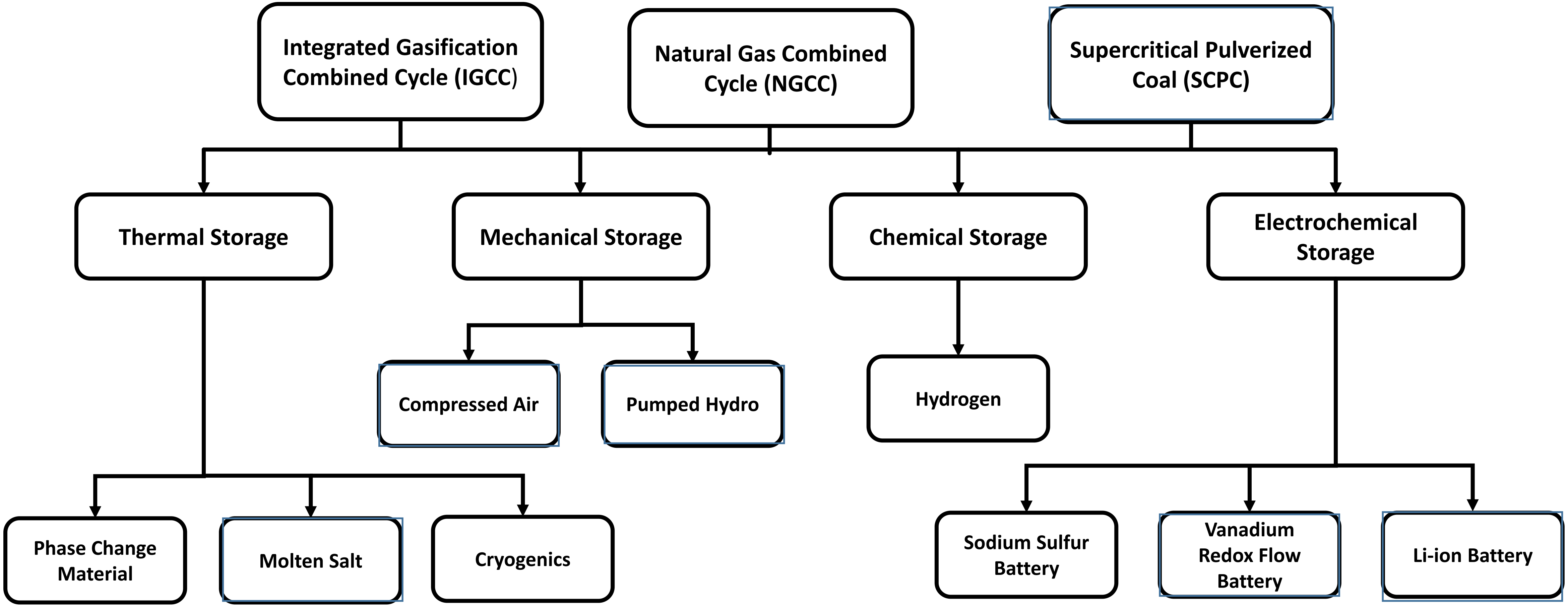
PI: Debangsu Bhattacharyya[a]
Co-PI: M. M. Faruque Hasan[b]
[a] Department of Chemical and Biomedical Engineering, West Virginia University
[b] Department of Chemical Engineering, Texas A&M University

2021 University Turbine Systems Research Project Review Meeting
November 9, 2021

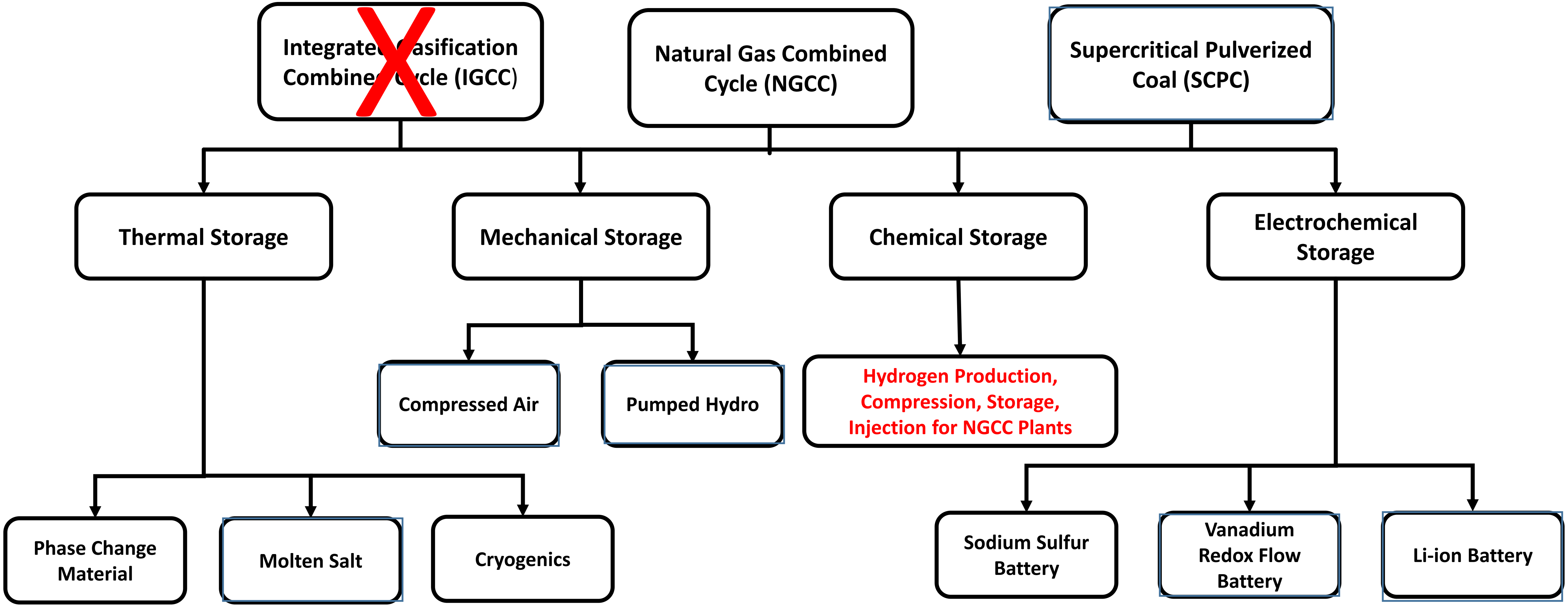
Outline

- Design Space
- Energy Storage Alternatives - High Fidelity and Reduced Order Models
- Optimal Downselection
- Ongoing and Future Works

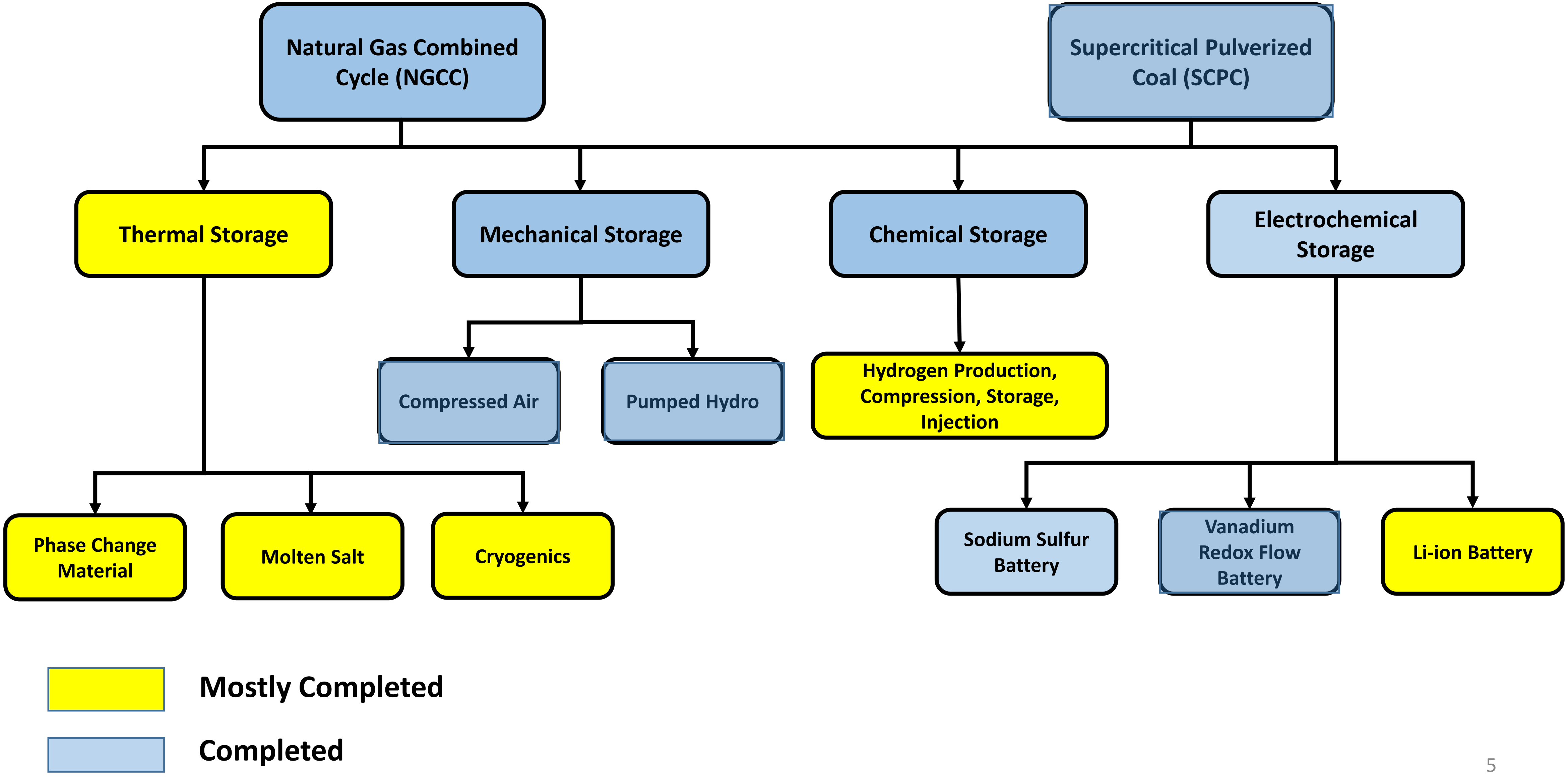
Design Space-Originally Proposed



Design Space-Modified Proposed



Design Space-Originally Proposed



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- **Energy Storage Alternatives - High Fidelity and Reduced Order Models**
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- Ongoing and Future Works

Reduced Order Models of NGCC and SCPC Power Plants

Reduced Order Modelling –NGCC Power Plant with H_2 Injection

- NGCC – Hydrogen Plant with 640.6 MW base load

	Nominal Load	Range of Operation-ROM development
Natural gas	Flowrate : 72871.1 kg/hr	Range : Nominal Load to Full Load(without Hydrogen) 50538.5-72871.1 kg/hr
Hydrogen	Flowrate : 4213.3 kg/hr (5wt% injection)	Range : Nominal Load to Maximum Load 4213.3-12826.7kg/hr

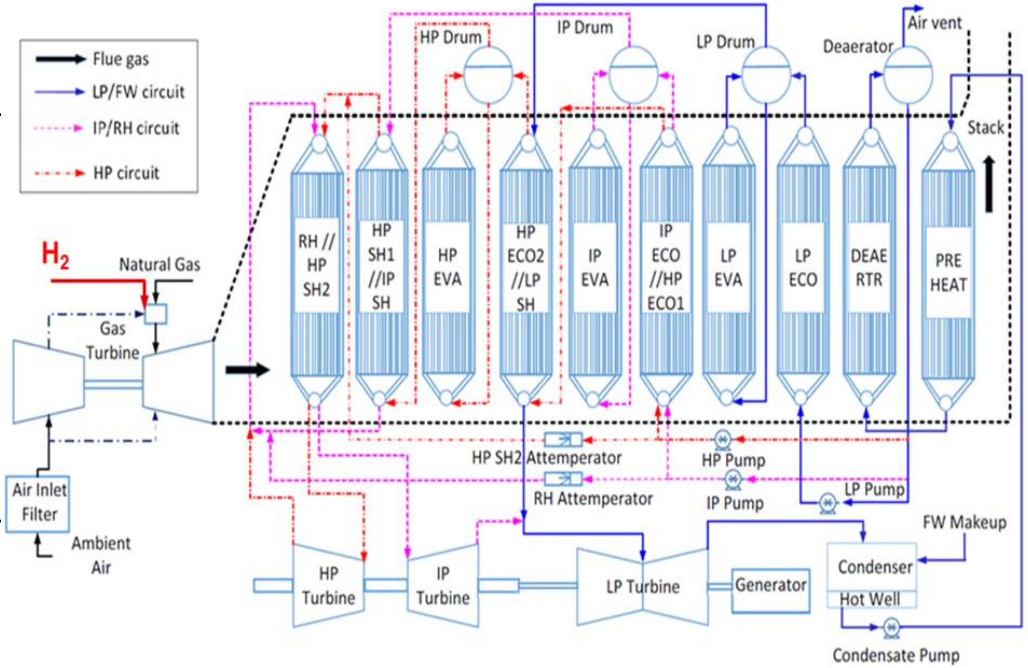
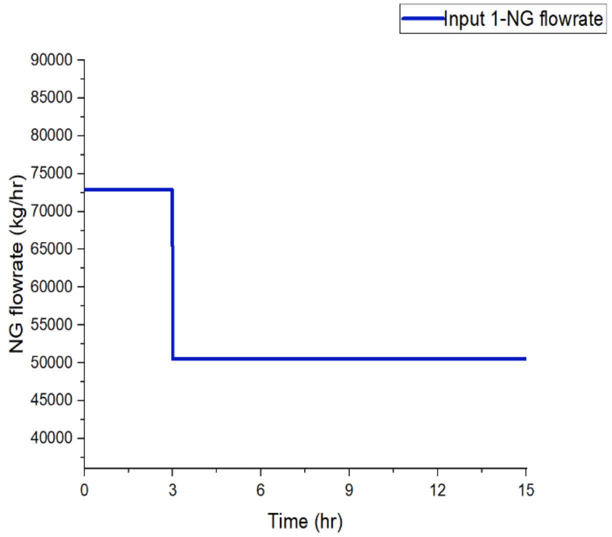


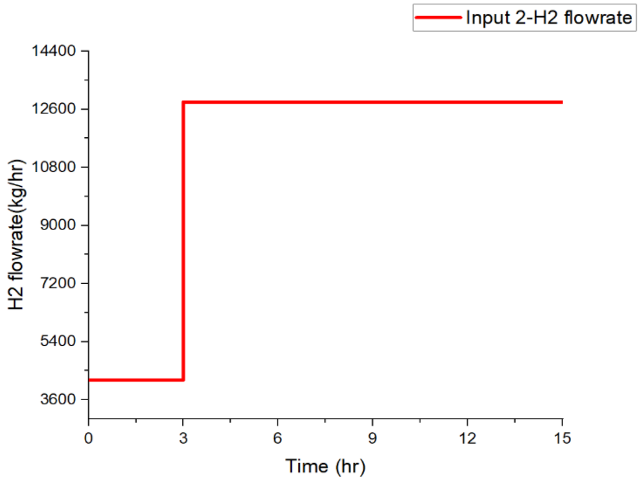
Fig 1. NGCC with Hydrogen Injection

- Discrete-time state space model developed by linearizing the nonlinear model
- Main Constraint: Hydrogen injection should be ≤ 20wt%

