Optimization of Strategic and Operational Decisions for the Recovery of Critical Minerals from Produced Water Networks

PARETO — The Produced Water Optimization Initiative

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Project Motivation

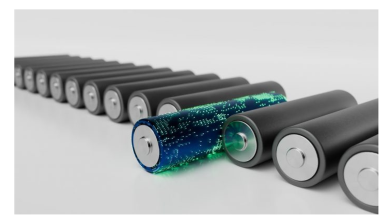
Critical Minerals

Importance to Energy

Supply Risk

50 critical minerals: Li, Al, Graphite …

Uses: Batteries, Solar Panels, Semiconductors, Fiber-Optics

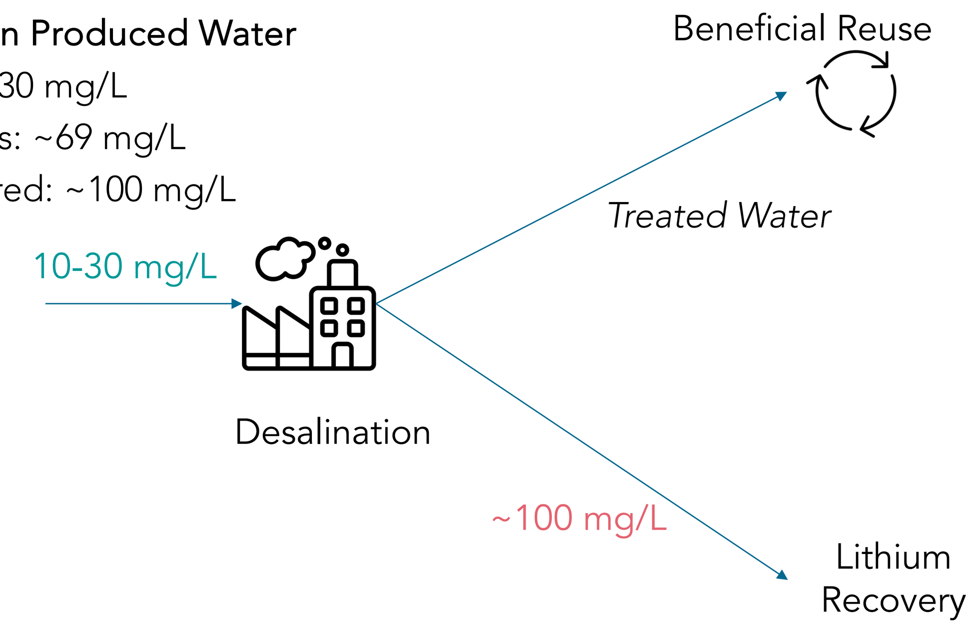


Produced Water

- Hydraulic fracturing can consume up to 1 million barrels of water in a 10-12 week frilling cycle
- Once fractured, the well produces oil & gas, but also water
  - Some of this is injected water
  - Most of it is water entrained underground with oil & gas
- It is collectively called **produced water** (PW)
- After separation, most of the produced water is injected underground in disposal wells

