National Alliance for Water Innovation

Valuing Energy Flexibility in Desalination

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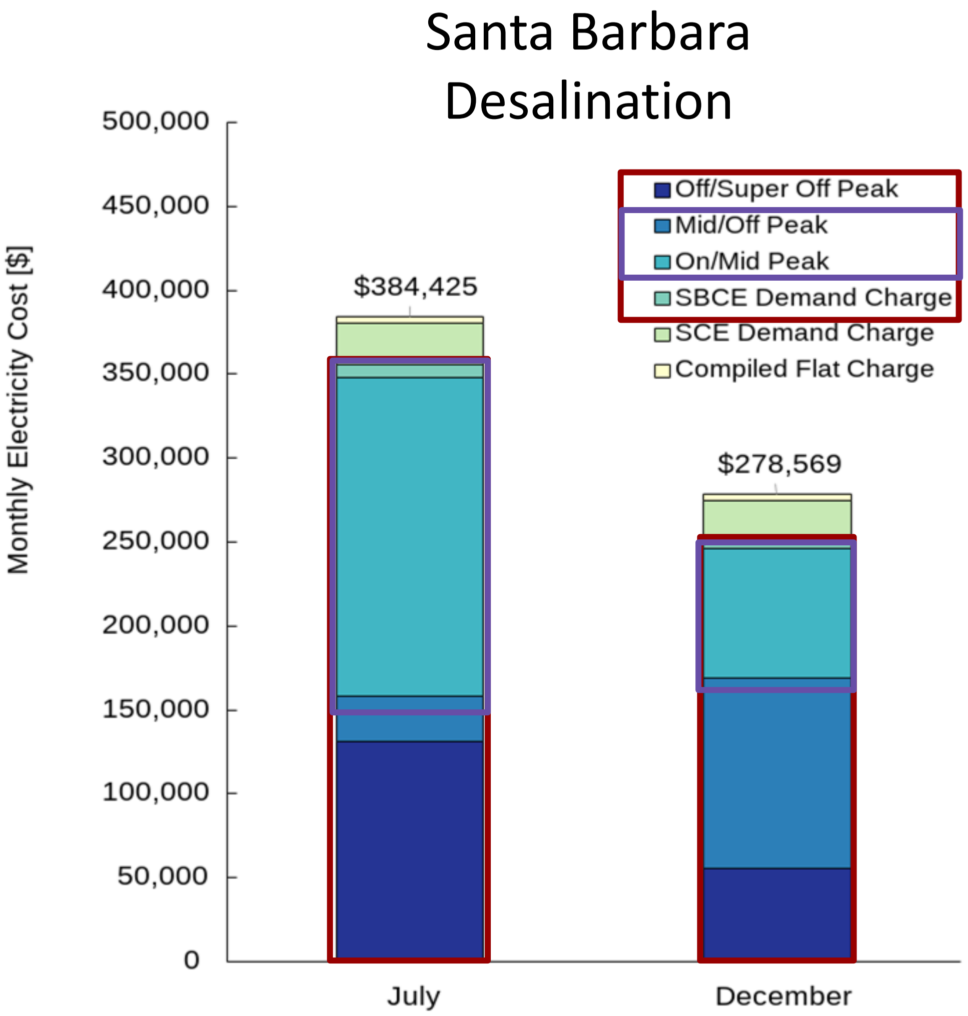
September 19, 2024


