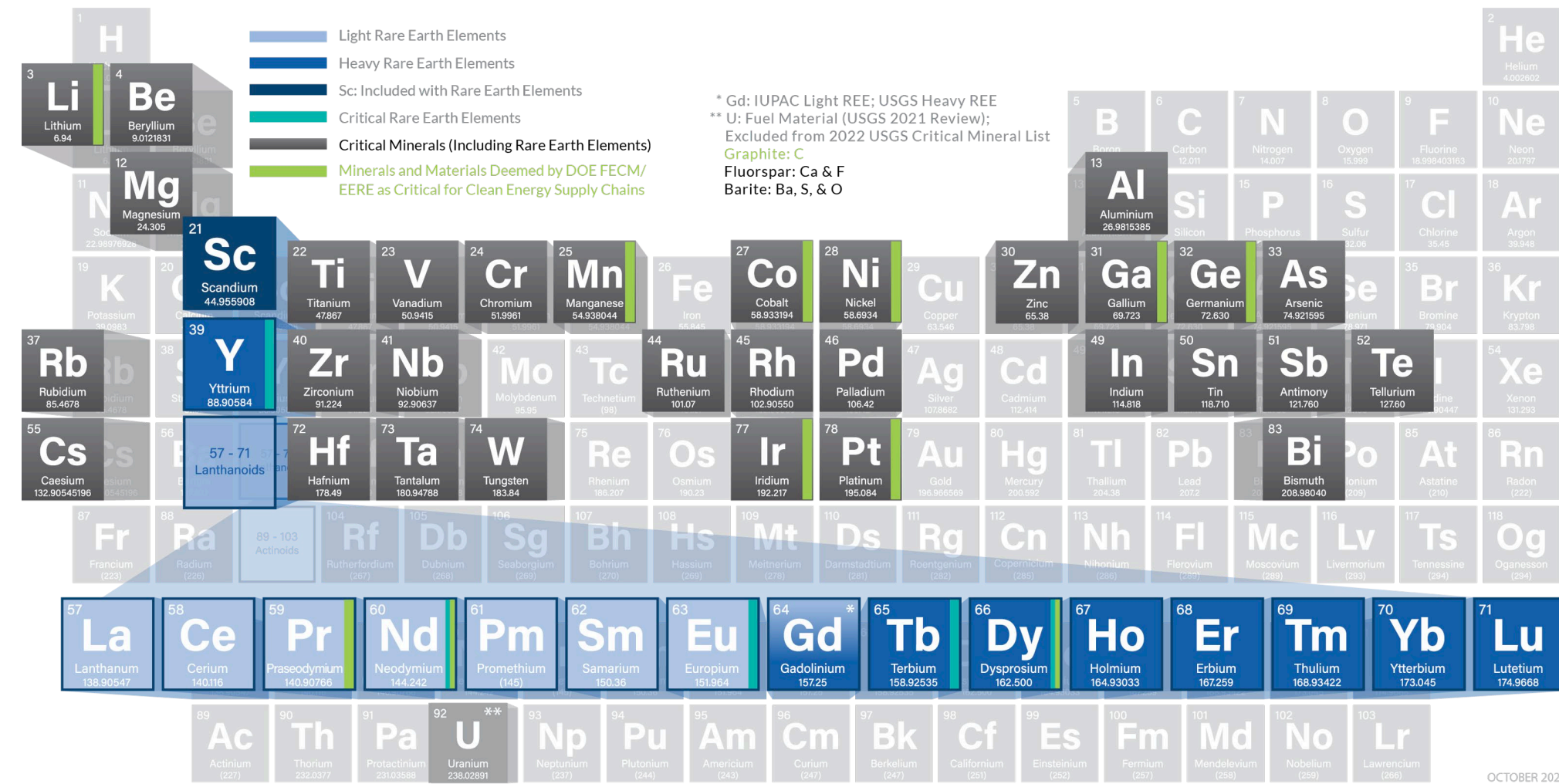


Critical Minerals Overview

The shift to clean energy systems is driving significant increase in demand for **critical minerals (CMs)**.