Observed Lithium concentrations in Produced Water

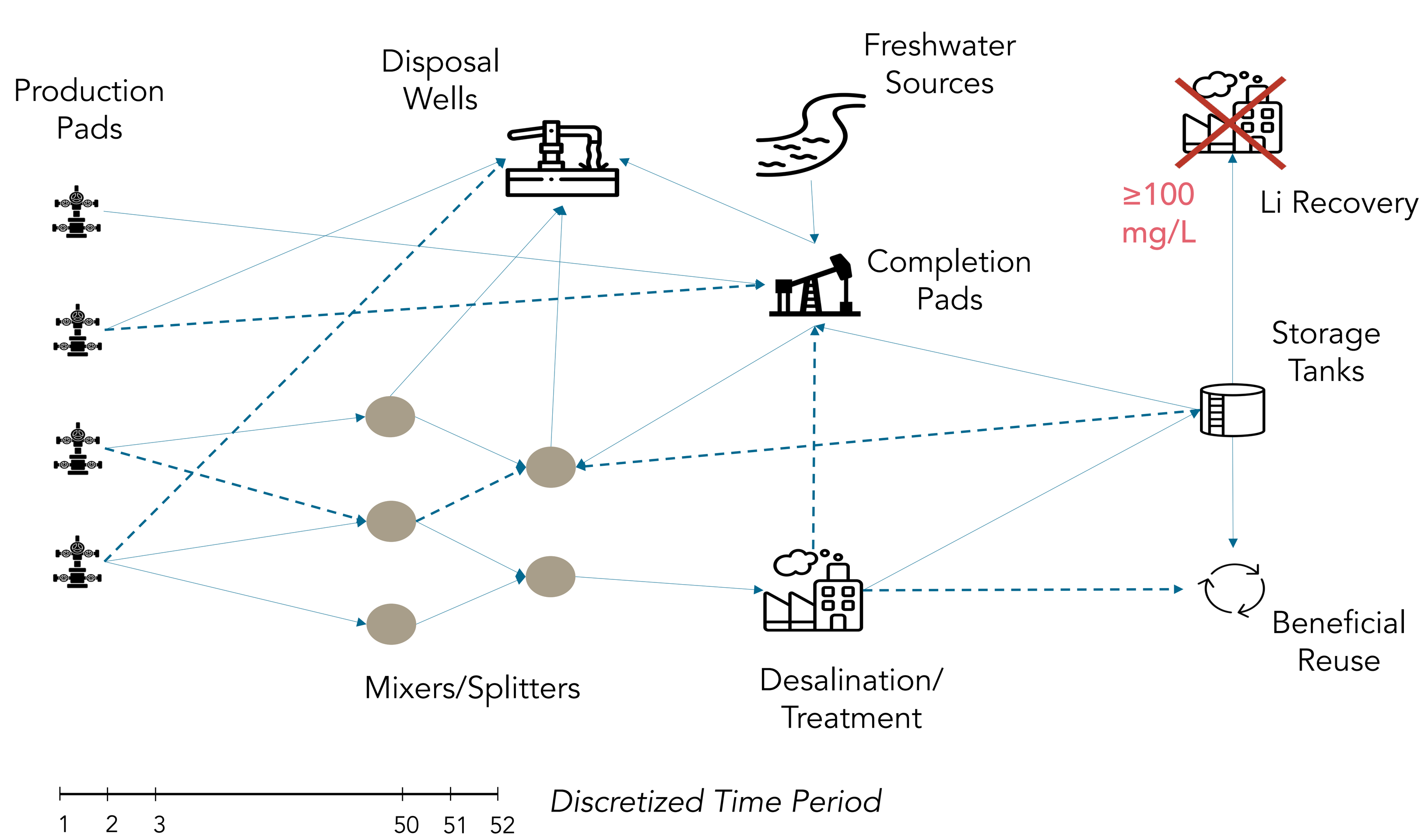
- Permian Basin Concentration: 10-30 mg/L
- Appalachian Basin Concentrations: ~69 mg/L
- Minimum Li Concentration Required: ~100 mg/L



Goal: Can Installation and Routing decisions help make Lithium Recovery Operationally viable?

- Systems Based Perspective
- Leveraging Optimization Tools

Problem Statement



Steps:

1. Operational Problem
   - Nonlinear Program (NLP)
   - Optimizes Flows, Concentration, Inventory
2. Strategic Problem
   - Mixed-Integer Nonlinear Program (MINLP)
   - Optimizes Flows, Concentration, Inventory
   - Also optimizes Installation decisions

Strategic Problem
Operational Problem
Routing decisions
Installation decisions

Operational Model

min. *Operating Cost + Storage Costs − Storage Revenue − Lithium Revenue*

$$\min \sum_{t\in\mathcal{T}}\left(\sum_{a\in\mathcal{A}}\beta_a^{Arc}F_{at}+\sum_{n\in\mathcal{N}^D}\beta_n^D\sum_{a\in\mathcal{A}_n^{In}}F_{at}+\sum_{n\in\mathcal{N}^W}\beta_n^W\sum_{a\in\mathcal{A}_n^{Out}}F_{at}+\sum_{n\in\mathcal{N}^{T,IN}}\sum_{a\in\mathcal{A}_n^{In}}\beta_n^T F_{at}-\sum_{n\in\mathcal{N}^{T,CW}}\sum_{a\in\mathcal{A}_n^{Out}}\sum_{q\in\mathcal{Q}}\gamma_{nq}F_{at}\hat{C}_{nq}^{min}\right)$$

s. t.