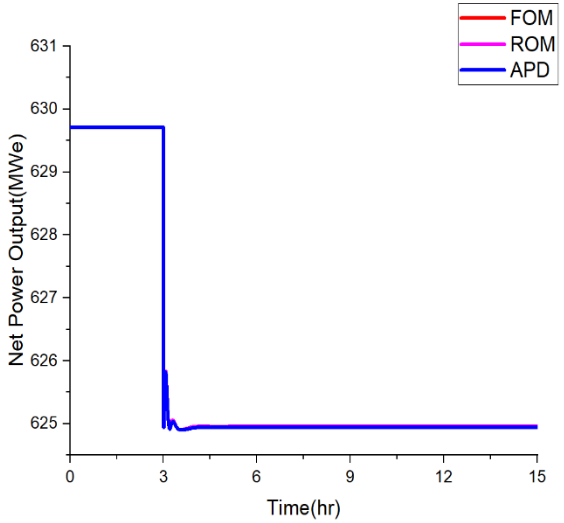
Model Validation- NGCC Power Plant with H_2 Injection

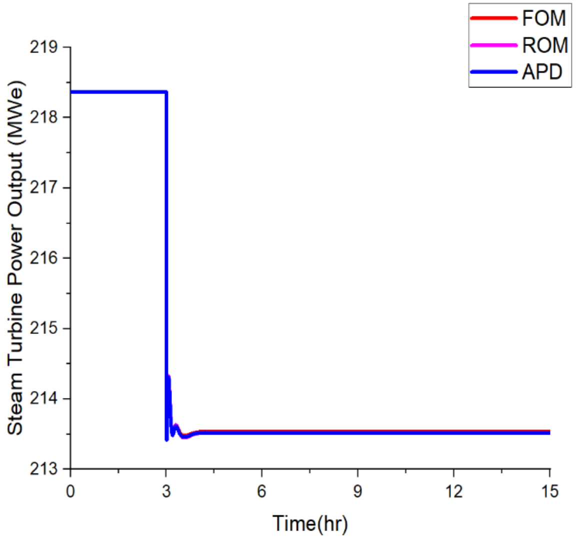
Inputs

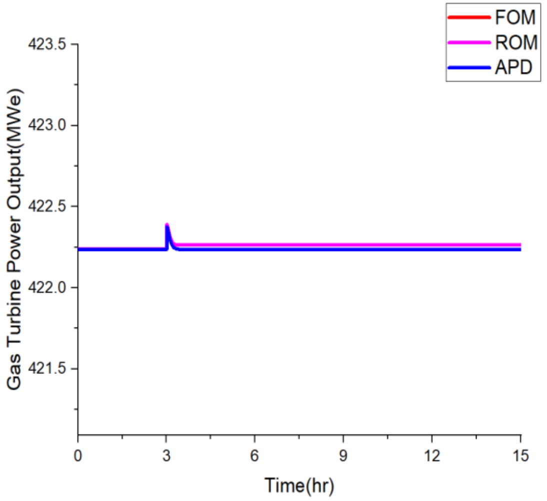


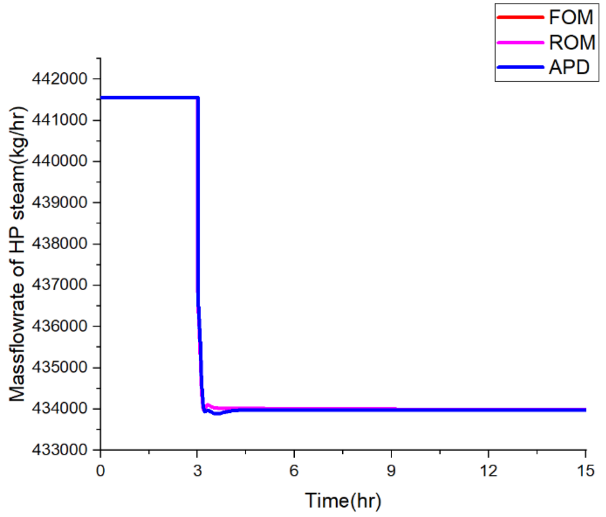


Outputs









SCPC Plant Model-ROM development

- **SCPC Plant Key Variables**

Parameter	Unit	SCPC Model
Gross Power	MW	620
Net Power	MW	532
Main Steam Pressure	MPa	24.1
Main Steam Temperature	°C	593

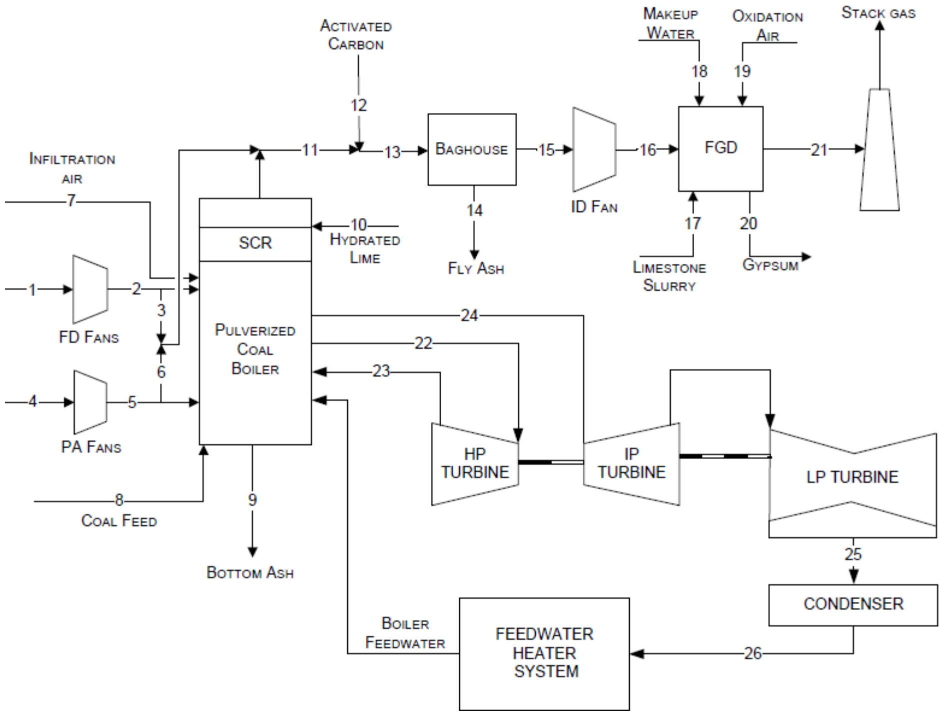


Fig 3. SCPC Plant Model [1]

- **Highlights**

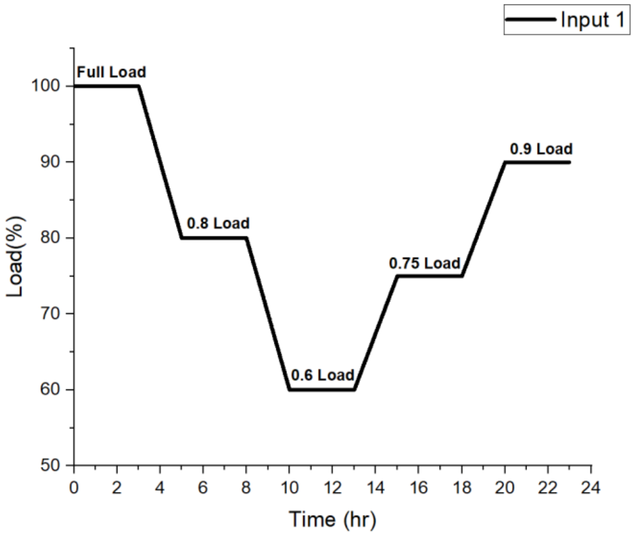
✓ **Reduced-order model generated using Hankel singular value (HSV) decomposition**

✓ **Range of operation for the ROM development evaluated between 60%-100% load.**

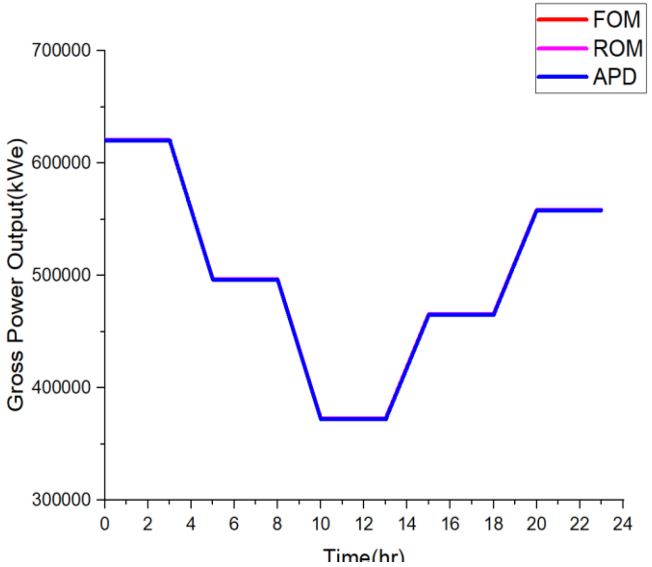
Reference : [1] Sarda, P.; Hedrick, E.; Reynolds, K.; Bhattacharyya, D.; Zitney, S.E.; Omell, B. Development of a Dynamic Model and Control System for Load-Following Studies of Supercritical Pulverized Coal Power Plants. *Processes* 2018, *6*, 226

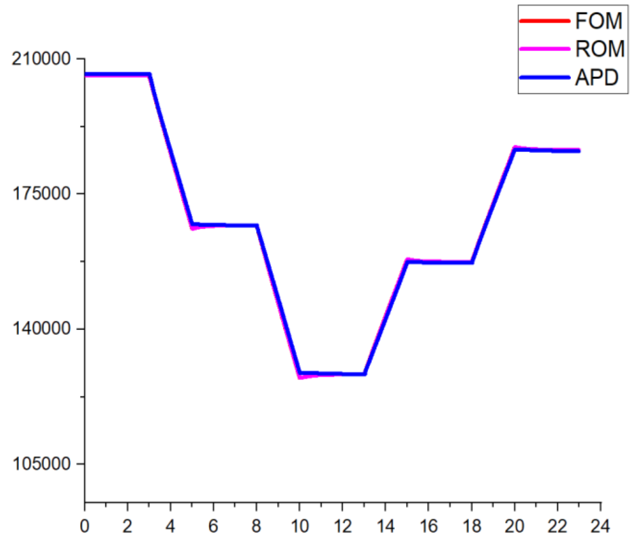
Reduced Order Modelling –SCPC Power Plant

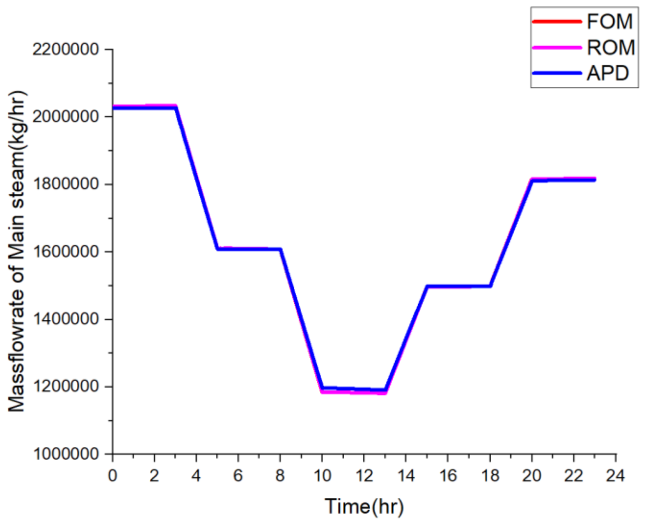
Input

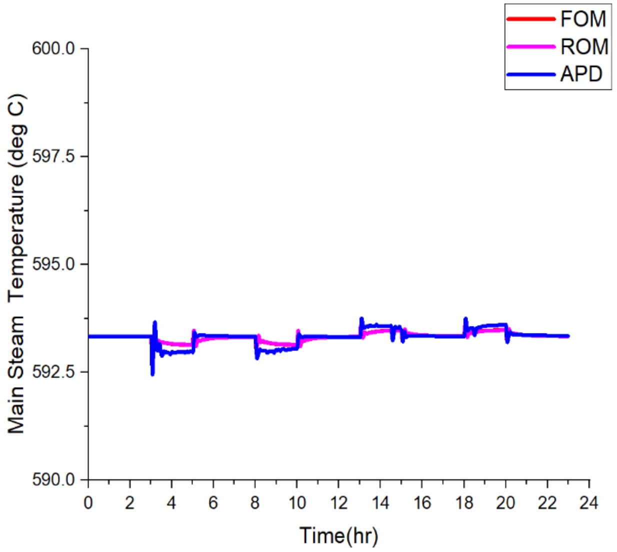


Output









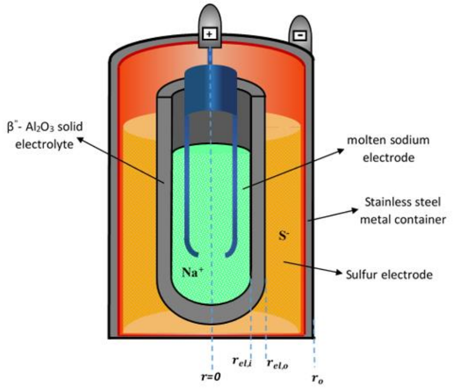
APD: High-fidelity Aspen Plus Dynamic Model
FOM: Full-order Model with 437 state variables
ROM: Reduced-order Model with 14 state variables

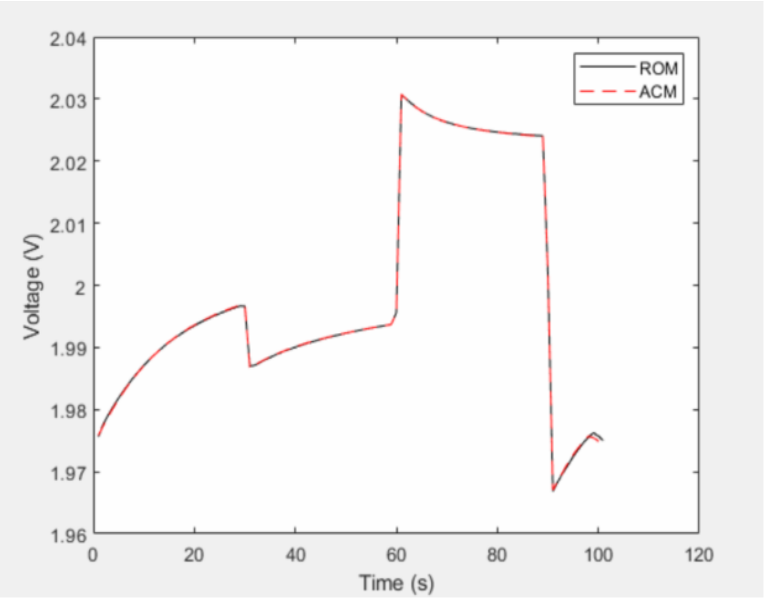
Electrochemical Storage: Detailed and Reduced Order Models of High Temperature Sodium Sulfur Batteries