FILTER BACKWASH
SEAWATER
FLUSHING
CIP
BRINE
FLUSHING
CIP
PERMEATE

Time-varying costs are an opportunity for arbitrage

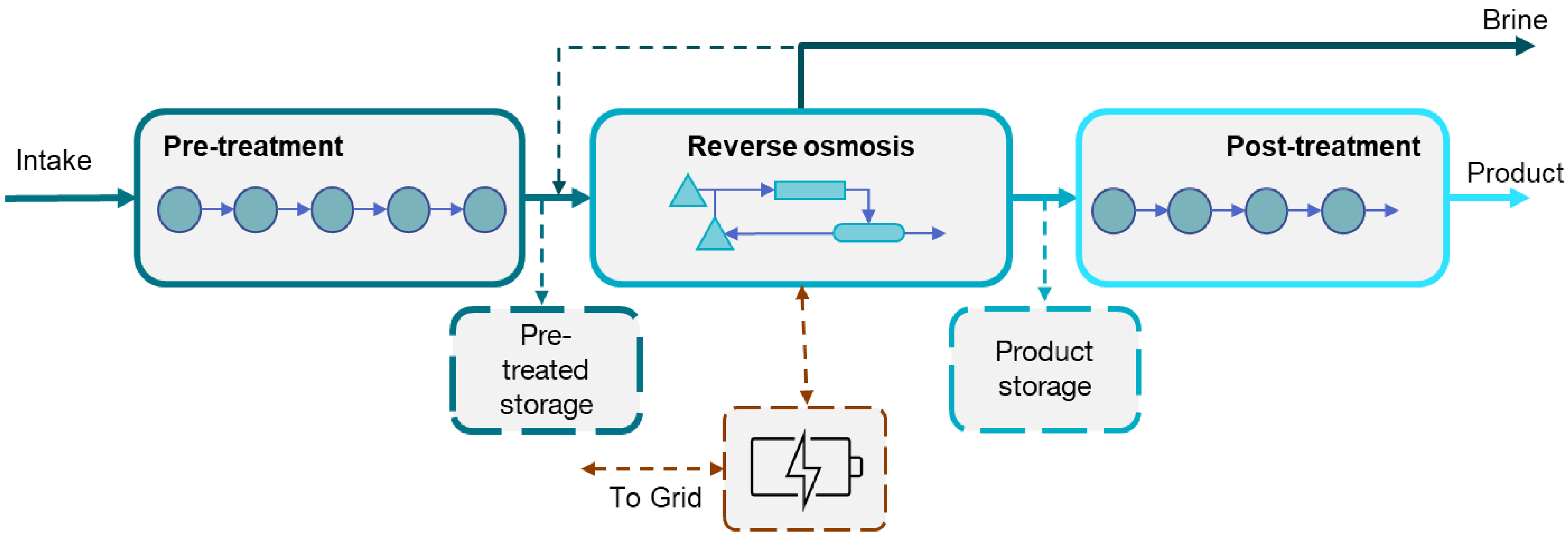


~90% of the electricity bill is tied to the time-of-use

30-50% of the electricity bill is charged during 4-9pm

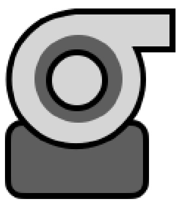
A.K. Rao, A. A. Atia, T. Bartholomew, & M.S. Mauter. (2023). *International Water Conference*.
E. Musabandesu, Y. Liu, & M.S. Mauter (2025). *Manuscript In-Preparation.*