Flow Balance

$$\sum_{a\in\mathcal{A}_n^{In}}F_{at}+\hat{F}_{nt}^{Prod}=\sum_{a\in\mathcal{A}_n^{Out}}F_{at}+\hat{F}_{nt}^{Cons}\quad \forall n\in\mathcal{N}^P\cup\mathcal{N}^{MS}, t\in\mathcal{T}$$

Component Balance

$$\sum_{a\in\mathcal{A}_n^{In}}F_{at}C_{nodeUp(a)qt}=\left(\sum_{a\in\mathcal{A}_n^{Out}}F_{at}\right)C_{nqt}\quad \forall n\in\mathcal{N}^{MS}, q\in\mathcal{Q}, t\in\mathcal{T}$$

Inventory Balance

$$I_{nt}C_{nqt}=I_{nt-1}C_{nqt-1}+\sum_{a\in\mathcal{A}_n^{In}}F_{at}C_{nodeUp(a)qt}-\left(\sum_{a\in\mathcal{A}_n^{Out}}F_{at}\right)C_{nqt}\quad \forall n\in\mathcal{N}^S, q\in\mathcal{Q}, t\in\mathcal{T}\setminus\{0\}$$

Treatment Balance

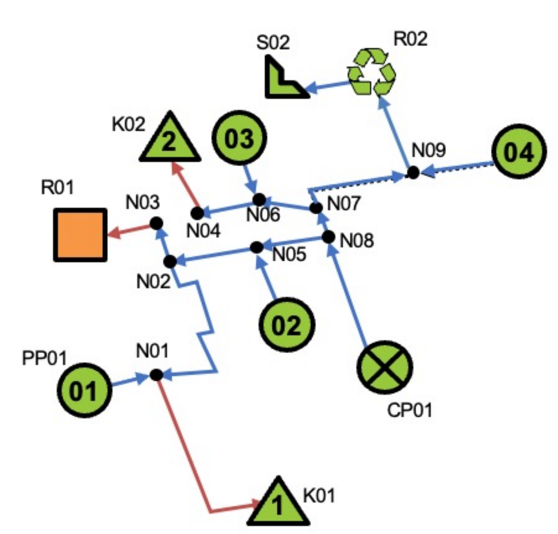
$$F_{arcOut(n)t}=\alpha_{n'}^w F_{arcIn(n')t}\quad \forall n\in\mathcal{N}^{T,TW}, t\in\mathcal{T}$$

$$C_{nqt}=(1-\alpha_{n'q})C_{n'qt}\quad \forall n\in\mathcal{N}^{T,TW}, q\in\mathcal{Q}_{n'}^{\alpha}, t\in\mathcal{T}$$

Concentration Requirement

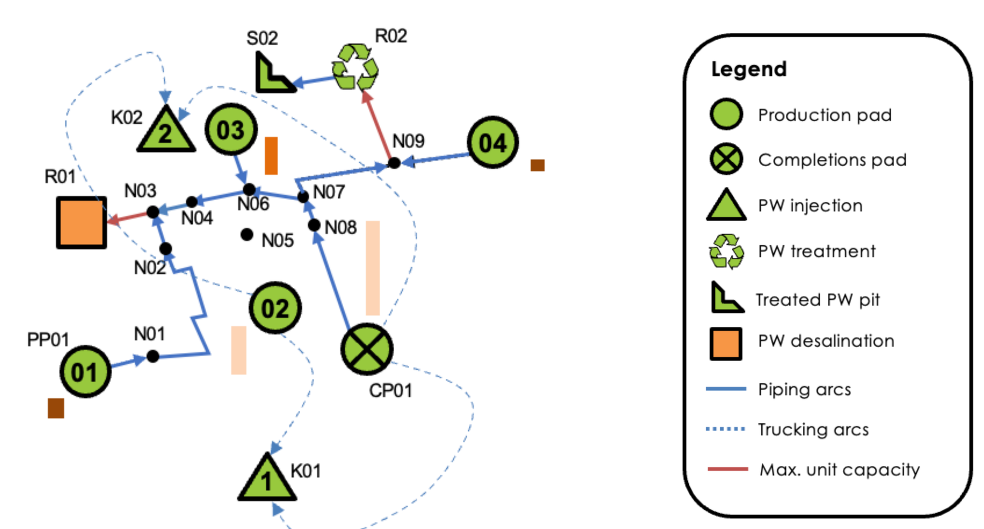
$$C_{n,q,t}\geq\hat{C}_{n,q}^{min}\quad \forall n\in\mathcal{N}^{T,CW}, q\in\mathcal{Q}, t\in\mathcal{T}$$