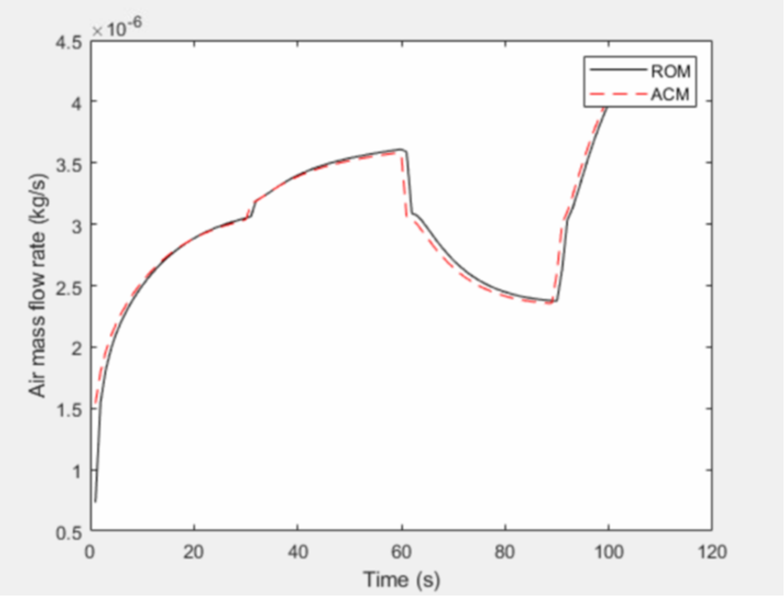
Sodium Sulfur Battery

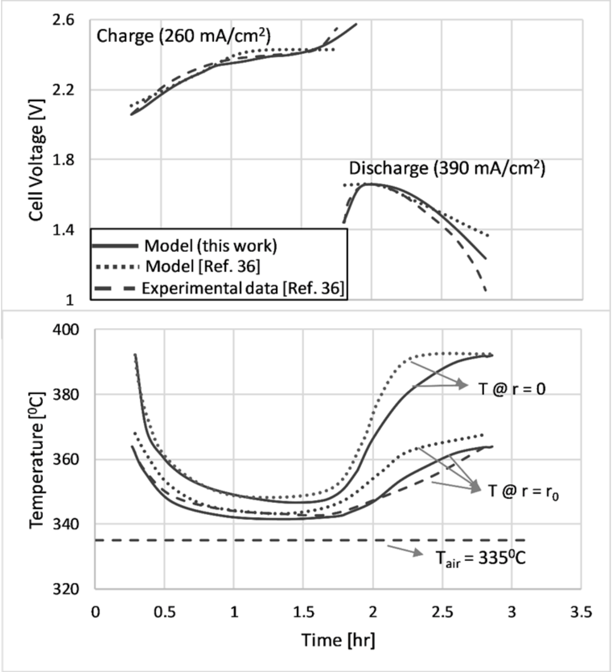
- **Advantages:**
  - **High energy density (~150–240 Wh/kg) and power capacity (~90–230 Wh/kg)**
  - **High round-trip efficiency (~90%)**
- **Half cell reactions:**

$$2Na \leftrightarrow 2Na^{+} + 2e^{-}$$
$$2Na^{+} + xS + 2e^{-} \leftrightarrow Na_2S_x$$
$$2Na + xS \leftrightarrow Na_2S_x$$









Schaefer (Caprio) S, Vudata S P, Bhattacharyya D, Turton R, "Transient Modeling and Simulation of a Nonisothermal Sodium-Sulfur Cell", 453, 227849, Journal of Power Sources, 2020

Electrochemical Storage: Detailed and Reduced Model of Vanadium Redox Flow Batteries

Vanadium Redox Flow Battery

- **VRFBs can offer practically unlimited energy storage**
  - **Nafion-115 ion exchange membrane**
- **Half-cell, overall reactions:**

$$VO^{+2} + H_2O \leftrightarrow VO_2{}^{+} + 2H^{+} + e^{-}$$

$$V^{+3} + e^{-} \leftrightarrow V^{+2}$$

$$VO^{+2} + H_2O + V^{+3} \leftrightarrow VO_2{}^{+} + 2H^{+} + V^{+2}$$

- **Vanadium cross-over reactions**
  - **Negative electrode**

$$VO^{+2} + V^{+2} + 2H^{+} \rightarrow 2V^{+3} + H_2O$$

$$VO_2{}^{+} + 2V^{+2} + 4H^{+} \rightarrow 3V^{+3} + 2H_2O$$

  - **Positive electrode**

$$V^{+2} + 2VO_2{}^{+} + 2H^{+} \rightarrow 3VO^{+2} + H_2O$$

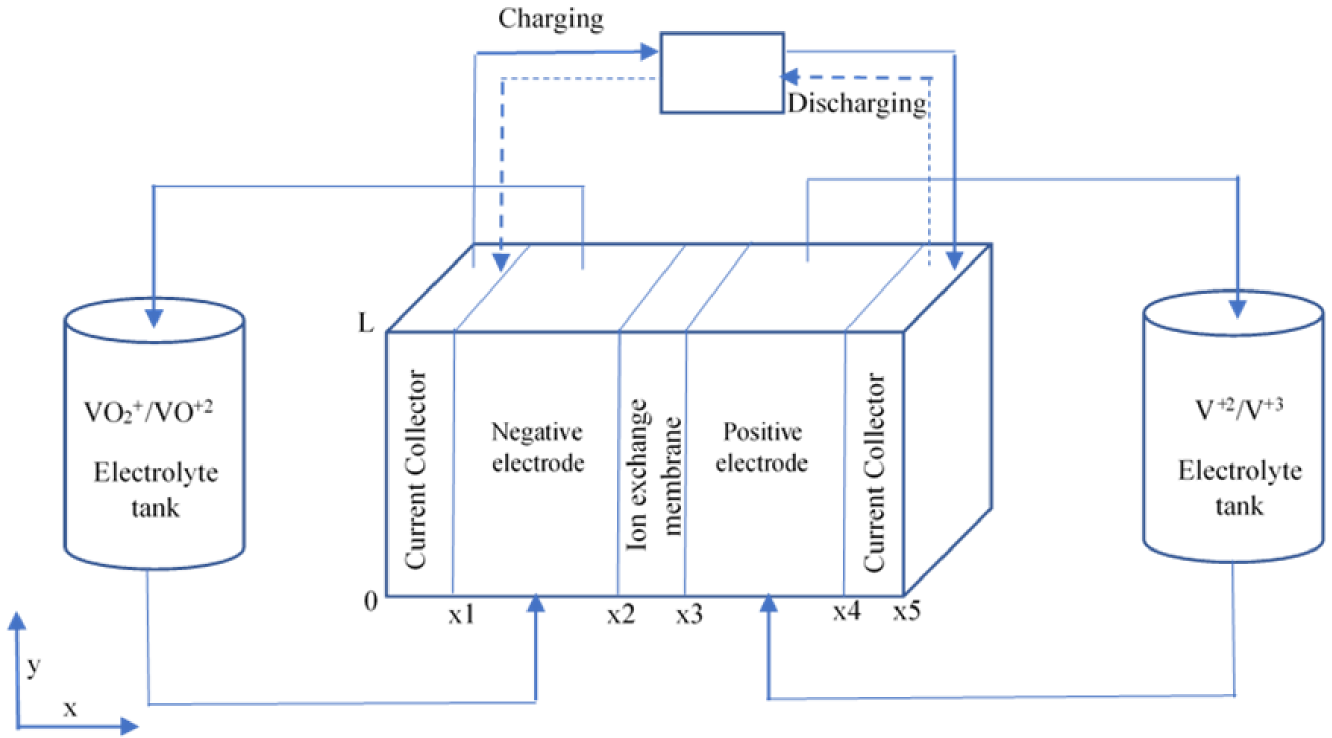
$$V^{+3} + VO_2{}^{+} \rightarrow 2VO^{+2}$$

- **Side reactions**
  - **Oxygen evolution at positive electrode**

$$2H_2O \leftrightarrow O_2 + 4e^{-} + 4H^{+}$$

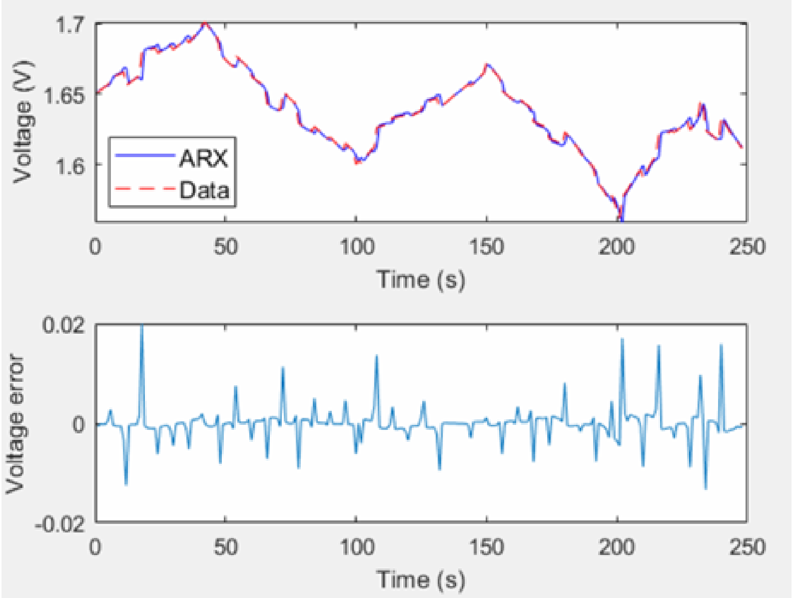
  - **Hydrogen evolution at negative electrode**

$$2H^{+} + 2e^{-} \leftrightarrow H_2$$

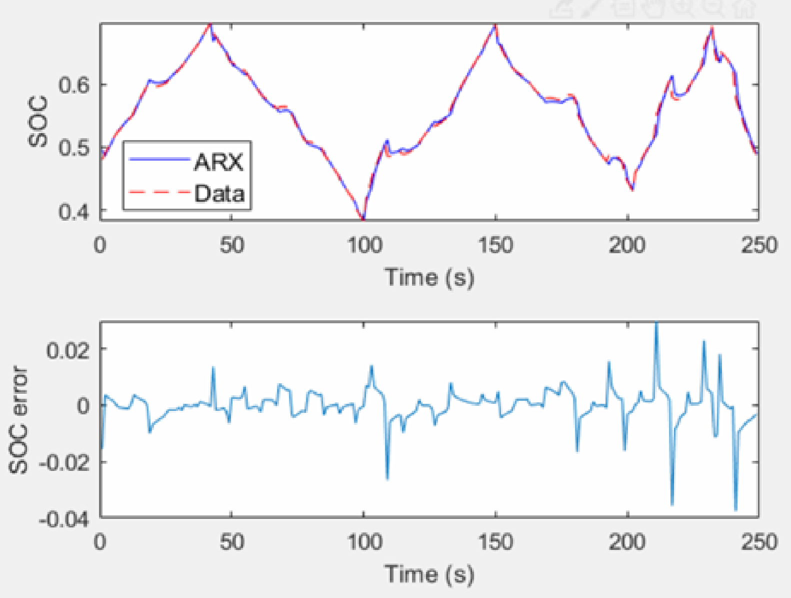


VRFB Surrogate Modeling

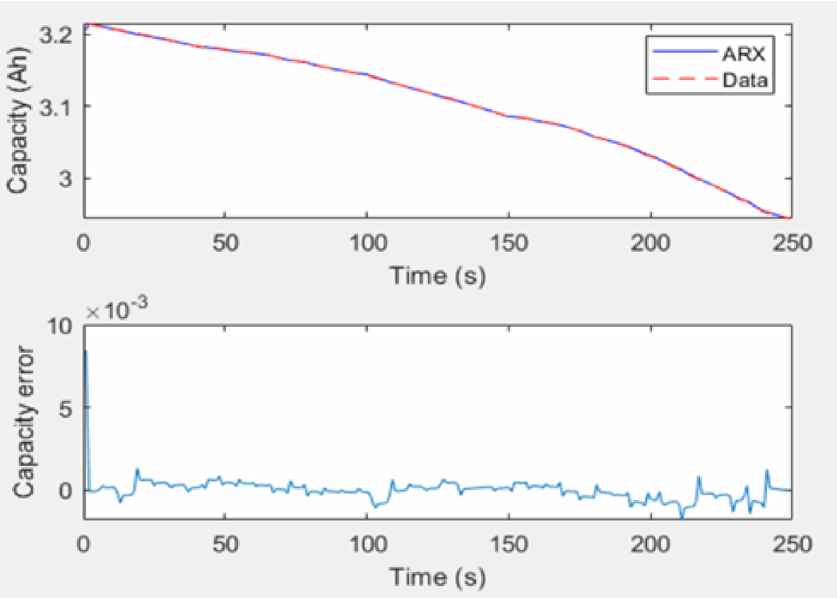
- **Reduced order model using a discrete-time state space model**



Voltage Vs time



SOC Vs time



Capacity Vs time

Electrochemical Storage: Detailed Model of Li-Ion Battery

Li Ion Battery

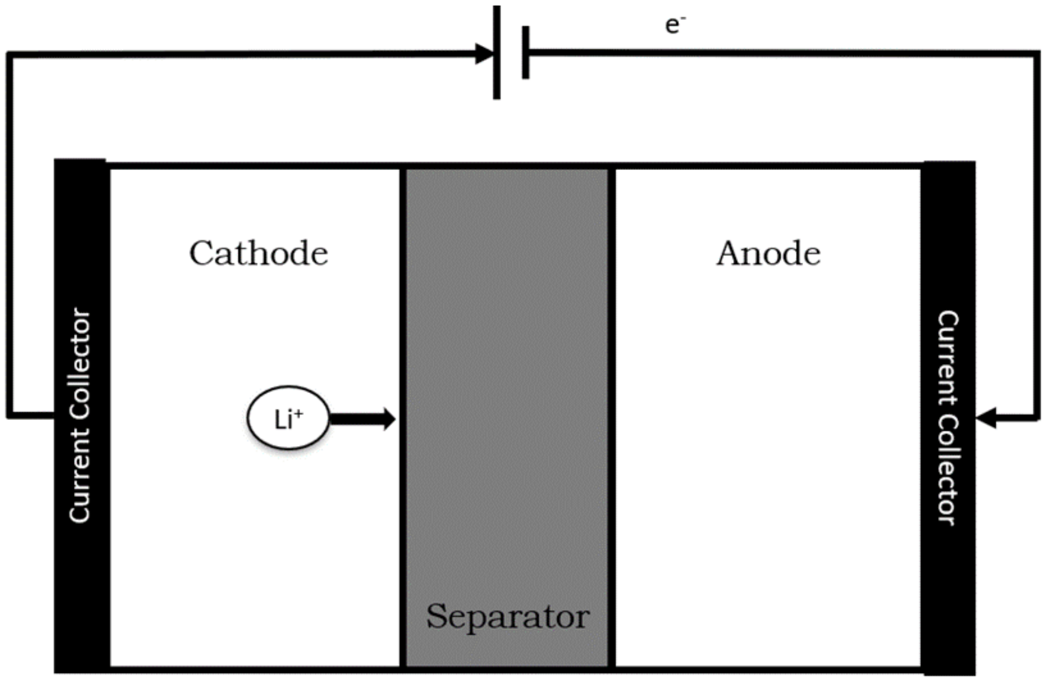
- **Higher power, energy density, and longer cycle life compared to other electrochemical storages**