Mechanisms of energy flexibility in municipal desalination

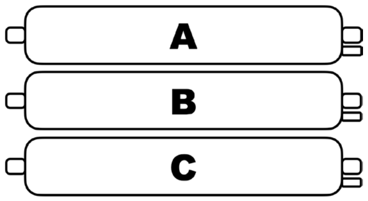


Each flexibility mechanism has unique energy dynamics and cost implications

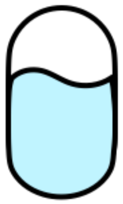
Pump Flows and Pressures



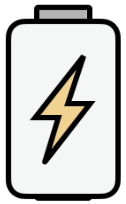
Parallel Skid Shutdown



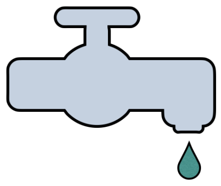
Water Storage



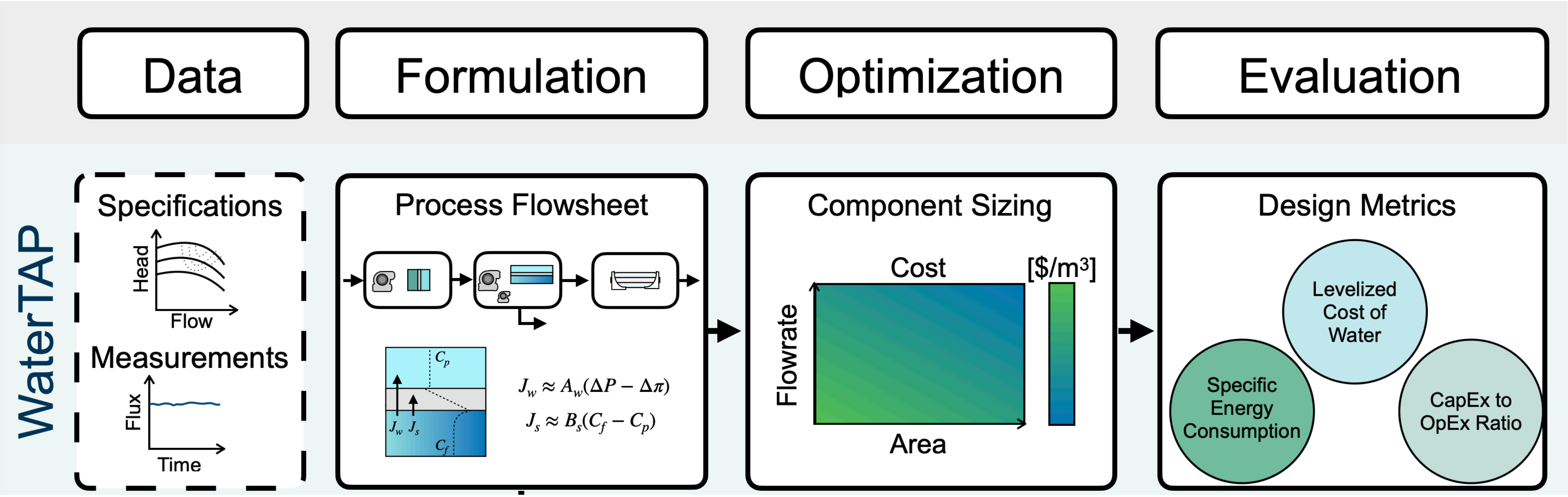
Energy Storage



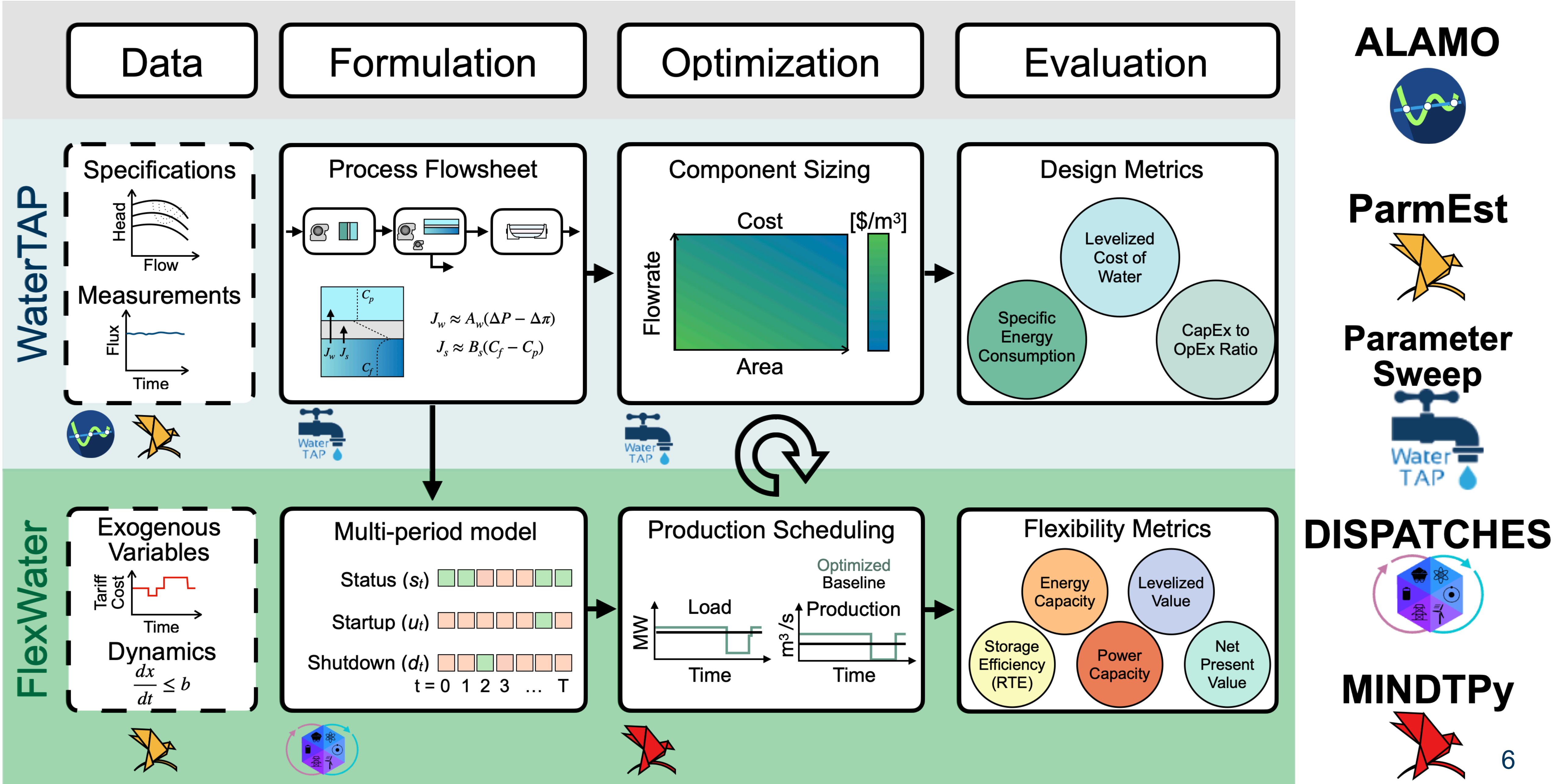
Supply Curtailment



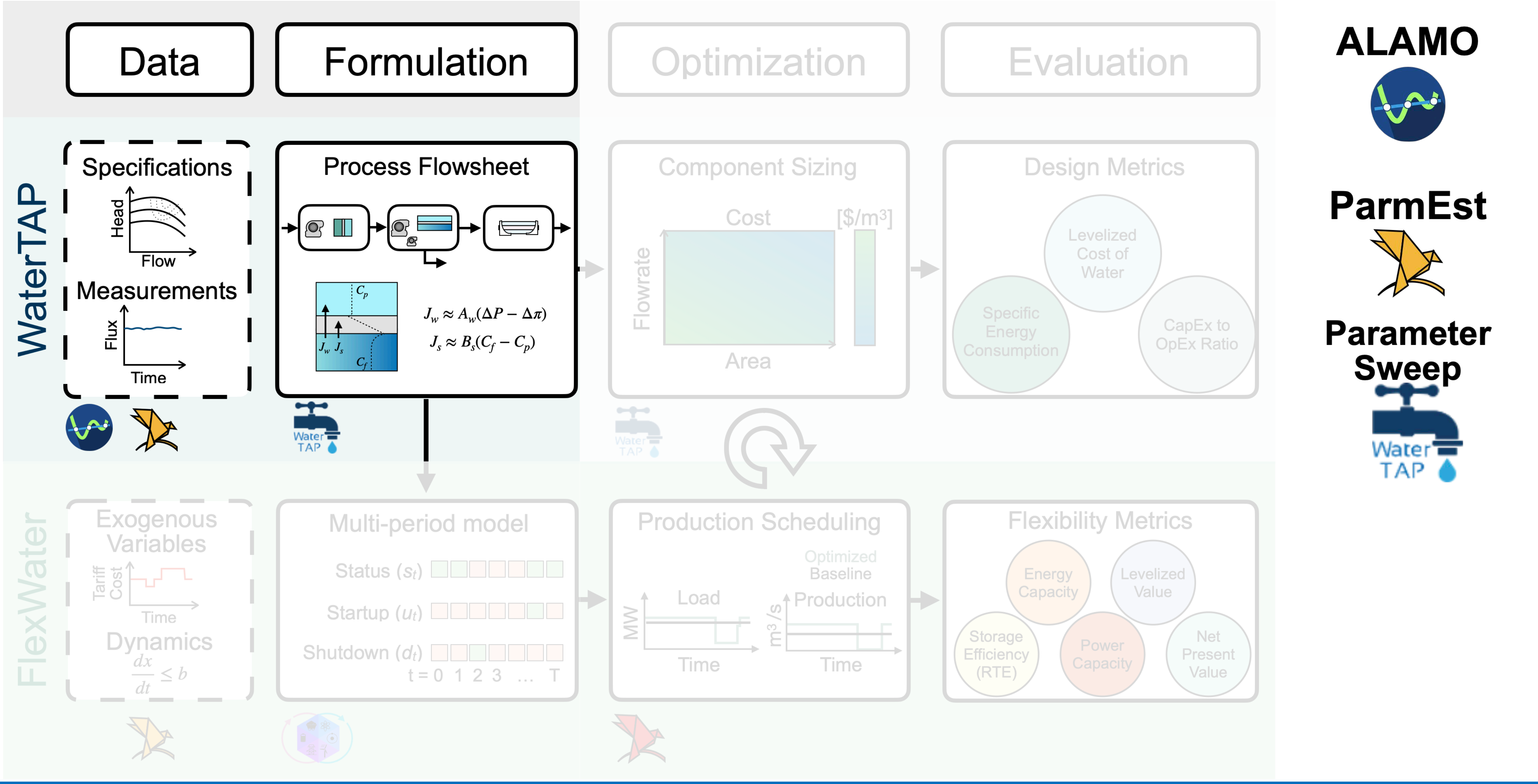
A framework for optimizing & valuing energy flexibility