Current Challenges:

- High **geographical concentration** of CM resources
- Long project times** and **environmental concerns** of mining operations
- Higher **vulnerability of supply chains** for CMs

Membrane technologies are promising low-energy, aqueous processes with potentially high purity CM recoveries

Multi-Stage Diafiltration Model

(Based on original model from [1])

$$\max \text{Cobalt Recovery}$$

s.t. **Stage Connectivity Balances**

Permeate Mass Balances

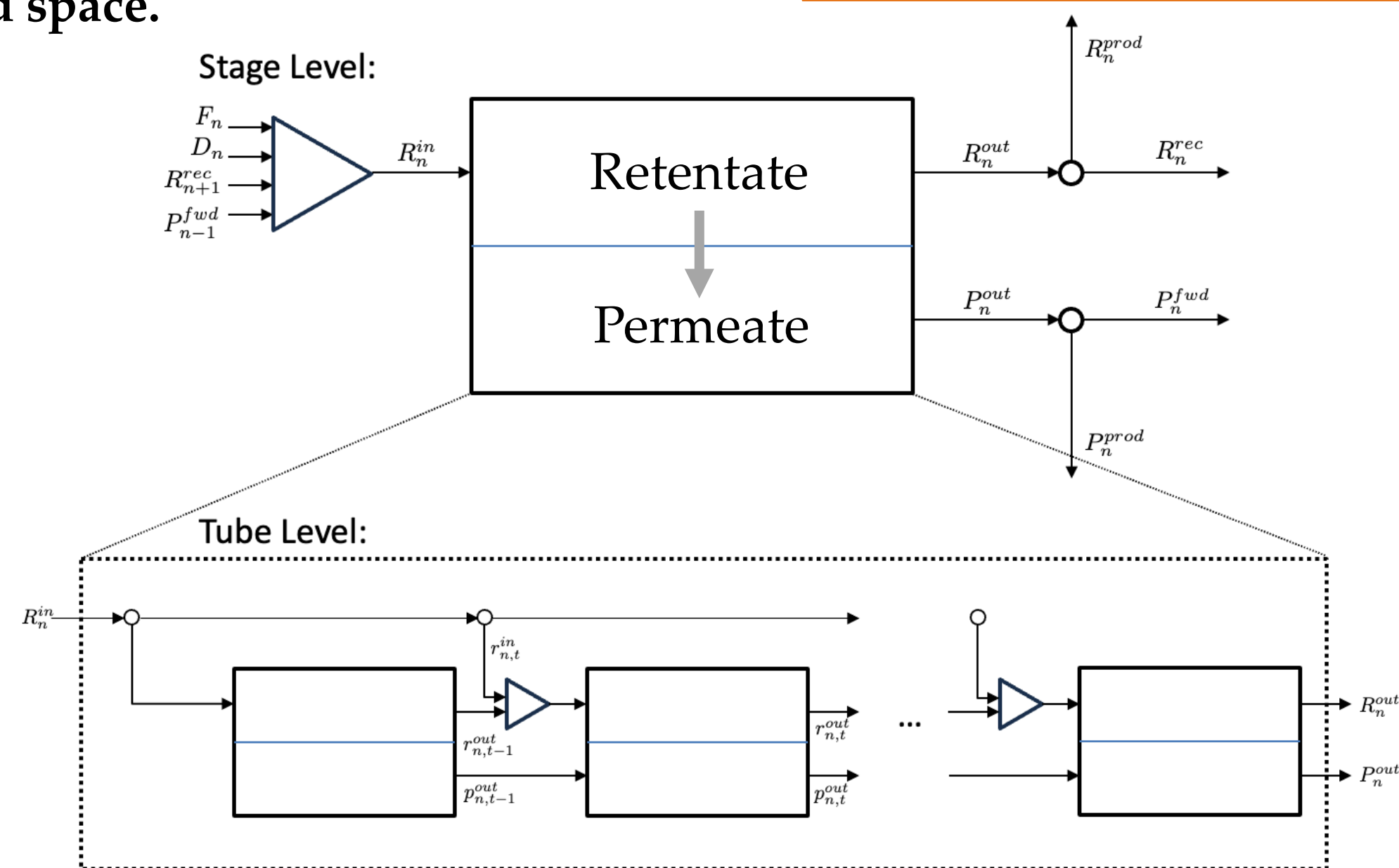
Retentate Mass Balances

Membrane Performance Equations

Lithium Recovery Bound

Flow Rate Bounds

- Adjustable number of **membrane stages (NS)** and number of **tube elements (NT)** using **IDAES unit models**.
- Multi-period** applications for changes in process conditions over time.