- **Positive electrode reaction:**

$$LiMO_y \leftrightarrow MOy + Li^+ + e^-$$

- **Negative electrode reaction:**

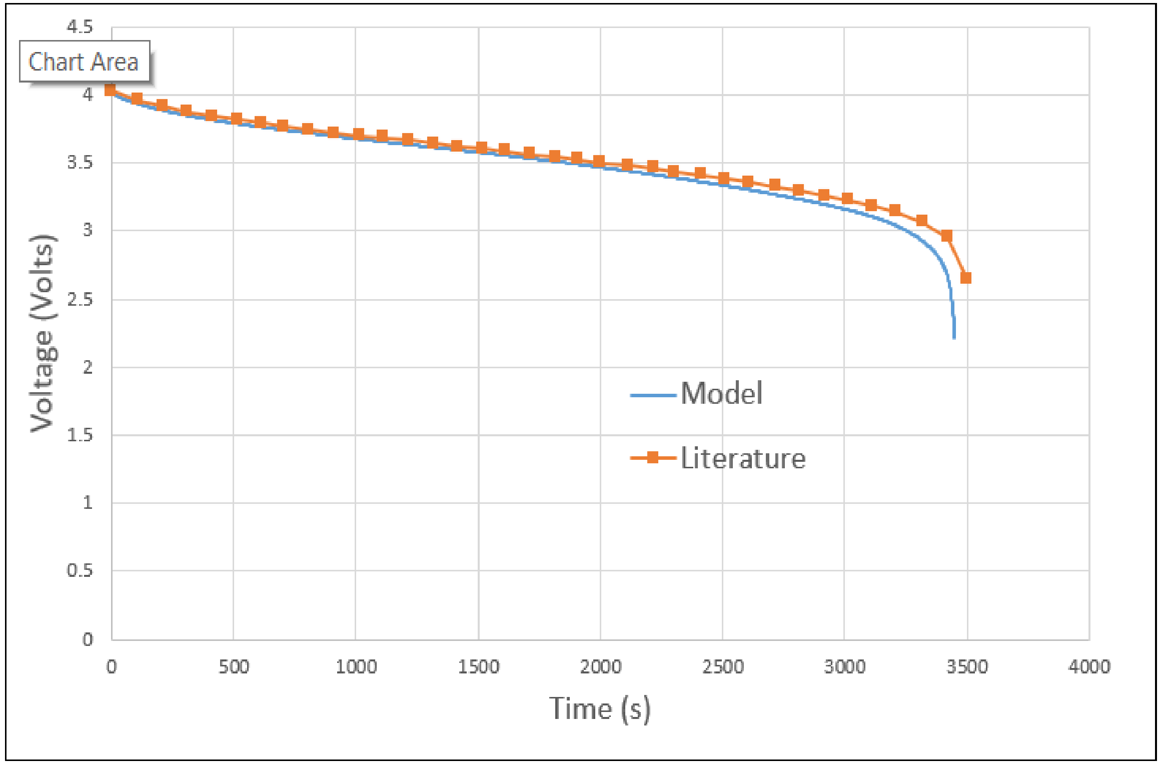
$$C_6 + Li^+ + e^- \leftrightarrow \mathrm{Li}C_6$$



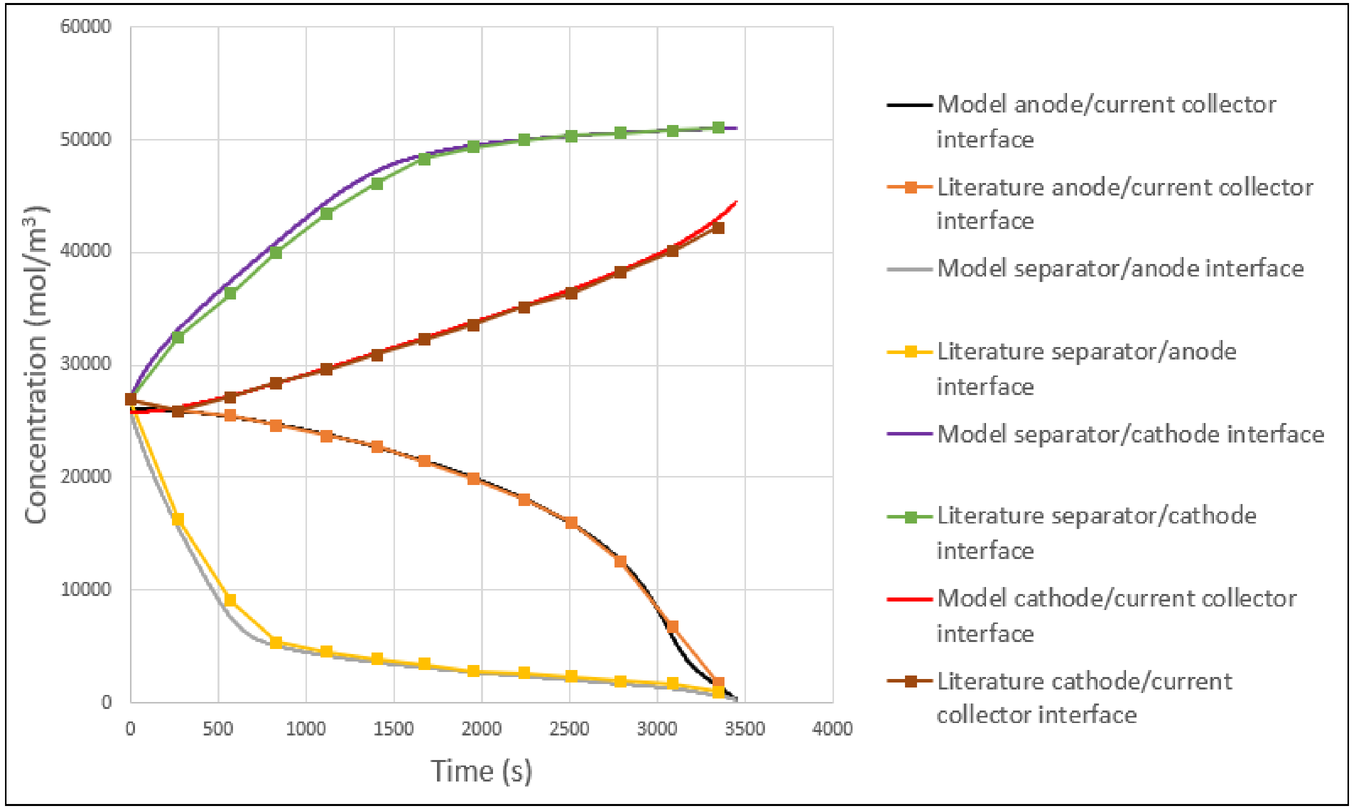
- **Porous electrode pseudo two-dimensional model**
  - **Spatial and temporal variation of variables such as solid/liquid phase potentials and solid/liquid phase Li+ concentrations is modeled**
  - **Model based on concentrated solution theory**
  - **Solid phase reformulation – using a parabolic approximation to reduce spatial dimensions**
  - **Coordinate transformation**

Model Validation – Li Ion Battery

- System of partial differential algebraic equations
- Simulated using Aspen Custom Modeler
- Validated using literature data*



Validation of Voltage Transient under 1C Discharge

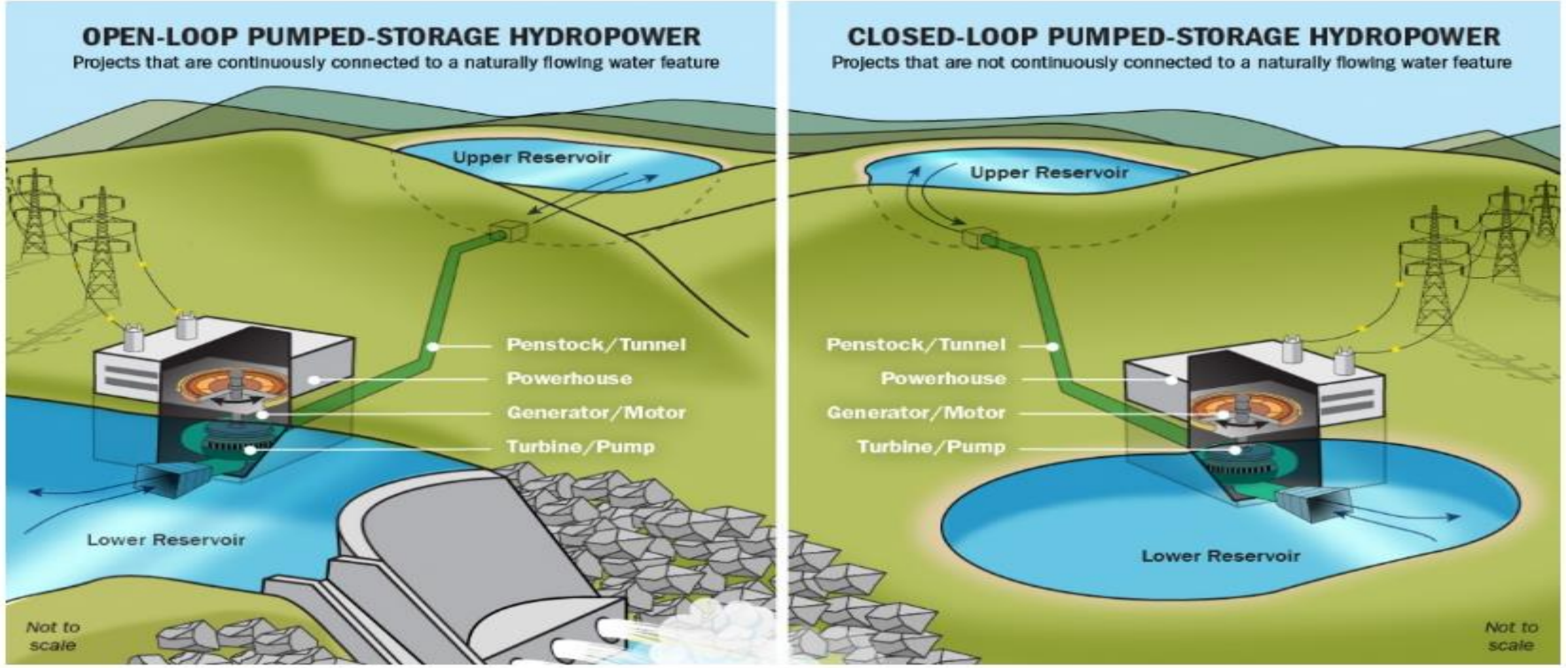


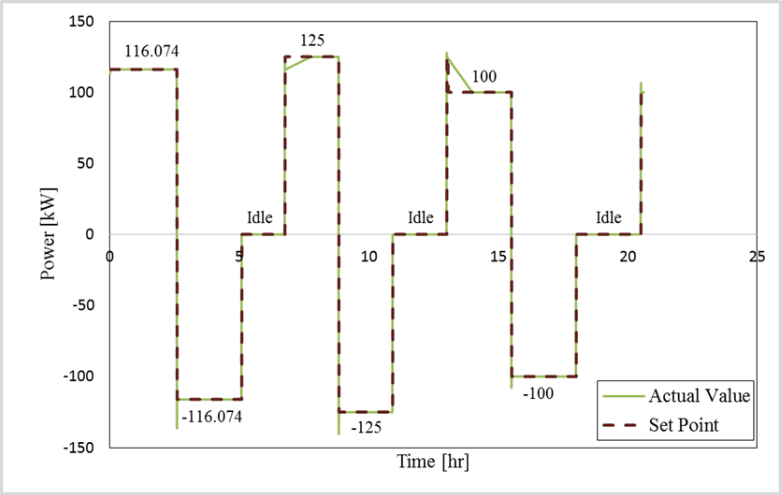
Validation of Transients in Solid Phase Surface Concentration of Li Ions under 1C Discharge

* Northrop, P., Ramadesigan V., De S, Subramanian V,, *Journal of the Electrochemical Society*, **158**, A1461-A1467 (2011).

Mechanical Storage: Pumped Hydro

Types and Configurations





Load following power profile during generation and pumping modes with PID controllers

- two hydraulic machines
- two shafts
- two electric machines

Conventional PHS

- one hydraulic machine
- one shaft
- one electric machine

Adjustable Speed PHS

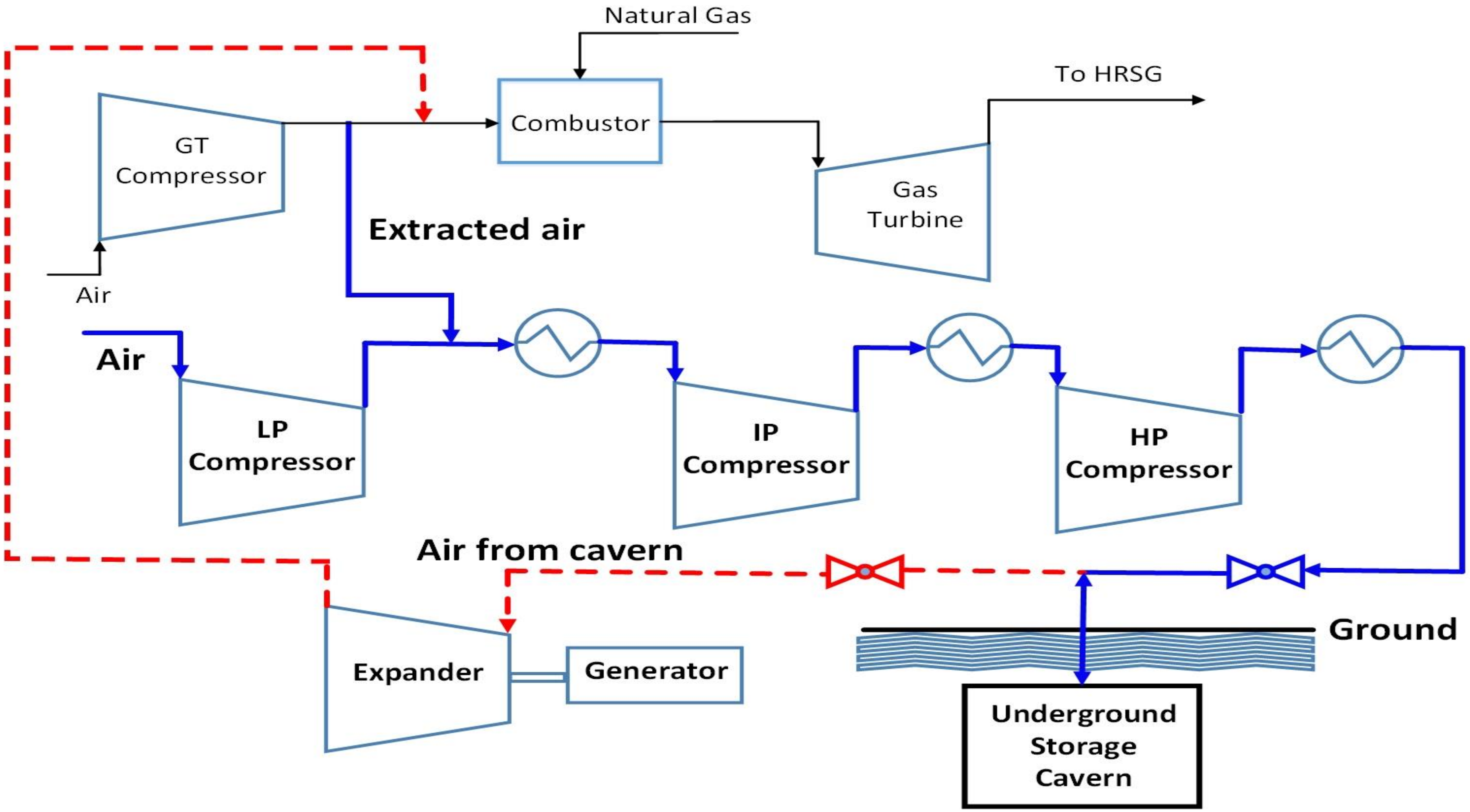
- two hydraulic machines
- one shaft
- one electric machine