A framework for optimizing & valuing energy flexibility



Steady-state model tuning and parameter estimation



Steady-state model tuning: Variable efficiency pumps

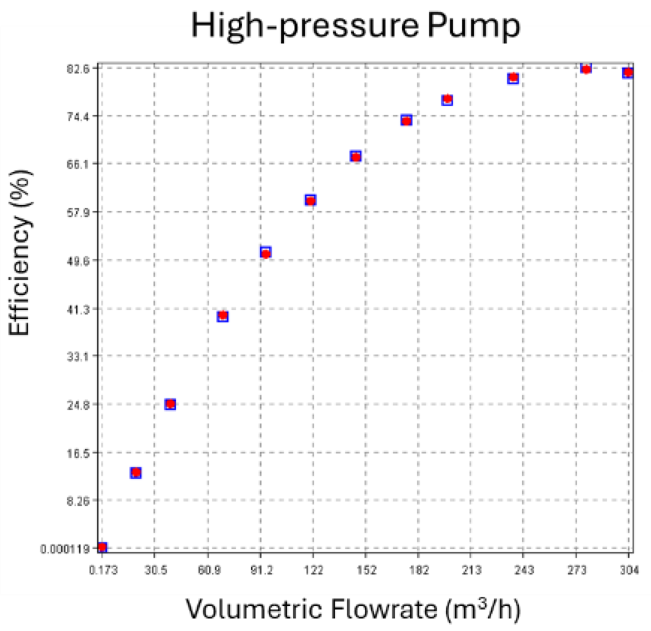
ALAMO

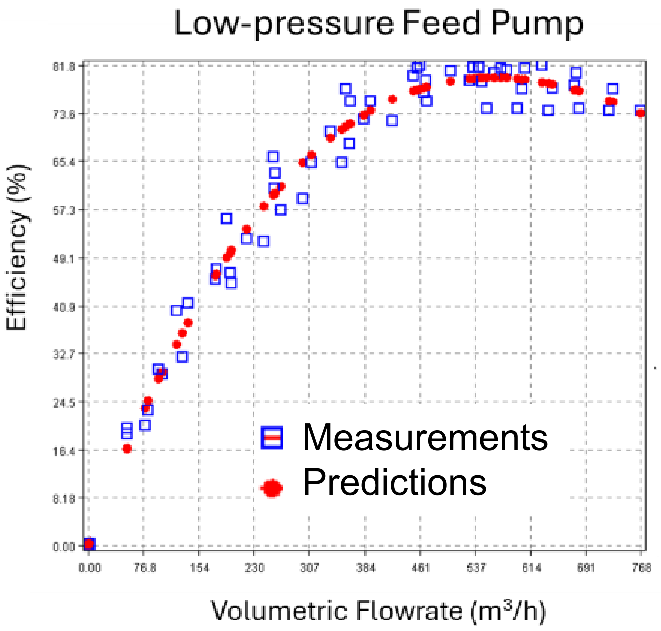
Minimize Model predictions vs. measured data

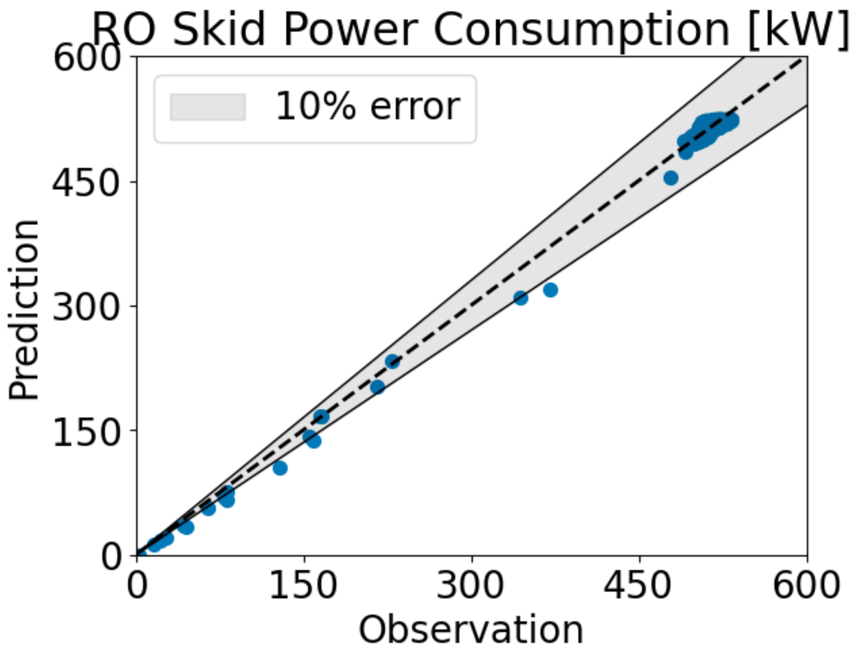
$\eta_{\mathrm{VFD}\,\&\,Motor}$

Subject To Manufacturer pump curves

Tune pump curves with motor and VFD losses







Wilson, Z. T., & Sahinidis, N. V. (2017). *Computers & Chemical Engineering*, 106, 785-795.
Klise, K., A. et al. (2019). *Computer Aided Chemical Engineering*, 47 (2019): 41-46.

NAWI

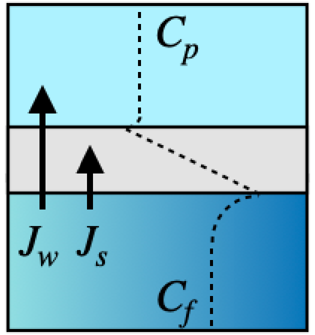
Estimating model parameters: Membrane transport