Production-Focused Model



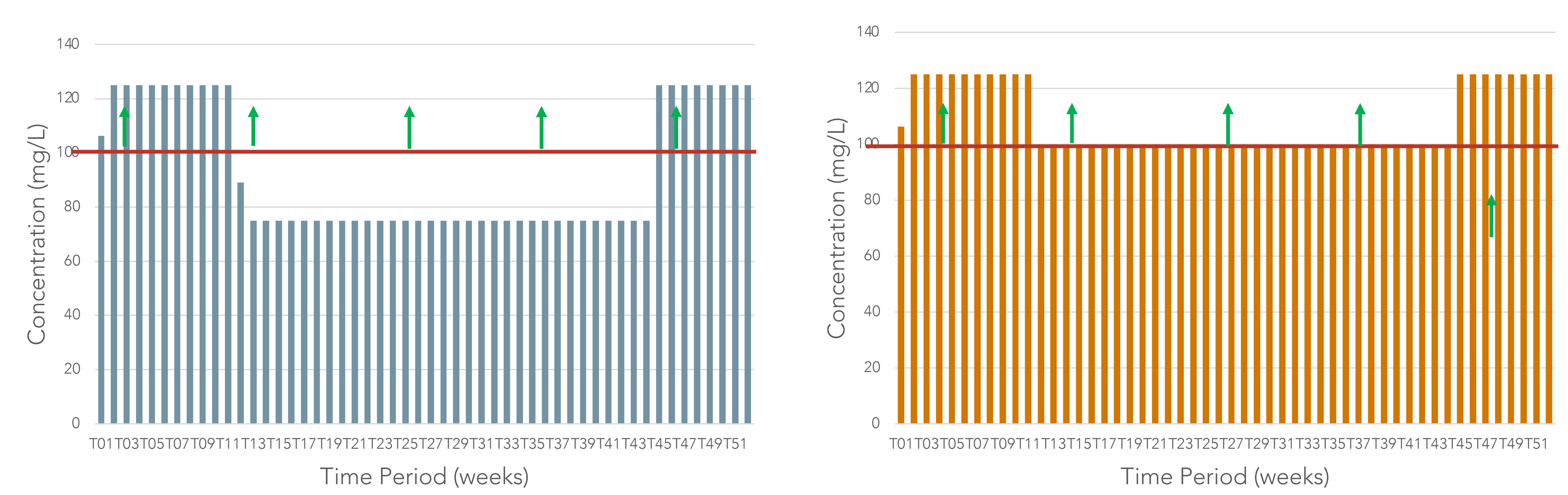
Minimizing Operating Costs

Our Lithium-Focused Model



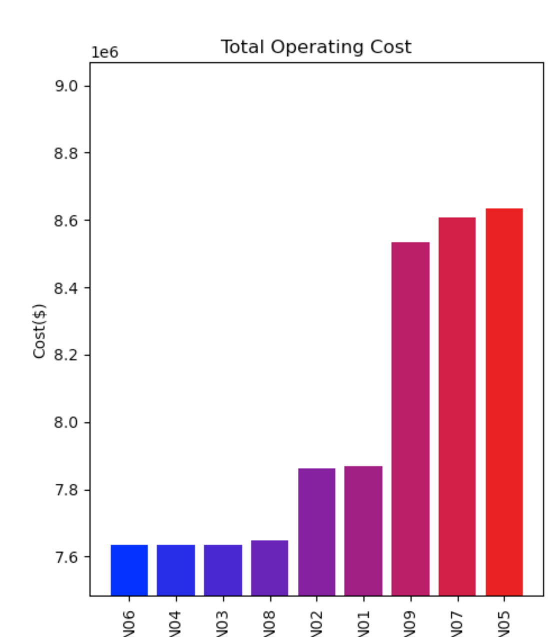
Minimizing operating costs including lithium recovery revenue

Solved with IPOPT



Concentration of Lithium exiting desalination facility for the entire time horizon. Production Focused Case (left), Lithium Focused Case (right).