Ternary PHS

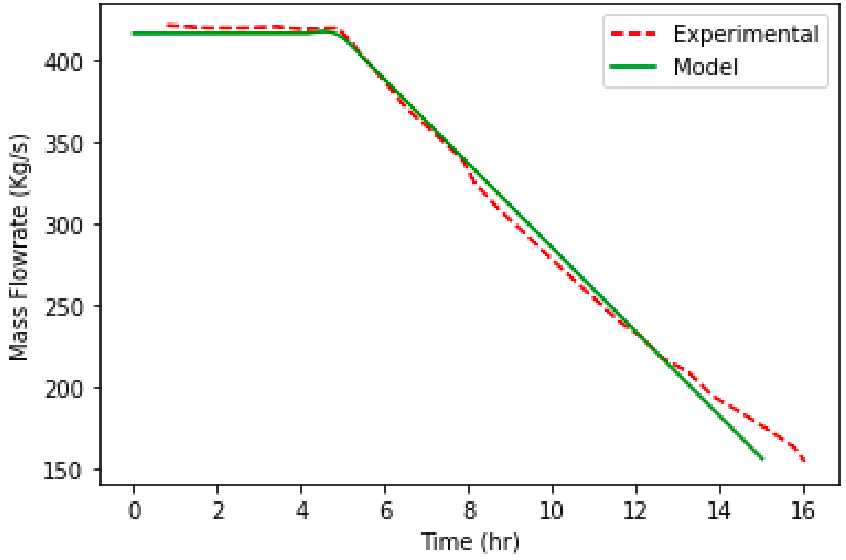
https://www.energy.gov/eere/water/pumped-storage-hydropower

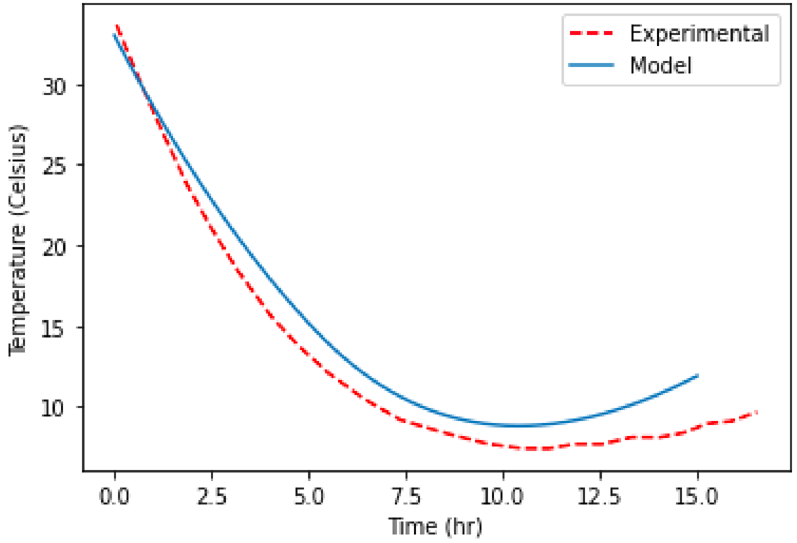
Mechanical Storage: Compressed Air Energy Storage

Synergistic Mechanical Storage in an NGCC Plant Using Compressed Air Energy Storage (CAES)

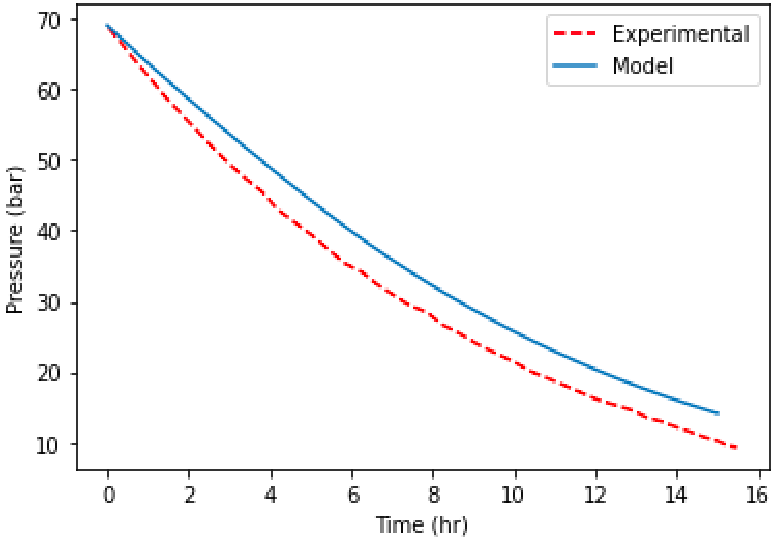


CAES Storage Model –Validation Results





Discharge cycle of the Huntorf CAES simulated for 15 hr period

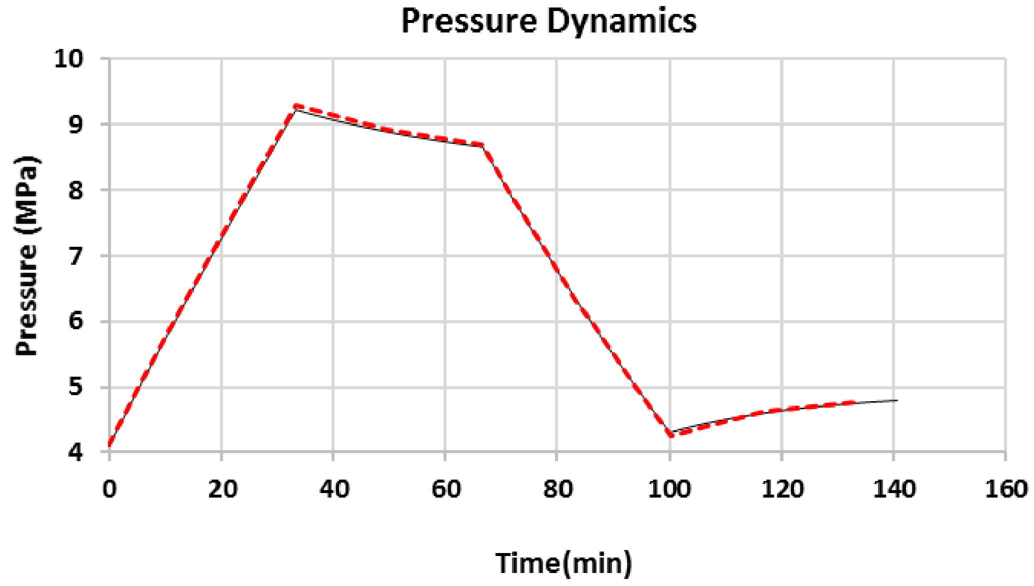


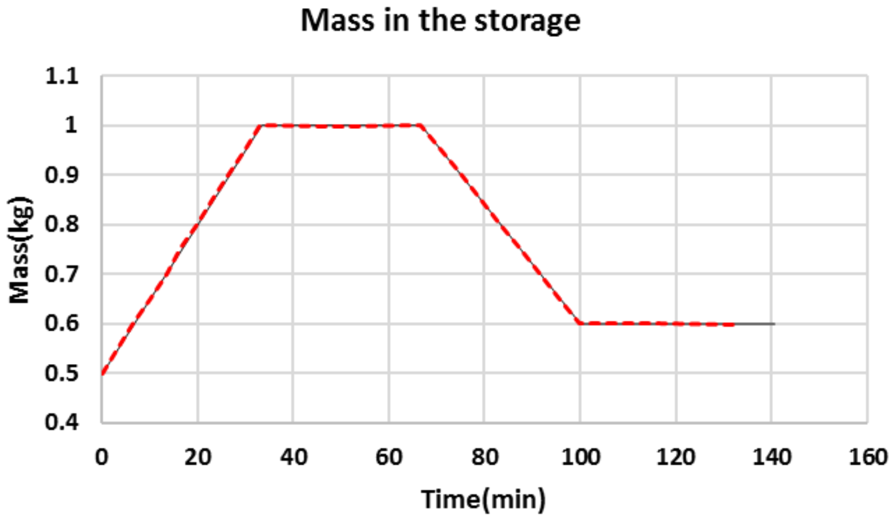
Experimental Data from: F. Crotogino, K.-U. Mohmeyer, and R. Scharf, "Huntorf CAES: More than 20 Years of Successful Operation," ***Solut. Min. Res. Inst. Spring Meet.*****, no. April, pp. 351–357, 2001.**

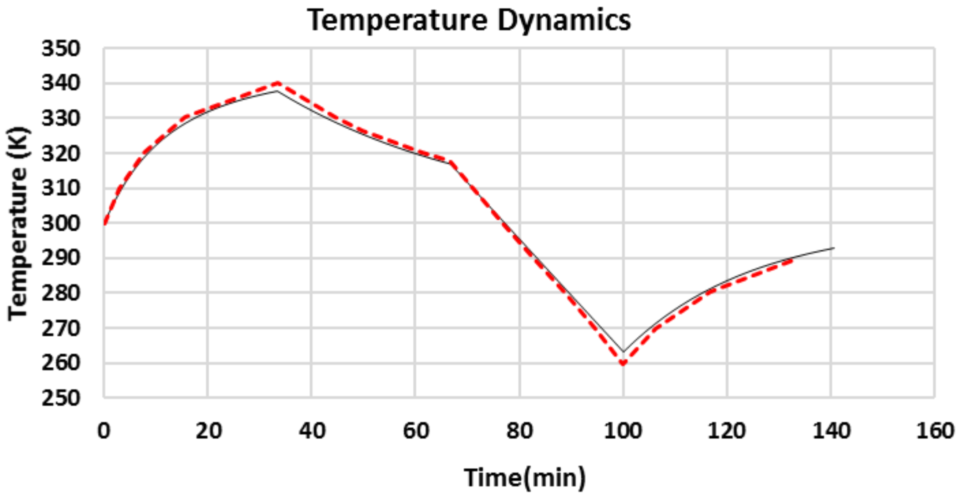
Chemical Storage: Hydrogen Storage

Hydrogen Storage Model- Validation with Literature Data

Constant Inflow and Outflow temperature ($T_{in} = T_{out} = T$)
Charging and Discharging cycle (2 hr cycle)







Data from Literature: Xiao, J., Bénard, P., & Chahine, R. (2016). Charge-discharge cycle thermodynamics for compression hydrogen storage system. *International Journal of Hydrogen Energy*, *41*(12), 5531–5539.