ParmEst

Minimize Model predictions vs. measured data

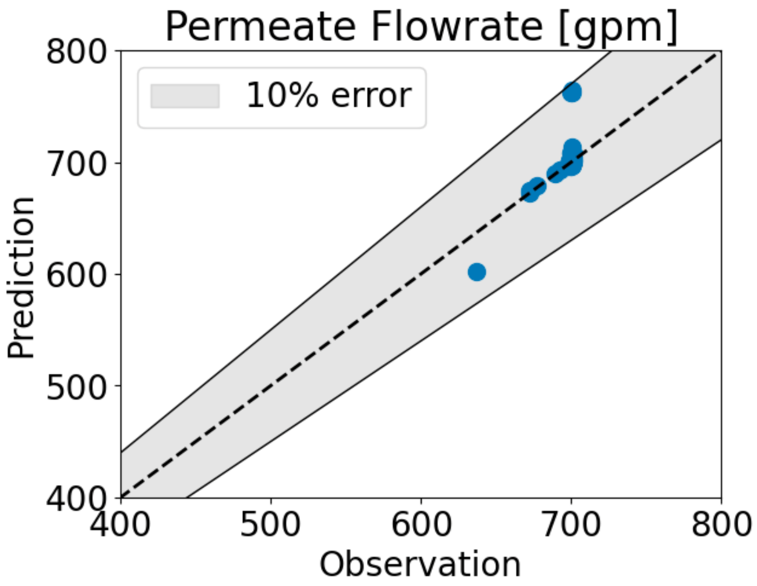
A, B

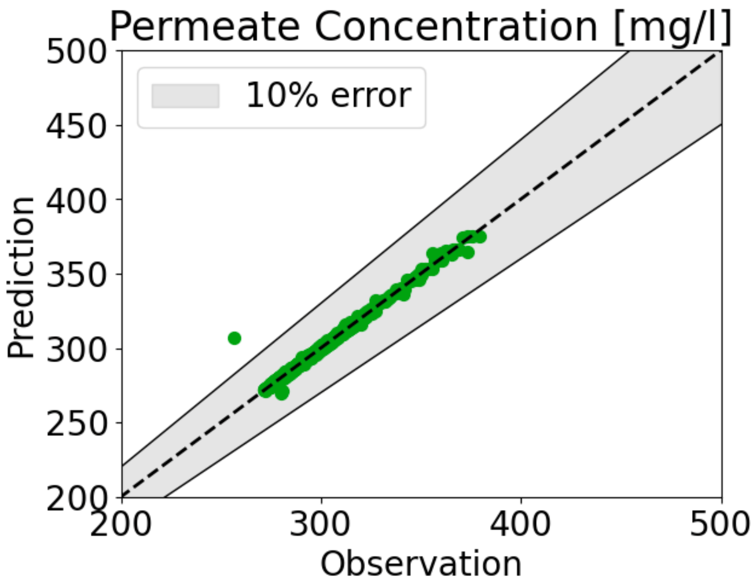
Subject To WaterTAP Reverse Osmosis Unit model



Estimate membrane transport properties

Parameter	**Estimated Value**
Water Permeability (A)	$1.56 \pm 0.13 \times 10^{-12}$
Salt Selectivity (B)	$3.38 \pm 0.267 \times 10^{-8}$





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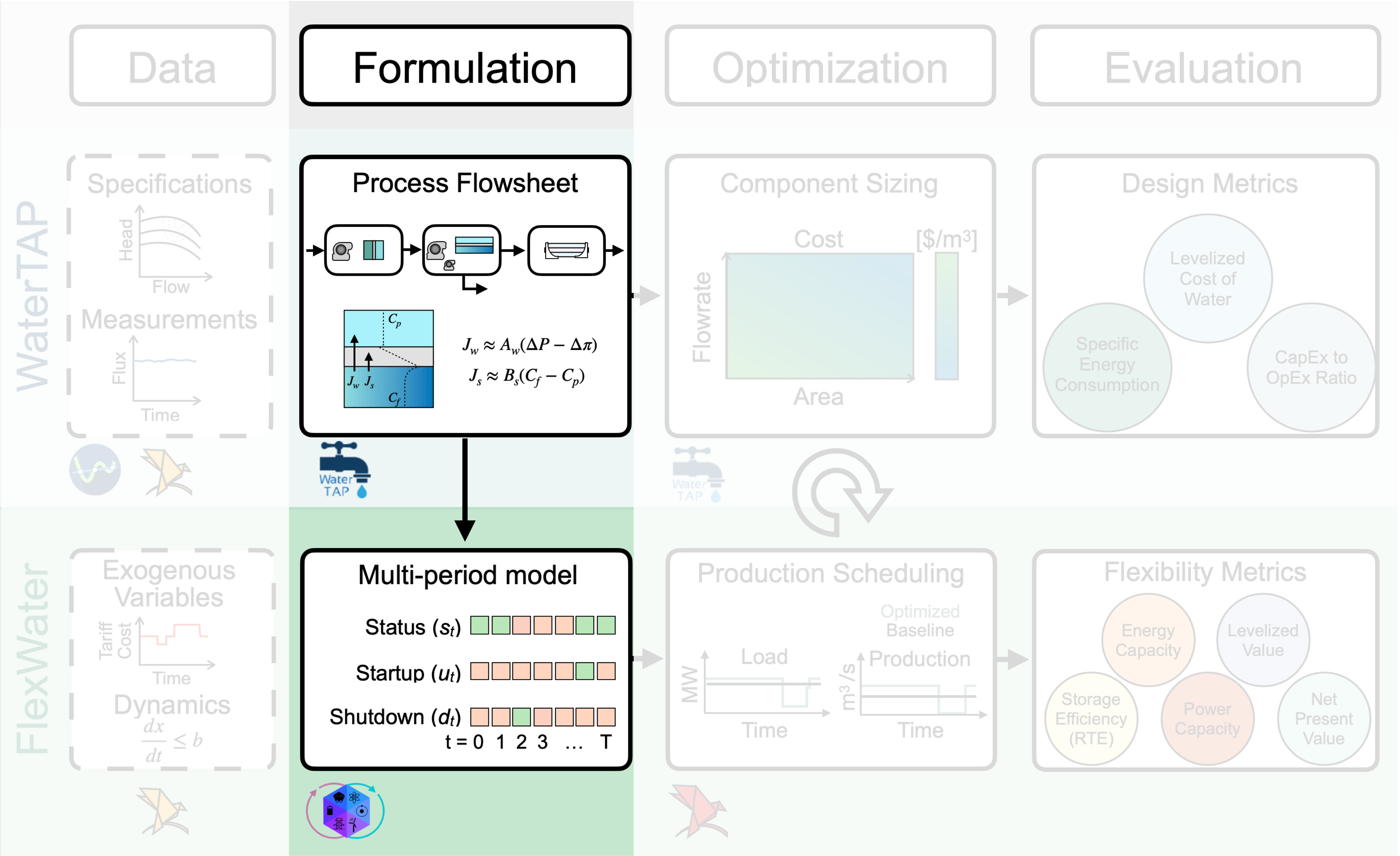
Multiperiod models from steady-state flowsheets