- Membrane performance parameters **indexed over time and space**.



Process Design Flexibility

Industrial processes must be able to perform under uncertain and changing operating conditions.

Two types of variables in robust process design:

- Design Variables** (set during construction):
 - Membrane stage length
- Control Variables** (adjustable during operation):
 - Flows (feed, diafiltrate, recycle, products)

Operational flexibility can be added through additional control **degrees of freedom (DoF)**, increasing a system's ability to respond to changes.

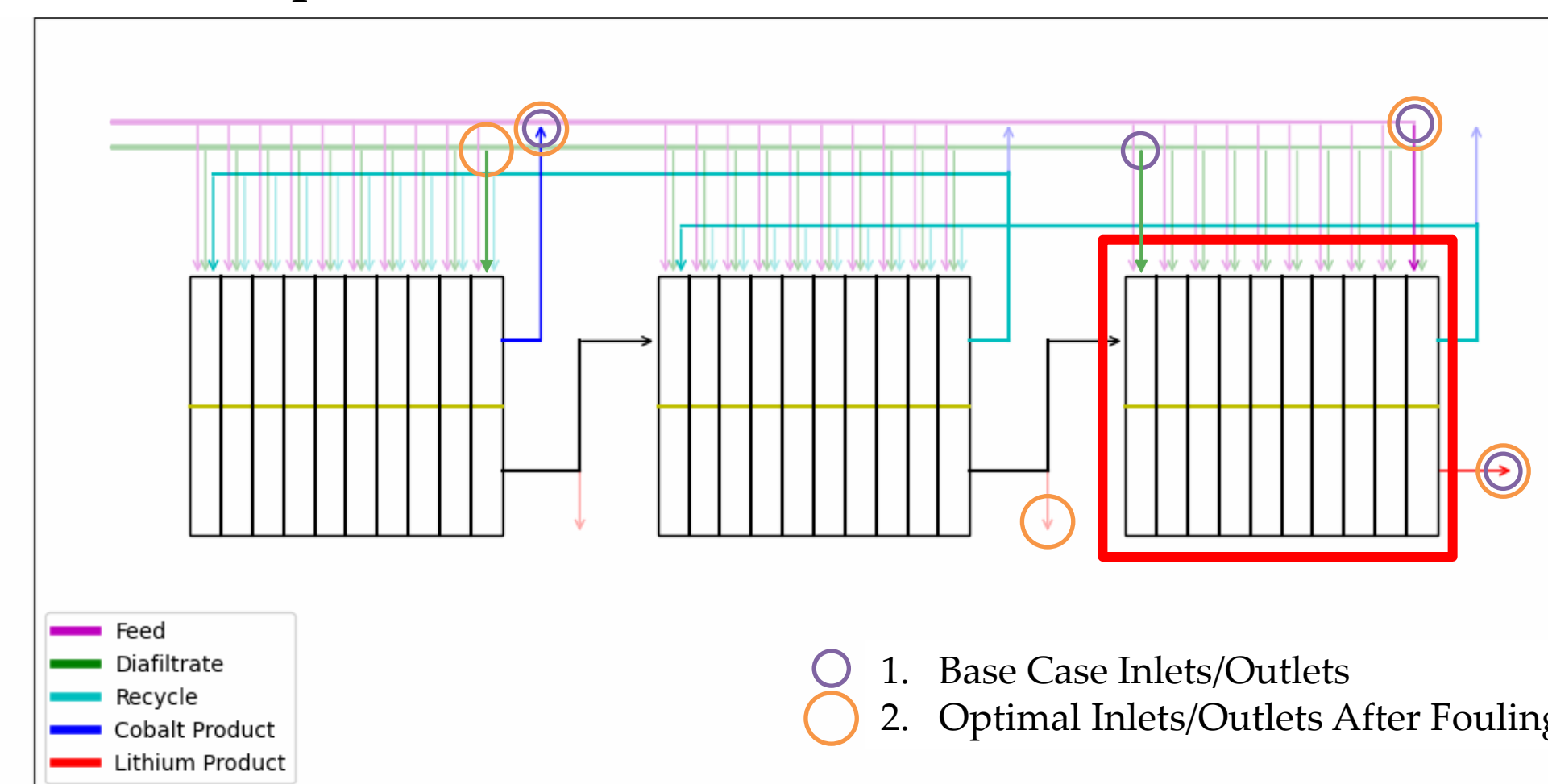
- Stage-Level Mixing:** Flows mixed before each stage. The flow of the mixed inlet into each tube can be controlled.
- Tube-Level Mixing:** Flows mixed before each tube. This is the most generalized superstructure with greatest capital costs.