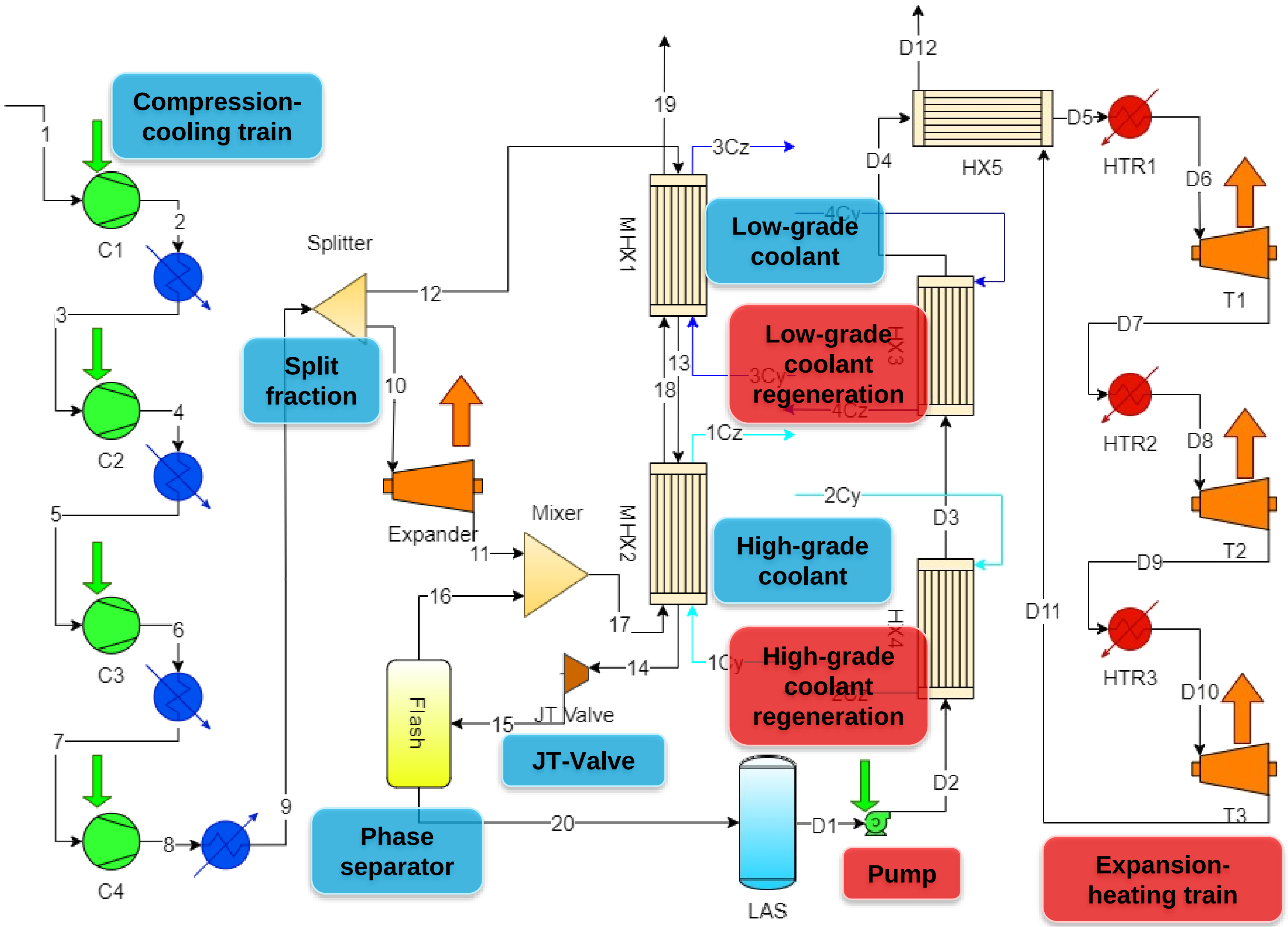
WestVirginiaUniversity

ATM

Cryogenic Energy Storage: Process Design, Simulation and Optimization

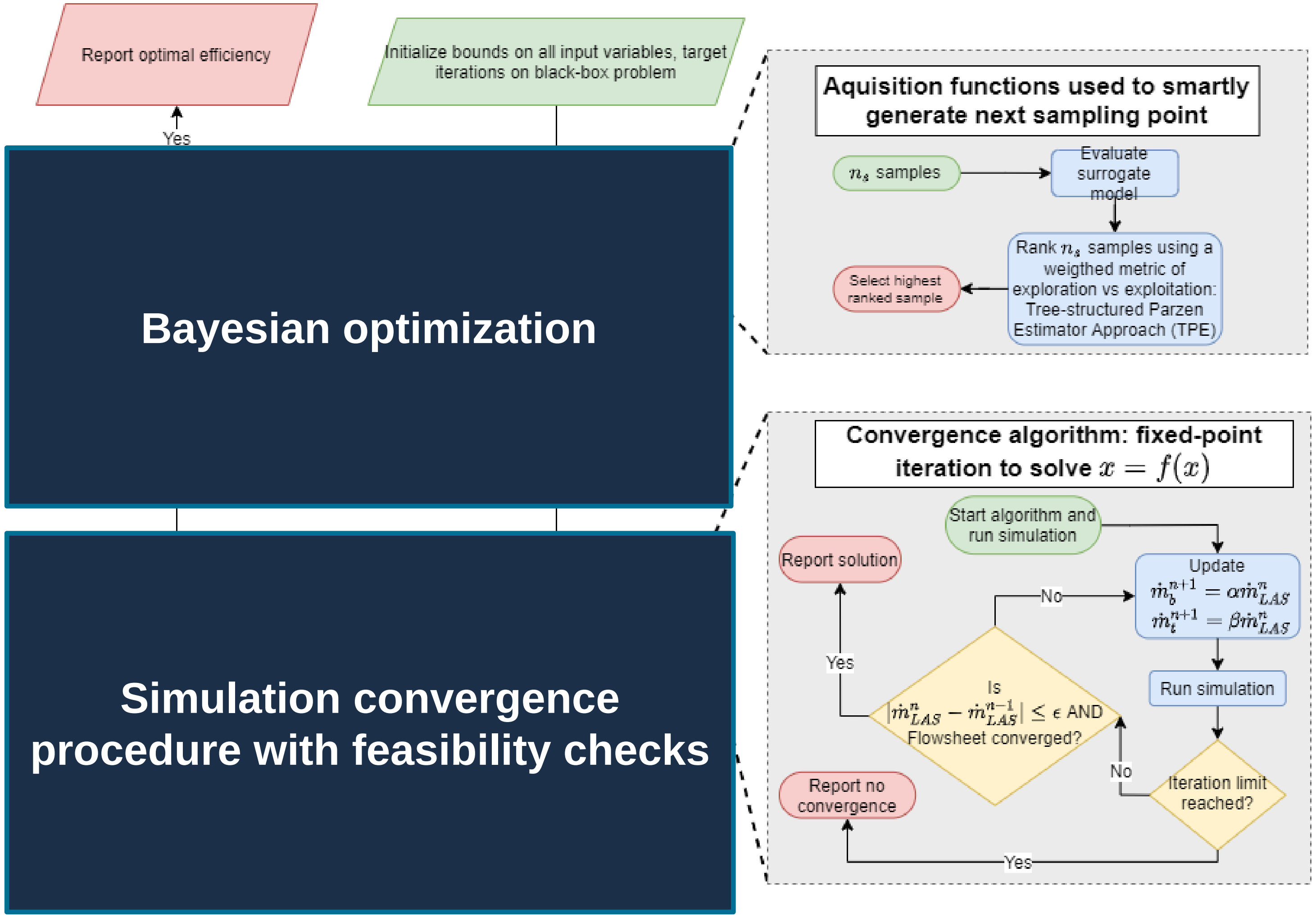
Cryogenic Energy Storage: Heylandt Process Flowsheet

- **Charging cycle: liquefaction & air storage**
- **Inlet temperature to JT-valve impacts the liquid air yield**
- **Charging cycle: Coolant regeneration**
- **Expansion using air turbines to generate work with intermediate heating**
- **Simulation and convergence challenges with several recycle loops**



Simulation-based Optimization

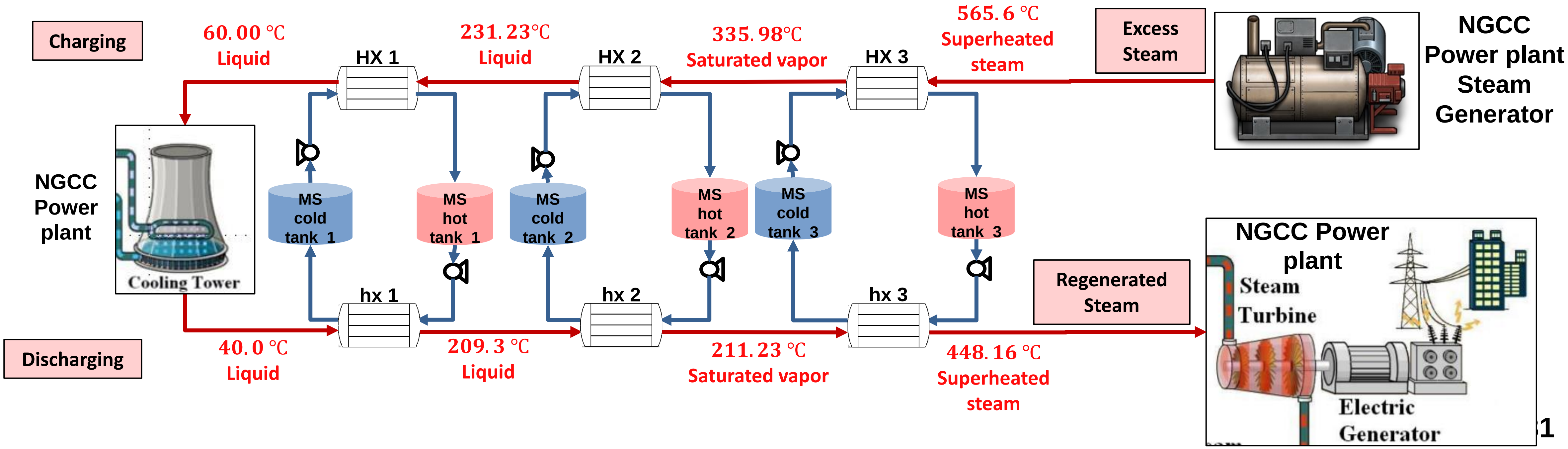
- **ASPEN Plus simulation for the CES cycle**
- **Bayesian optimization for exploration using acquisition functions to smart guess next sampling points**
- **Fixed point algorithm over pseudo input variables for simulation convergence at new sampling points**
- **Limited-memory Broyden–Fletcher–Goldfarb–Shanno algorithm (L-BFGS) for final refinement of local optima**
- **Automated in Python**



High Temperature Thermal Storage (Molten Salt-based Storage): Process Design, Simulation and Optimization

Steam Powered High Temperature Thermal Storage

- Energy is stored in the form of sensible/latent heat (e.g., molten salt, PCM)
- HTTS charges and delivers energy in the form of steam
- Storage medium circulates between cold and hot storage tanks
- More than one cycles are needed to achieve high round-trip efficiency
- Optimal synthesis of HTTS process cycle configurations
  - Process superstructure to embed all plausible process configurations
  - Mixed-integer nonlinear program (MINLP) to select optimal storage sizes and molten salts



Multiple Cycles Achieve High RTE

- The hot tank temperature needs to be high to be able to regenerate same quality (degree of superheat) of steam during discharging
- There is a trade-off between the salt temperature and storage efficiency suggested by one-cycle simulation

Molten salt flow rate	Hot tank temp.	Charging efficiency
Low	High	Low
High	Low	High

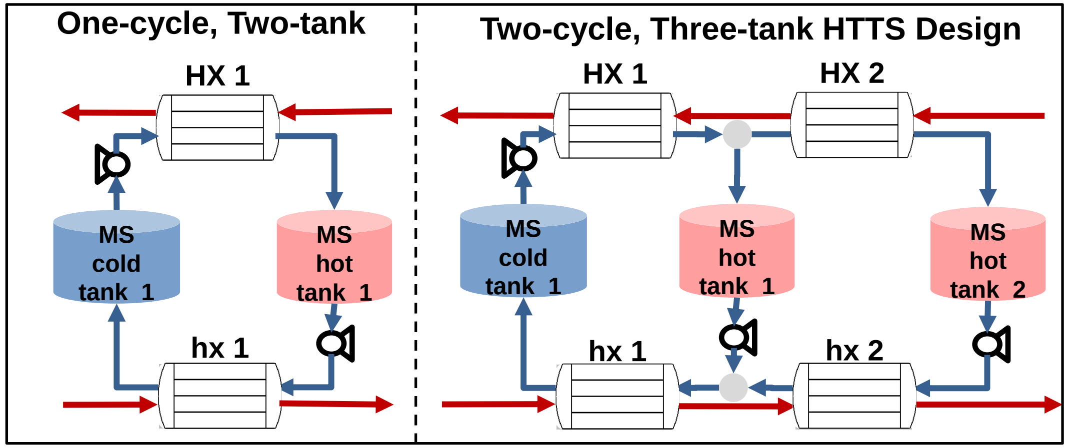
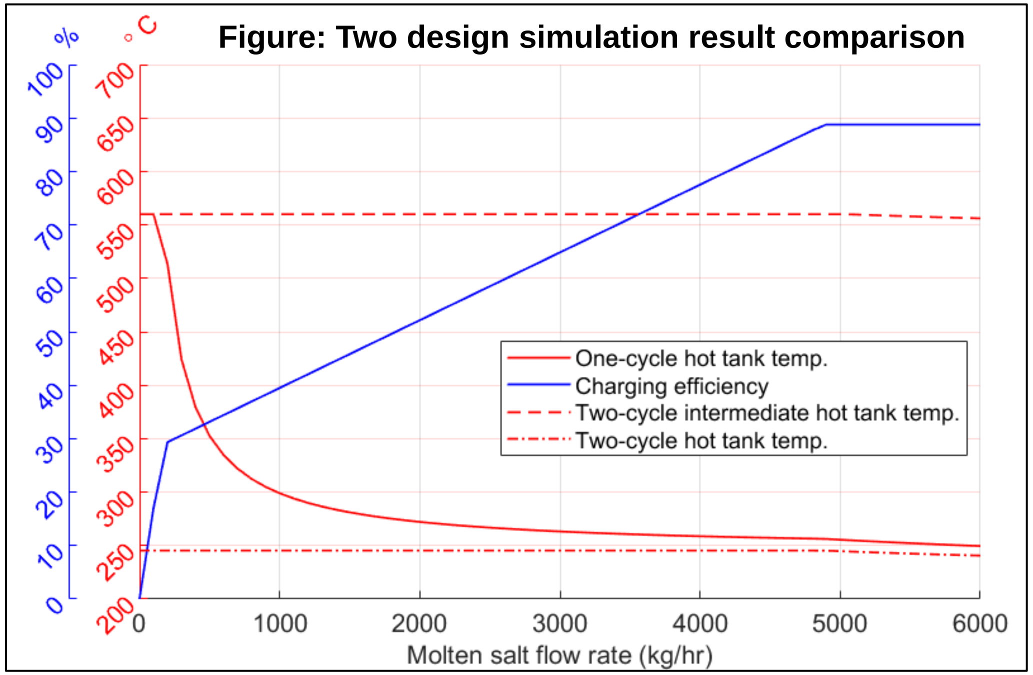


Table: Steam thermal properties in charging heat exchangers ($41.15\ bar$, $565\ ℃$)

40 bar steam	H1	H2	H3
Steam Energy Form	Liquid sensible heat	Latent heat	Vapor sensible heat
Steam Enthalpy KJ/kg	453	1713.5	793.7
Temperature Change	150- 250.4	250.4	250.4–565

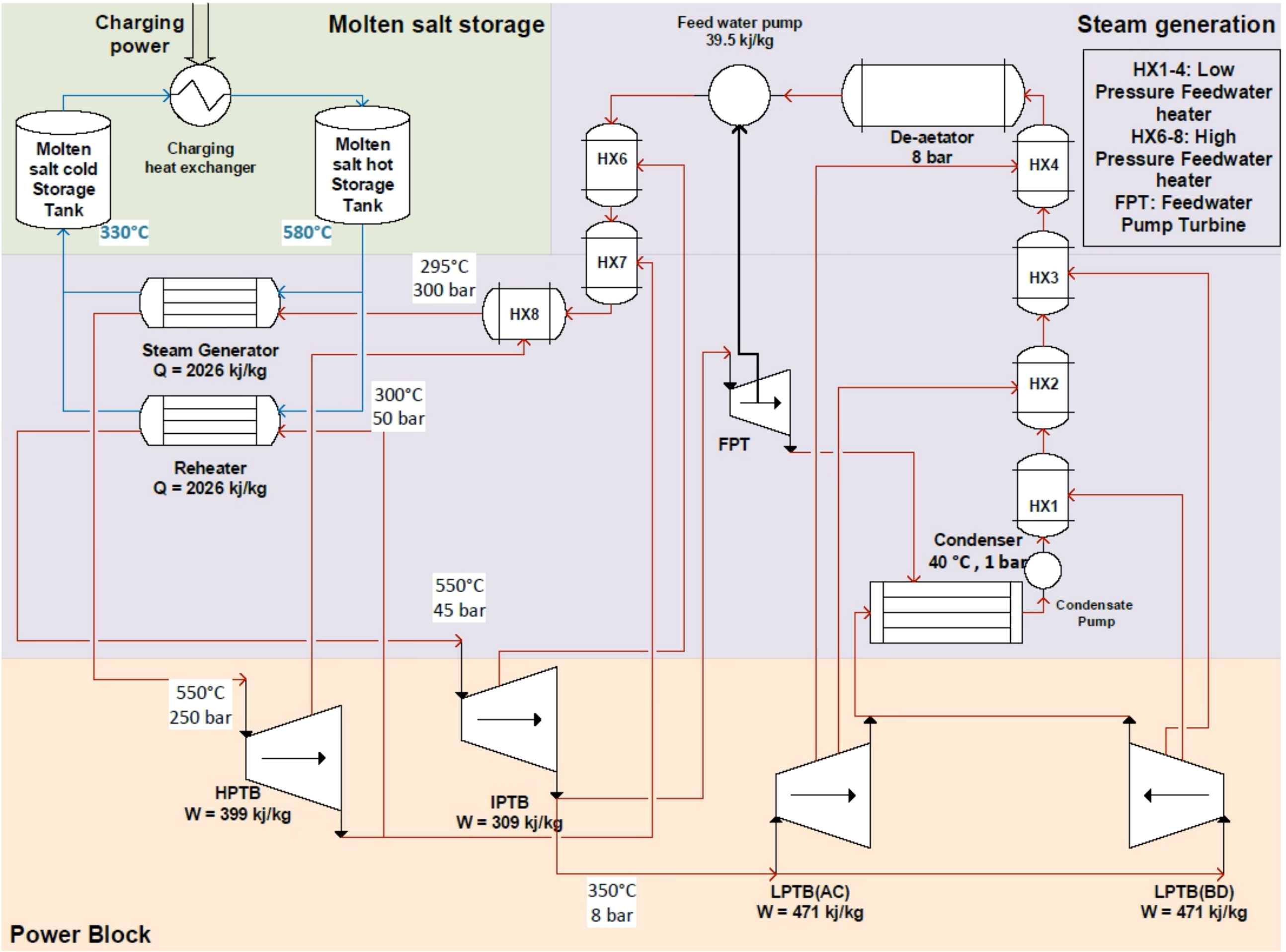


Two-cycle design is more advantageous due to higher efficiency and flexibility in charging and discharging