ParmEst

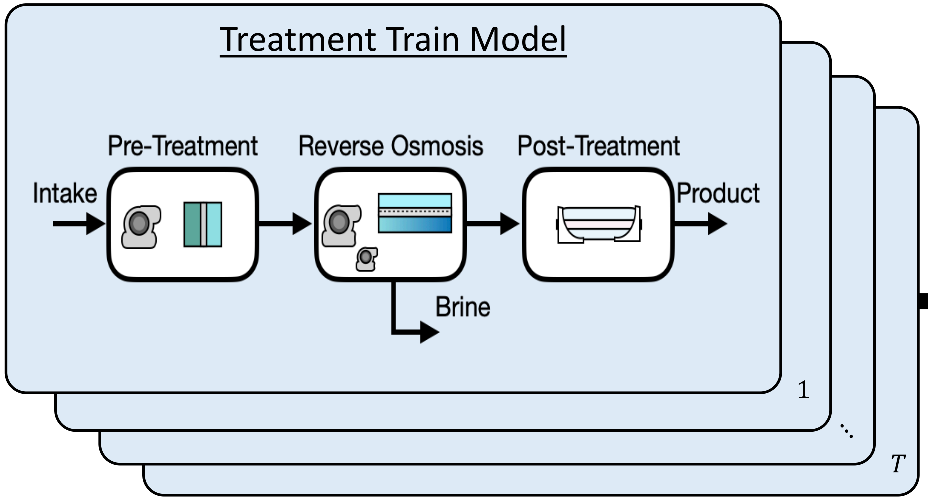
Parameter Sweep

Water TAP

DISPATCHES

Multiperiod models from steady-state flowsheets

DISPATCHES



MultiPeriod flowsheet

Multi-Period Model (e.g., seawater RO)

Multi-step constraints (e.g., ramping, yield)

Unit Commitment (status, start-up, shut-down)

Price Signals (e.g., tariff, grid emissions)

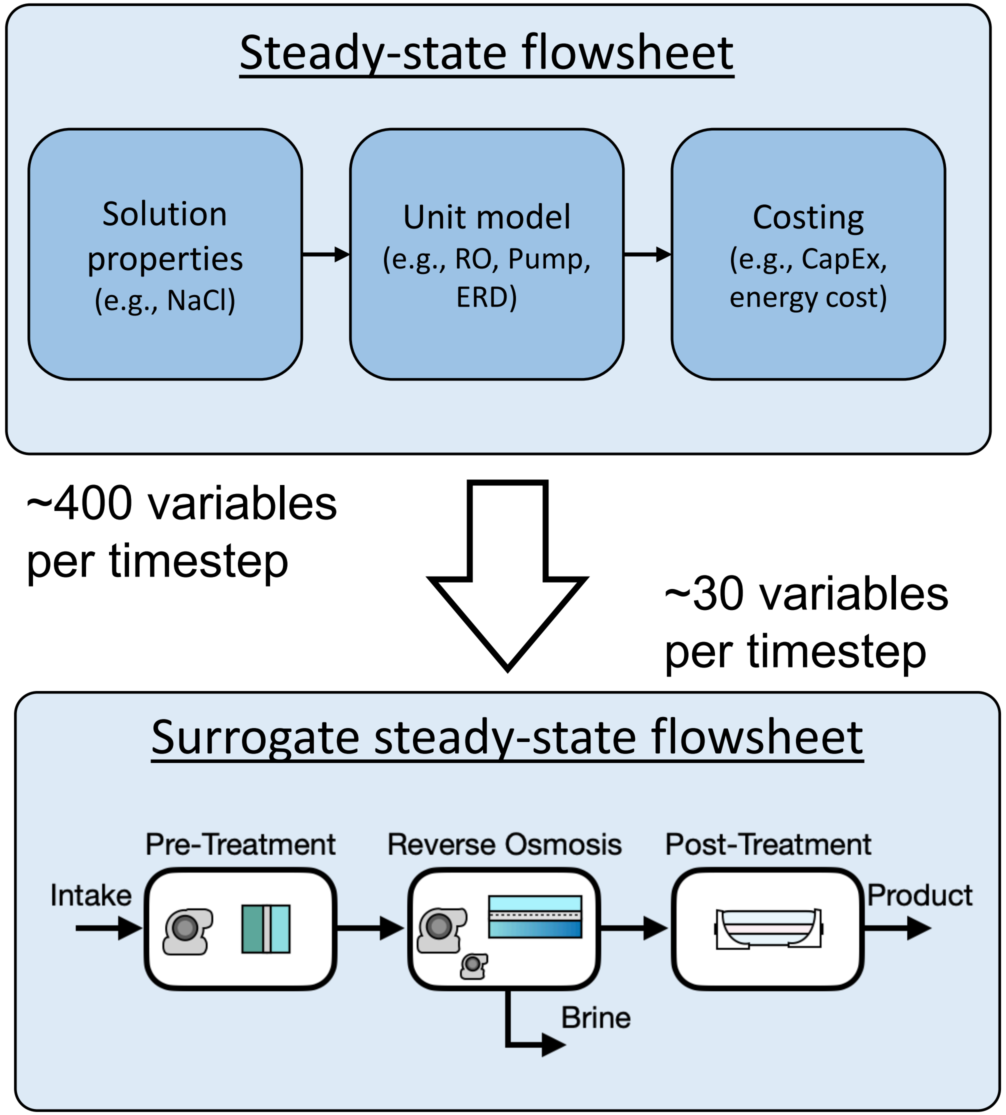
Formulates the water production scheduling problem as a mixed integer non-linear program