Variables	Stage-Level Mixing DoF		Tube-Level Mixing DoF	
	Stage	Tube	Stage	Tube
Length	1	—	1	—
Feed Split	$NS - 1$	—	$NS - 1$	$NS(NT - 1)$
Diafiltrate Split	$NS - 1$	—	$NS - 1$	$NS(NT - 1)$
Recycle Split	—	—	—	$(NS - 1)(NT - 1)$
Mixed Inlet Split	—	$NS(NT - 1)$	—	—
Product Outlets	$2NS - 2$	—	$2NS - 2$	—
Total DoF	$NS(NT + 3) - 3$	—	$3NS \cdot NT + NS - NT - 2$	—

Case Studies

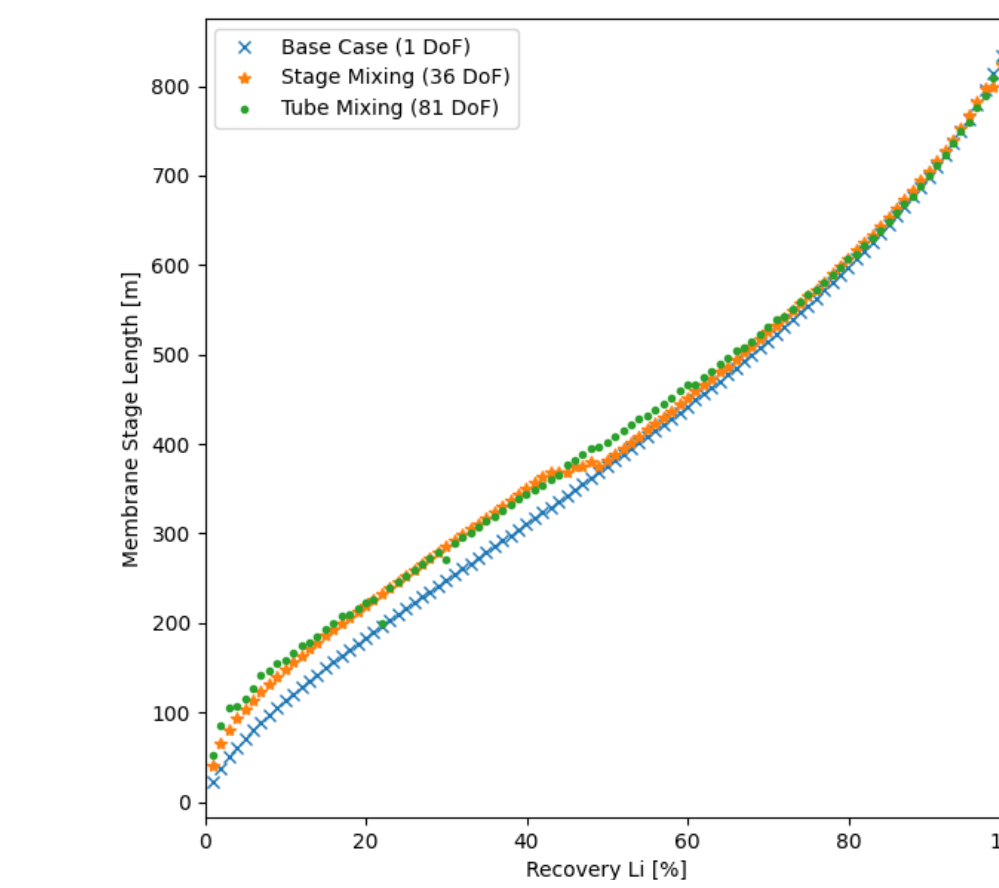
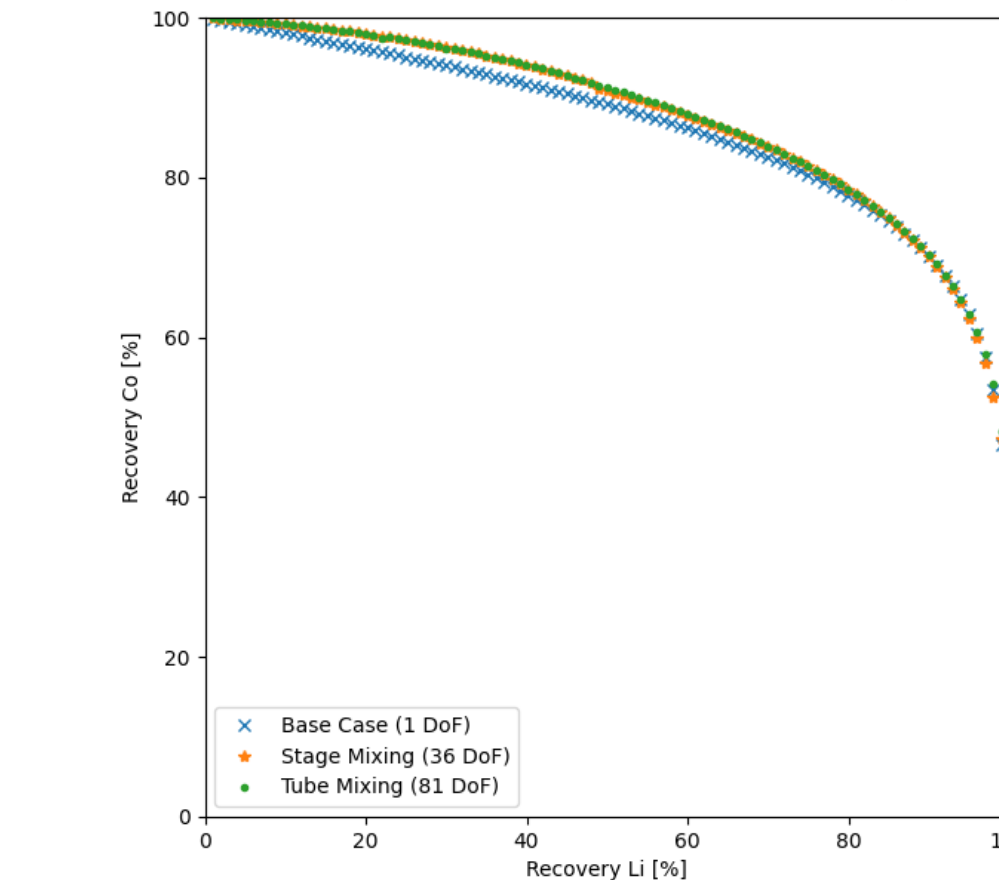
Base Case: Optimal flow configuration for 95% lithium recovery and choice of membrane stage length (1 DoF)

- Compare base case with flexible design superstructures
- Investigate effect of decrease in membrane flux over time on process design
 - Fouling** is an inevitable phenomenon in membrane processes and may contribute to a decrease in flux.
 - We study a **linear decrease in membrane flux to 50%** of its original value over **three periods**.
 - Membrane stage three** is chosen as an important location of process inlets/outlets for the base case.