Electric Powered High-temperature Thermal Storage

- HTTS is charged by **electrical heating**
  - Molten salt is heated from 330℃ to 580 ℃
- Supercritical HTTS discharging converts energy **from heat to electricity**
  - Steam generation: Steam generator (boiler and superheater) and reheater are powered by hot molten salt
  - Power block: High, medium and low-pressure steam turbine
- Compared with steam powered HTTS
  - Pros: integration to power plant is less complicate and more adoptable
  - Cons: **Lower efficiency** and higher investment cost (additional power block)
- Comparing with Other Technologies
  - Lower LCOS but Lower efficiency
  - Requires more land space for discharging process
  - More cost-effective for large size storage

HTTS Round trip Efficiency:40.91%



Outline

- Design Space
- Energy Storage Alternatives - High Fidelity and Reduced Order Models
- **Optimal Downselection**
- Ongoing and Future Works

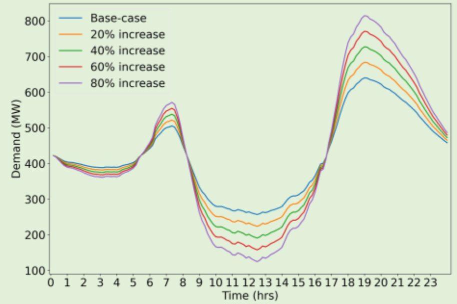
THESEUS: Technology Downselection Software Prototype

Inputs

Power plant model parameters
- Fixed and variable O&M costs
- Cycling costs for ramping
- Nominal capacity
- Minimum load factor

Region specific parameters
- Cost of electricity
- Ambient conditions

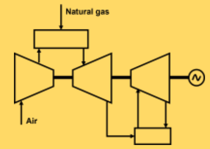
Demand load profile
- Discretized demand profile to be met by the energy system



THESEUS Framework

TecHno-Economic framework for Systematic Energy Storage Utilization and downSelection

Power plant model



Based on inputs of power plant:
-Ramping costs
-Minimum load
-Cost expressions

-Storage states/flow decisions
-Power and energy function
-Cost function parameters

MINLP-based Downselection model

- Python interface
- GAMS back-end

Vanadium Redox	CES
Li-ion	H_2
Sodium Sulfur	HTTS
Pumped Hydro	CAES

Storage models

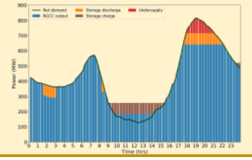
Outputs

Design of storage technologies
- Sizing of equipment in selected energy storage technology

Economic analysis
- Levelized cost of storage for selected technology

Systems integration and optimization
- Individual technology optimal configuration

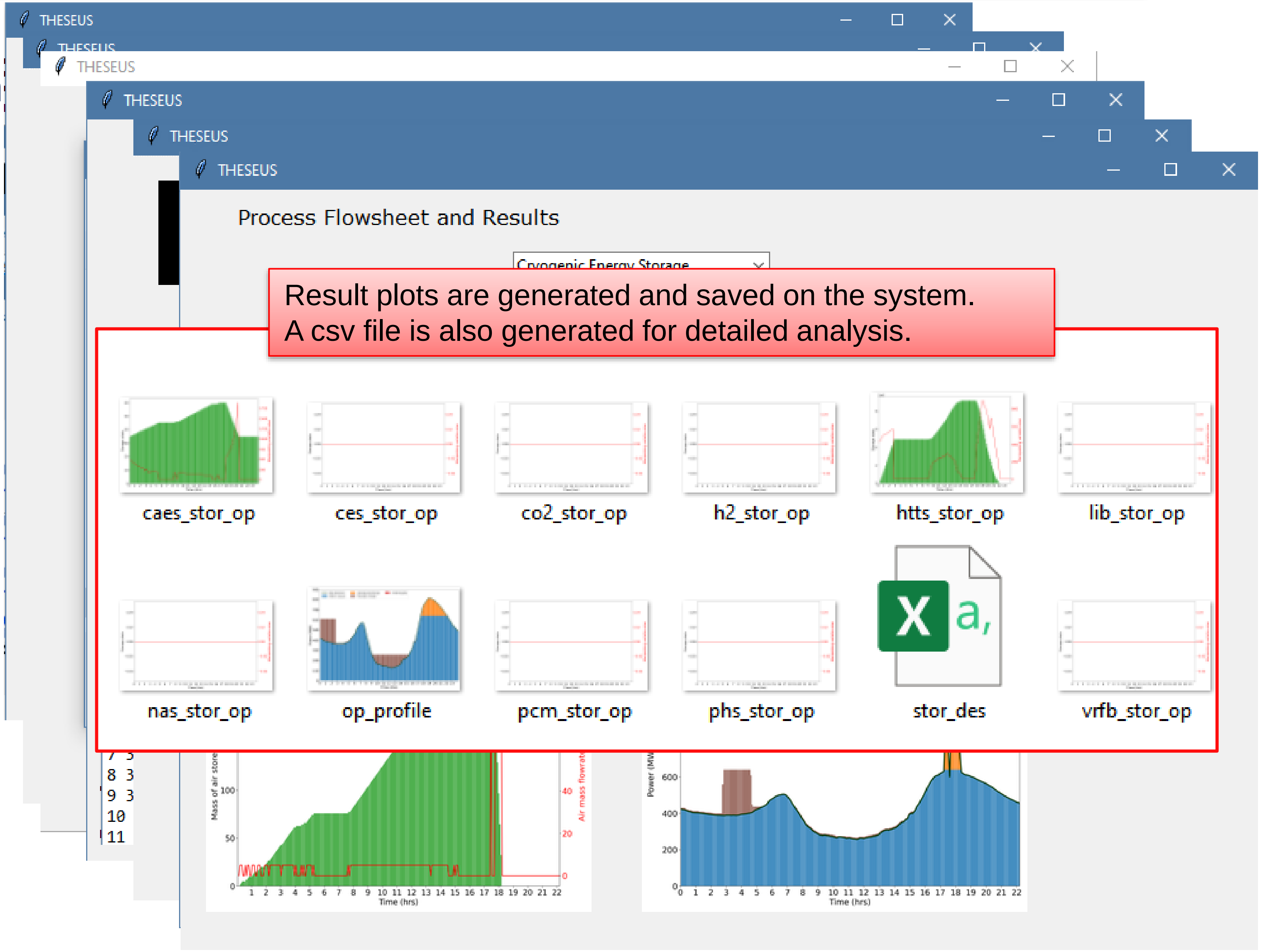
Schedule for power plant
- Operational schedule for all systems to ensure demand profile is met



http://people.tamu.edu/~hasan/software/theseus

THESEUS User Interface

- Application open page where user can select which **technologies to integrate**
- Update **power plant** model **Inputs** based on the power plant design for integration
- Upload **Demand profile** as csv
- Solve **Downselection model in GAMS** using the selected technologies for integration
- Results are obtained on the **Analysis** page
- For **detailed analysis**, user can visit the **Results** folder



http://people.tamu.edu/~hasan/software/theseus

Framework Back-End: Optimization Formulation

$$\min TC = \sum_{i=1}^{NI}\left(C_i^{S,iv} + C_i^{S,of} + \sum_{t=1}^{NT}\left(C_{i,t}^{S,ov} + C_{i,t}^{FP,ov}\right) + C_t^{FP,rc} + C^{os} + C^{us}\right)$$

Objective: Minimizing total system cost

Grid-level constraints

- Energy balance
- Electricity oversupply/undersupply penalty

Power plant model

General operational model
- Ramping constraints
- Efficiency model
- Capacity constraints

General cost model
- Operating and fuel cost
- Ramping cost

Storage model

Technology-specific models
- Power model
- Energy model

General operational model
- Constraints on power output
- Operational mode
- Energy balance
- Constraints on energy output
- Cyclical constraint on energy stored

General cost model
- Investment cost
- Fixed cost
- Variable cost

WestVirginiaUniversity

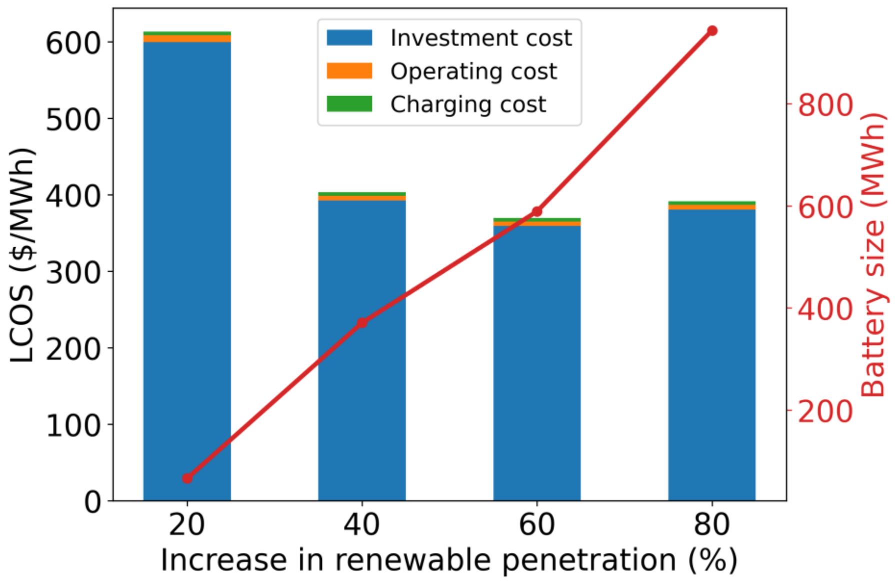
Sodium Sulfur Battery Integration Results

- **Integration not optimal for "normal day" due to high investment cost**
- **80% increase in renewable penetration to justify investment in large-scale storage**
- **Based on cost sensitivity analysis, for battery selection:**

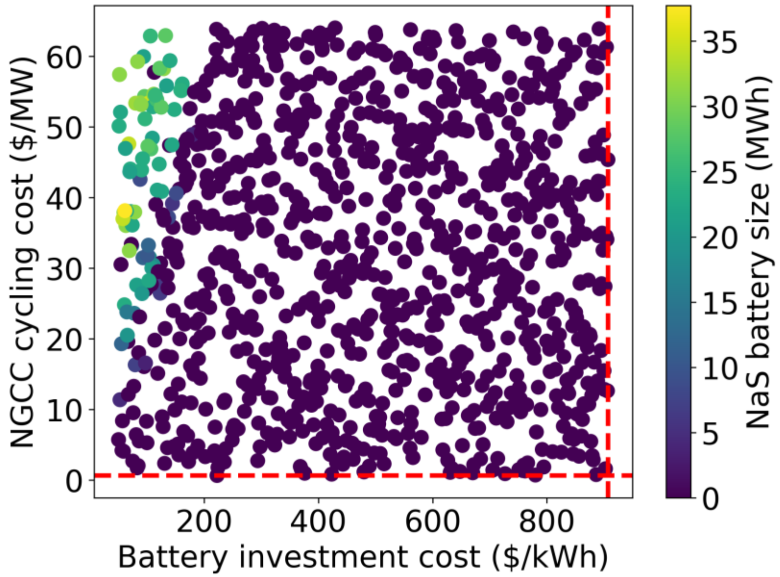
$$\frac{\text{NGCC specific cycling cost (\$/MW)}}{\text{Unit battery investment cost (\$/kWh)}} > 0.25$$

LCOS: $391/MWh

Efficiency: 85%



Battery size and LCOS at different renewable penetration levels



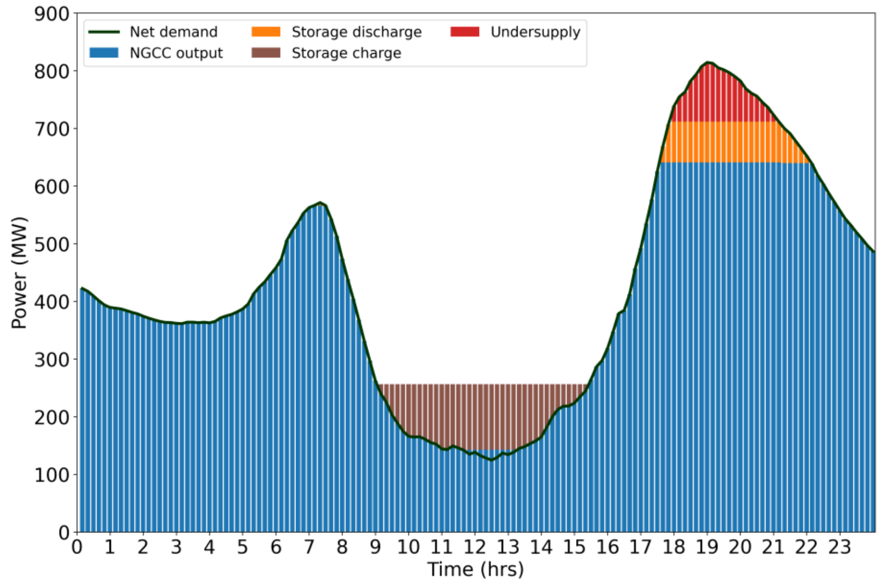
Optimal battery size variation with NGCC and battery cost parameters

Cryogenic Energy Storage Integration Results

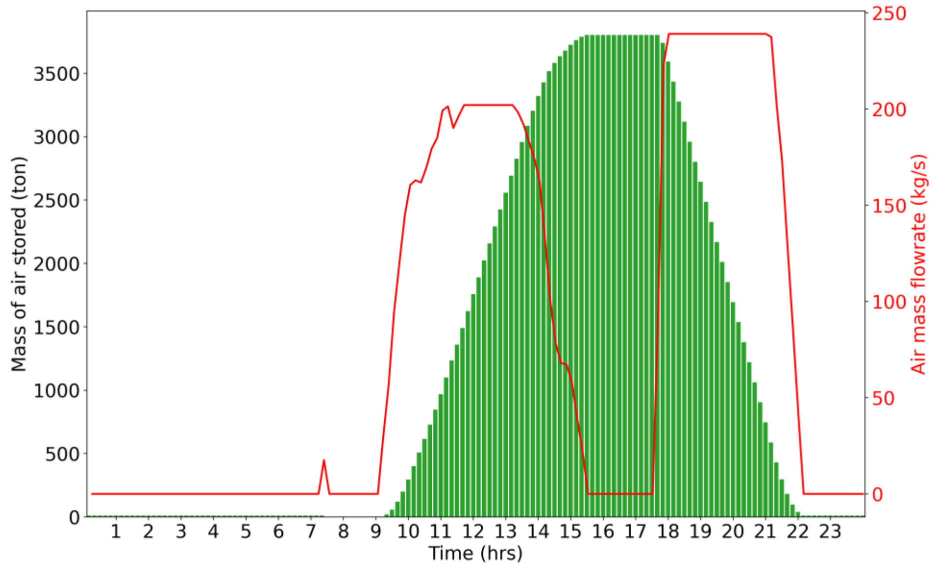
- Integration optimal to enable peak-shaving for 80% increase in demand variability
- Optimal storage design capacity: 71 MW/283 MWh
- Unmet demand due to upper bound on storage size
- Future analysis: Multiple CES storage systems to meet demand spike