What is the best location to install the desalination facility?



Challenges

Small Case Study

GUROBI, BARON (Global): no solution within 1 hour

4940 variables
4072 constraints

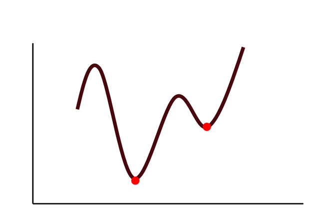
Large Case Study

GUROBI, BARON (Global): no solution within 1 hour

13252 variables
7292 constraints

$$\sum F_{in}C_{in}=\sum F_{out}C_{out}$$

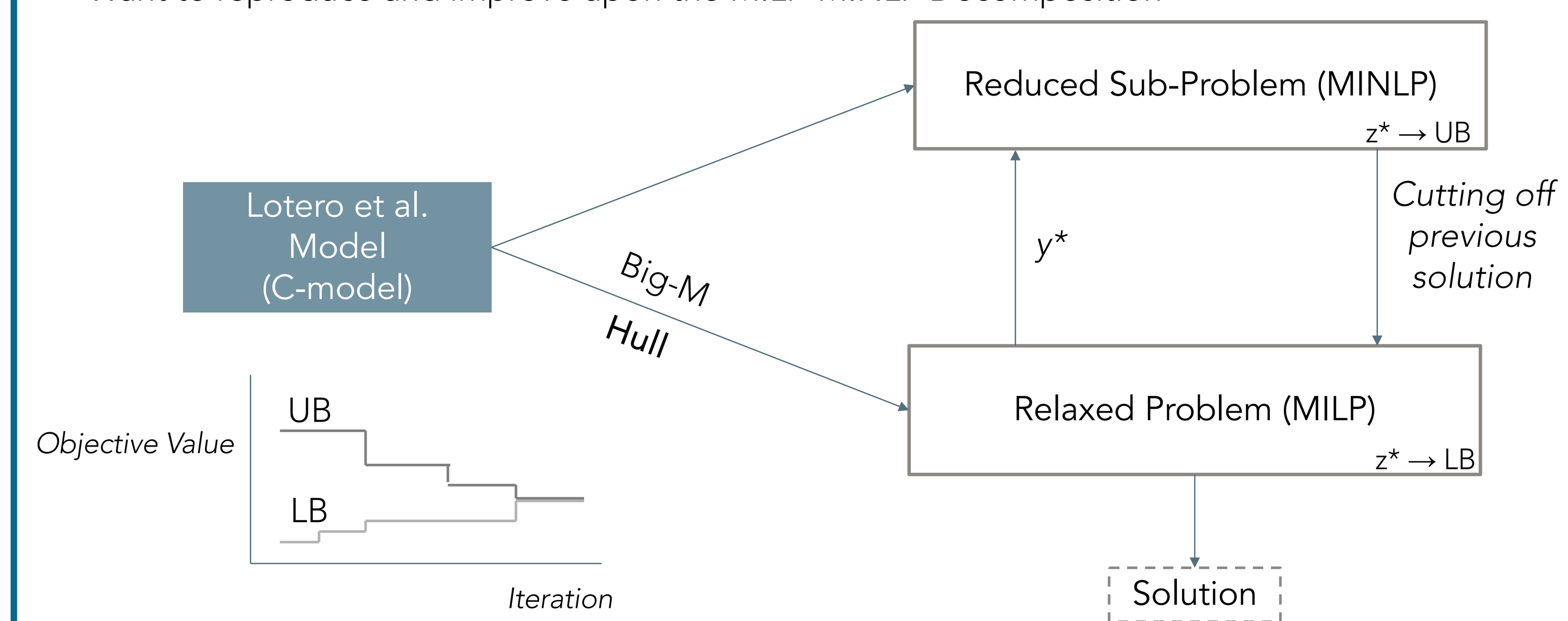
Non-Convex

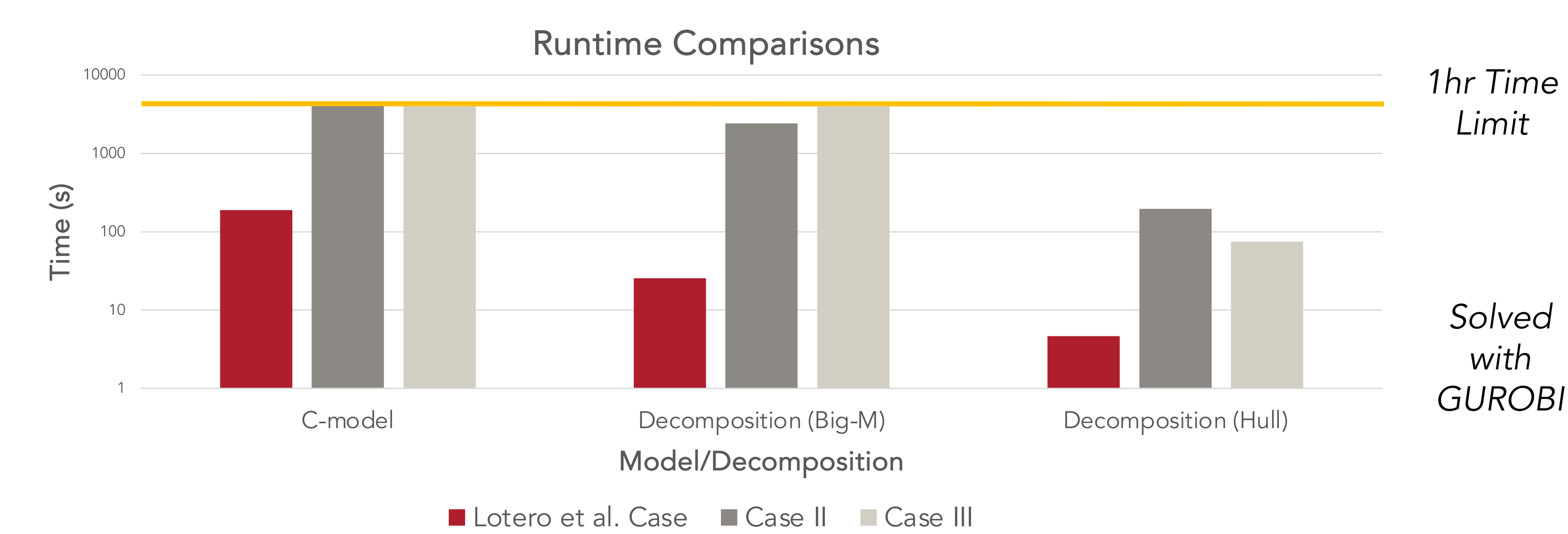


- MINLPs rely on global optimization solvers
- Off-the-shelf solvers are not able to solve the problem to global optimality
- Working on advanced decomposition algorithms to improve computational performance

Decomposition Algorithm

- Need to consider algorithms to improve computational performance
- **Pooling and Blending Problem** has very similar characteristics to the Produced Water Network Problem
- Past Approaches:
  - McCormick Envelopes
  - Lagrangean Relaxations
  - Piecewise Linear Relaxations
  - **MILP-MINLP Decomposition**
- Most approaches haven't been tested on large-scale strategic problems
- Want to reproduce and improve upon the MILP-MINLP Decomposition





Next Steps:

- Develop and test a similar decomposition for our Produced Water Network Operational Problem
- Test the decomposition on a strategic problem

Conclusions

- Produced Water has reasonable lithium concentrations that with the help of optimization could be potentially recovered
- Optimizing blending operations to achieve global optimality presents a formidable challenge
- The MILP-MINLP decomposition with the **Hull Reformulation** has shown promise in improving computational time
- Critical Minerals are poised to play a vital role in the future of power generation

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