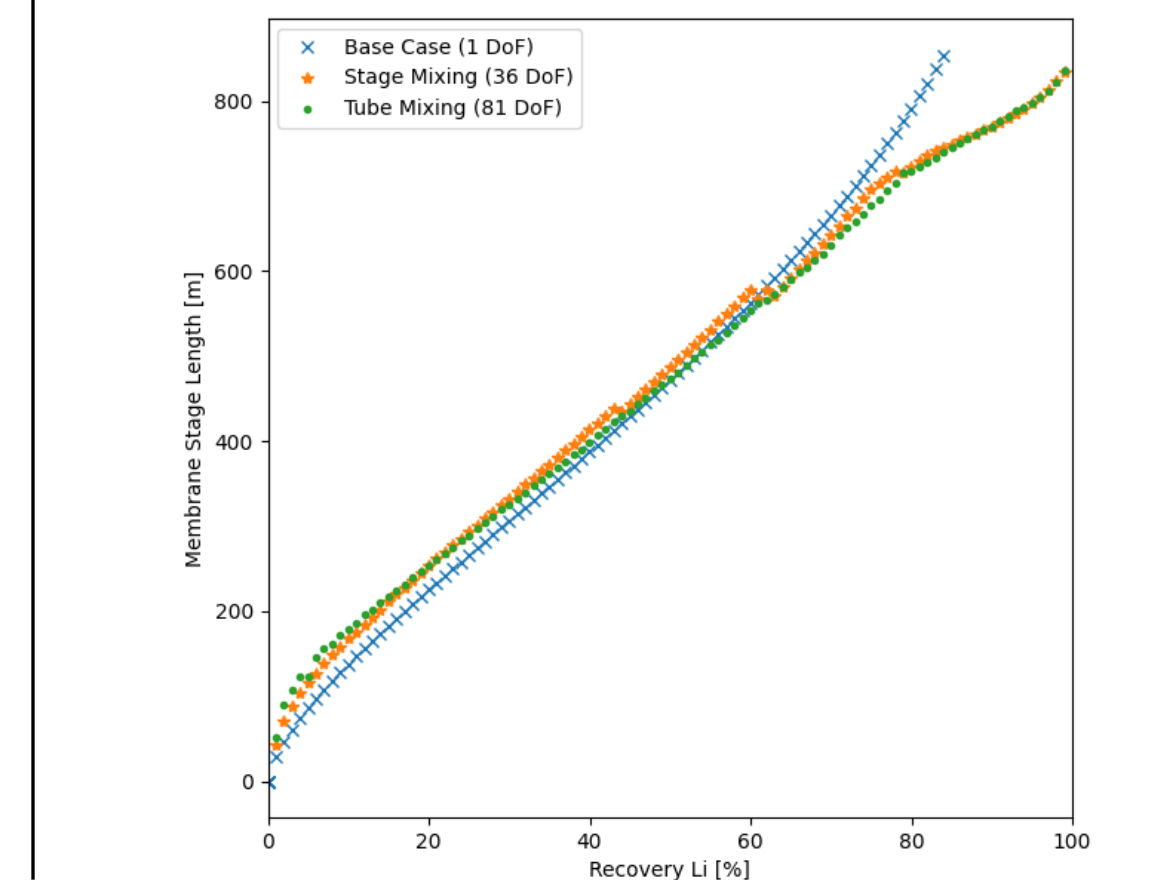
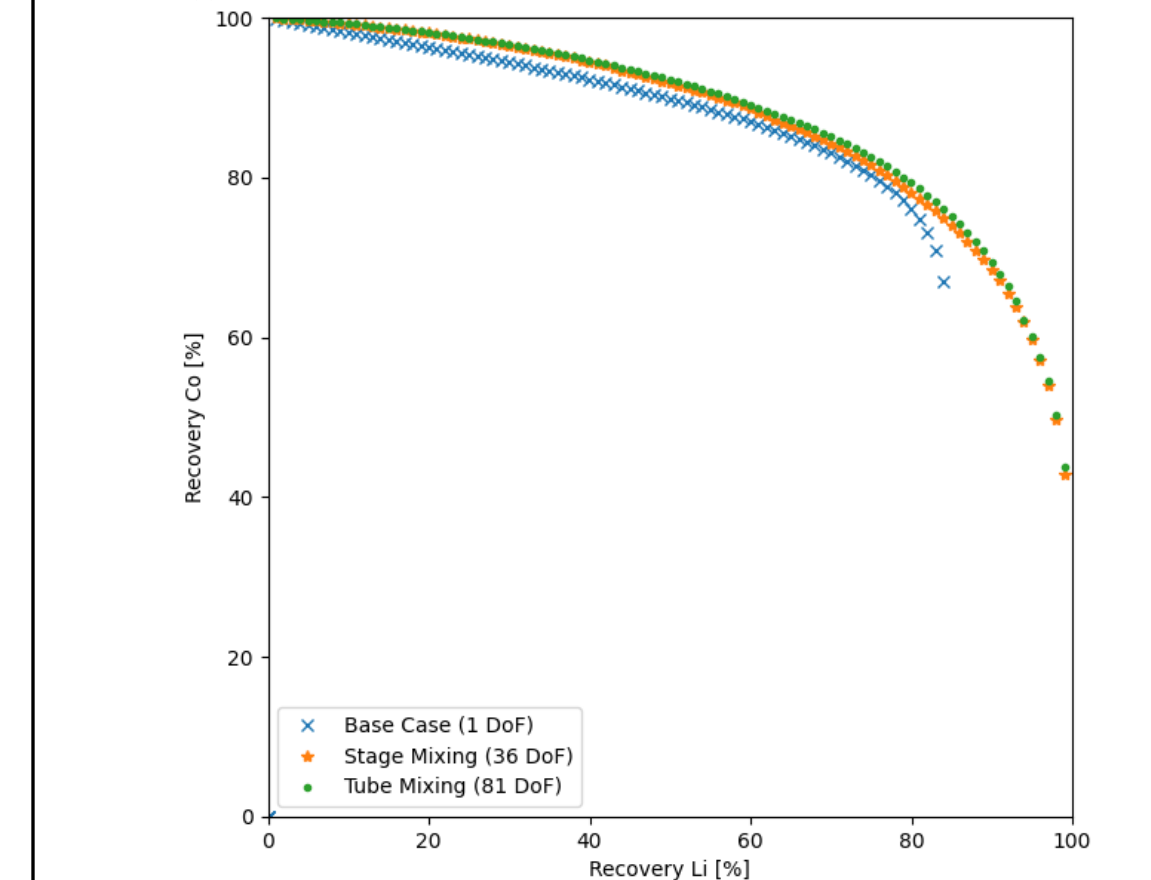


Computational Results

1. Single-Period Design Comparisons



2. Optimal Design with Decreasing Flux



- Operational flexibility** through added DoF (more complex design) obtains **noticeably higher cobalt recoveries**.
- Decrease in membrane performance** results in **infeasibility** of high lithium recoveries for **base case**.
- Flexible designs** are **feasible across the entire Pareto front** and effectively handle the different operating conditions.

Conclusions and Future Work

Conclusions:

- We developed **operationally flexible, multi-period diafiltration models** for process designs that can adjust to changes in operating conditions and membrane material performance over time.
- Our results allude to the fact that **incorporating flexibility in design is important for minimizing technical risks**.

Future work:

- Incorporate **uncertainty** into feedstock and membrane performance parameters and **perform robust optimization** using the Pyomo Robust Optimization Solver (PyROS).
- Add costing into models to allow for **developing diafiltration systems optimized for both cost and performance**.

Acknowledgements

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References

[1] Noah P. Wamble, Elvis A. Eugene, William A. Phillip, and Alexander W. Dowling. Optimal Diafiltration Membrane Cascades Enable Green Recycling of Spent Lithium-Ion Batteries. ACS Sustainable Chemistry & Engineering, 10(37):12207–12225, September 2022.