LCOS: $201/MWh

Efficiency: 52%



Integrated system operation



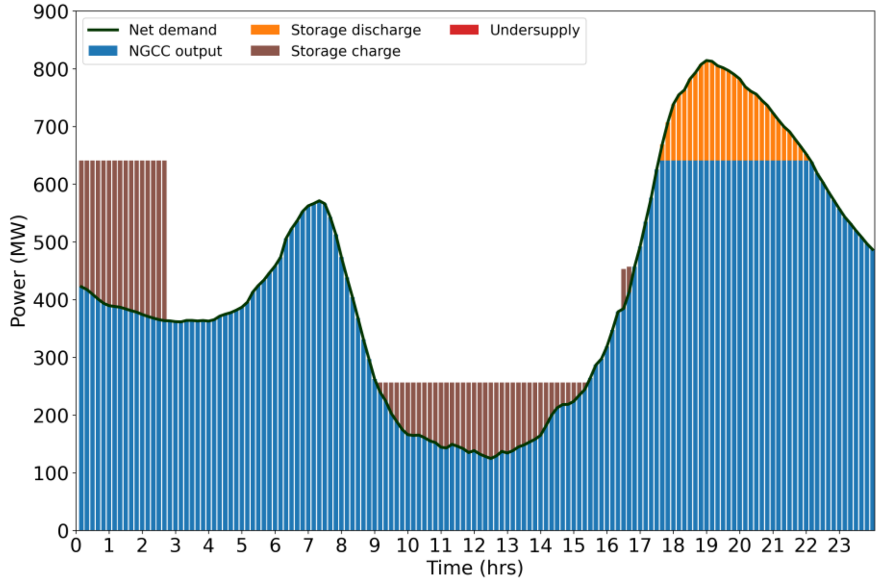
Storage system operation

Molten Salt Thermal Storage Integration Results

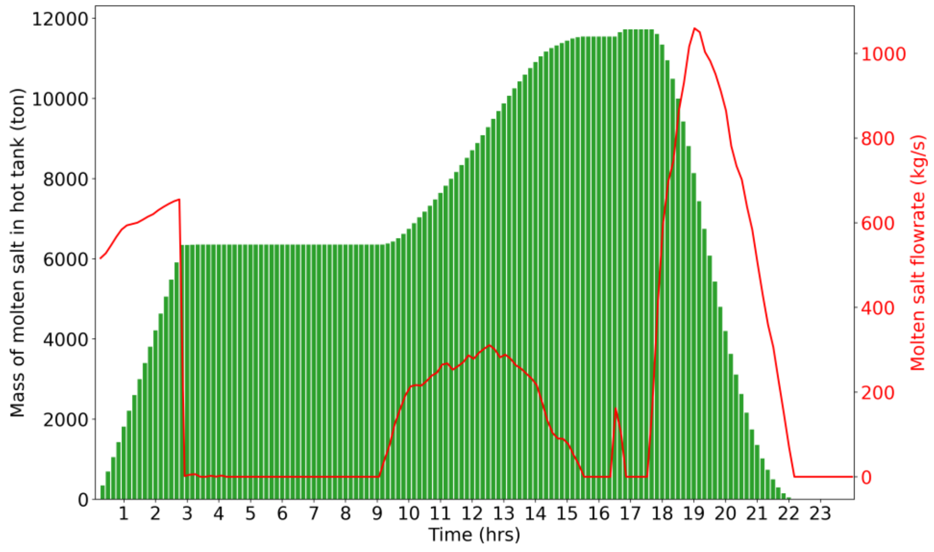
- **Integration optimal to enable peak-shaving for 80% increase in demand variability**
- **Optimal storage design capacity: 173 MW/483 MWh**
- **Demand peak above NGCC nominal capacity completely met by power discharged by storage**
- **Technology suitable for low-cost large-scale storage**

LCOS: $135/MWh

Efficiency: 39%



Integrated system operation



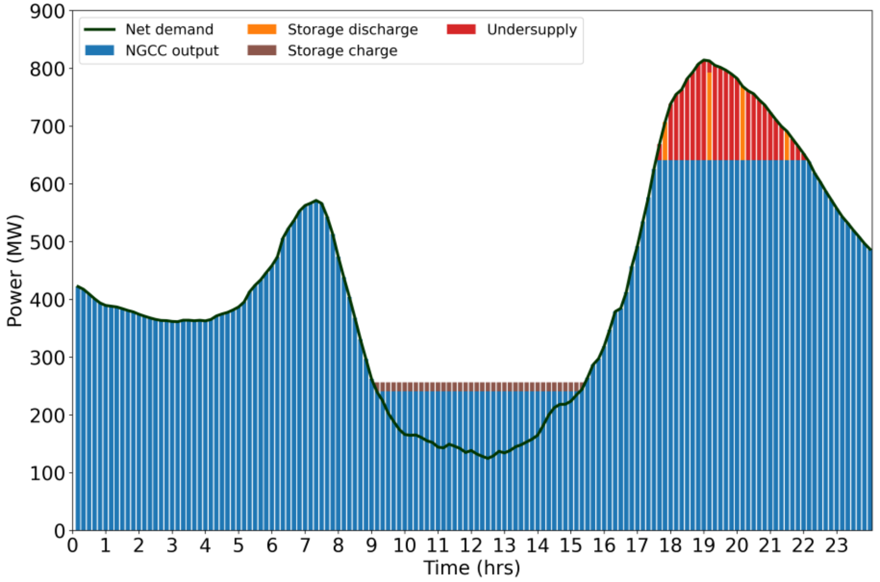
Storage system operation

Compressed Air Energy Storage Integration Results

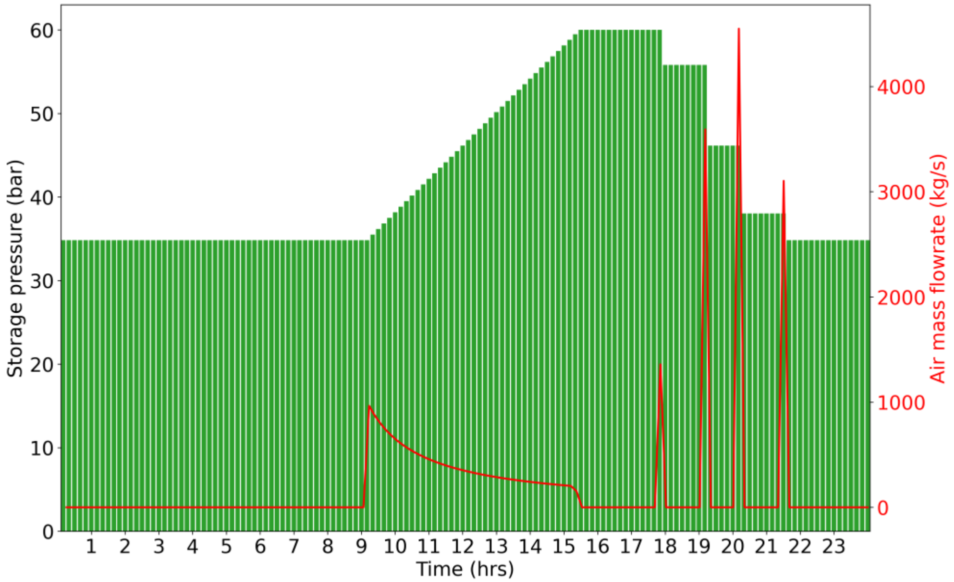
- Compressor inlet/turbine outlet pressure: 30 bar, Cavern operating pressure: 30-60 bar
  - Max pressure ratio: 2
- Pressure increases from 30 to 60 bar with small amount of charging: reduced storage capacity
- Although high round-trip efficiency (65%), max pressure ratio of 2 restricts the energy output and increases costs

LCOS: $216/MWh

Efficiency: 67%



Integrated system operation



Storage system operation

Results Summary

Among the technologies considered so far, following is the rank order of storage technologies as per the cost (LCOS):

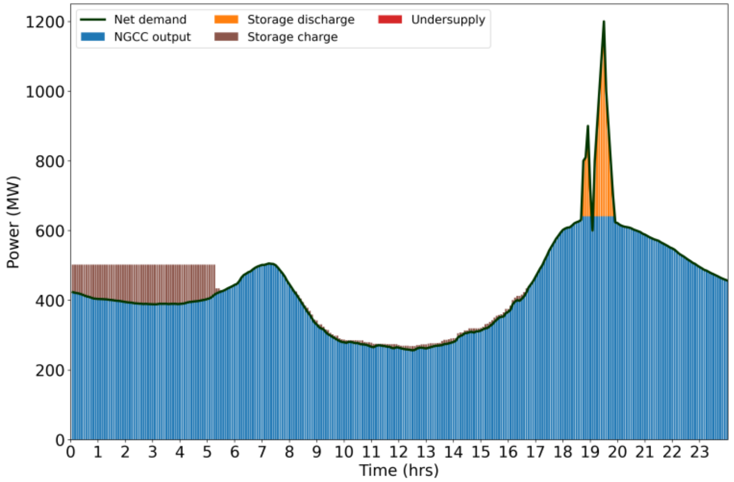
No.	Technology	Round-trip efficiency (%)	LCOS ($/MWh)
1	Molten salt thermal storage	39	135
2	Cryogenic energy storage	52	201
3	Compressed air energy storage	67	216
4	Sodium sulfur battery	85	391

- **This trend is inverse to what we may expect from the storage efficiency!**

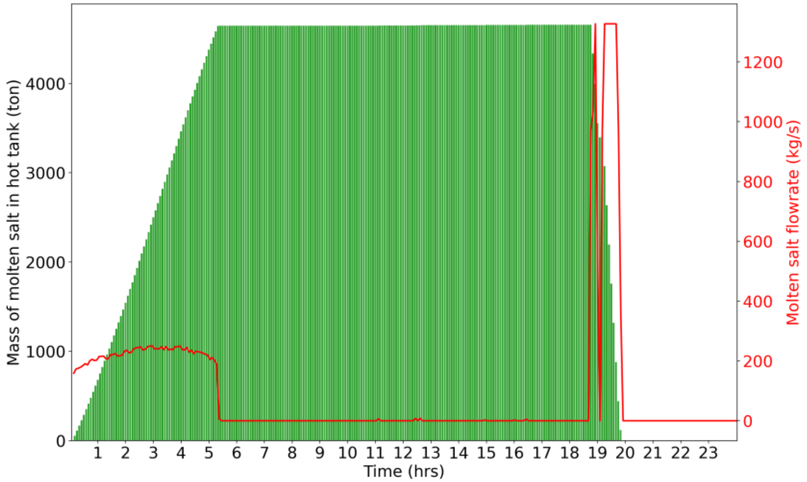
Downselection: Case Study 1

- Demand profile with extreme spike higher than NGCC nominal capacity
- Top 3 technologies considered for integration : CES, HTTS, CAES
- All 3 technologies selected
- Storage sizes and LCOS:
  - CES: 29 MW, $493/MWh
  - HTTS: 217 MW, $203/MWh
  - CAES: 313 MW, $374/MWh
- CAES has highest LCOS for stand-alone integration, but cheaper than CES in downselection

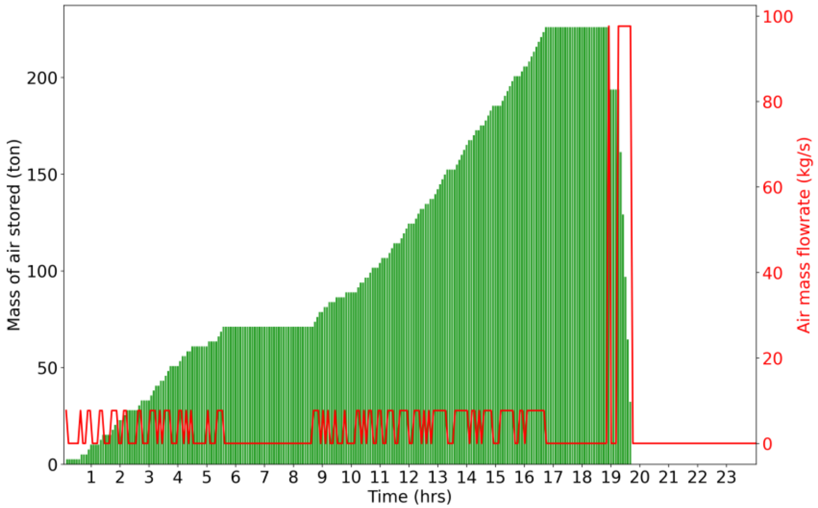
Integrated system operation



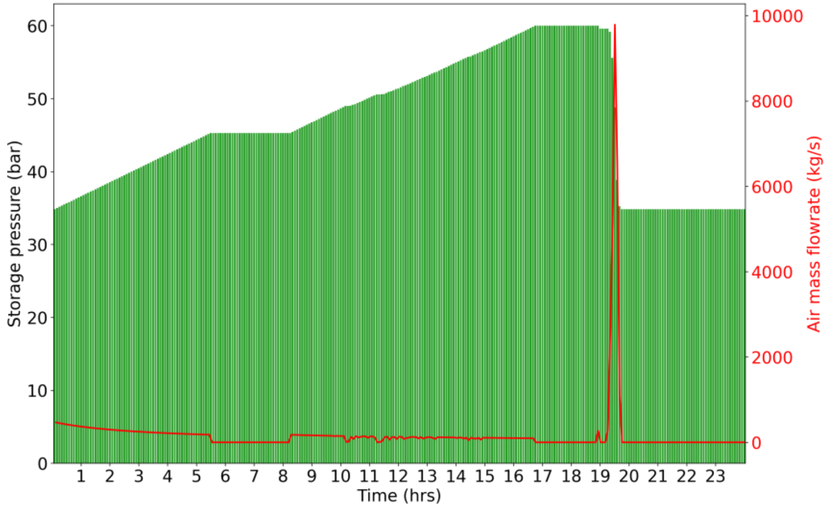
Molten salt storage system operation



Cryogenic storage system operation



Compressed air storage system operation



Ongoing and Future Works

- **Complete remaining ROM development**
- **Complete downselection**
- **Complete detailed dynamic simulation of promising storage technologies**
- **Complete detailed techno-economic analysis of promising storage technologies**

Acknowledgement

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Thank you for your attention

Questions?