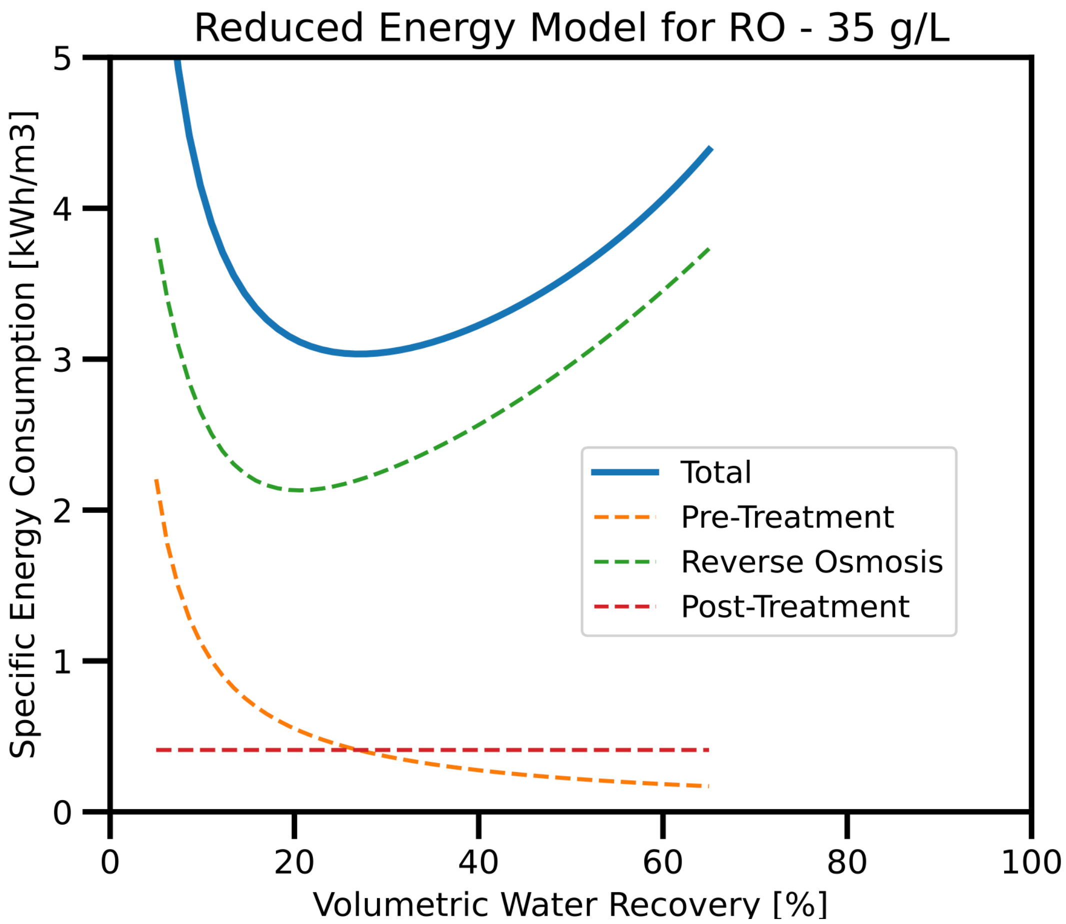
Daniel L. et al. (2024). *Living Archive for Process Engineering: 2024.1567*

Reduced order unit models for energy flexibility

Parameter Sweep

ParmEst



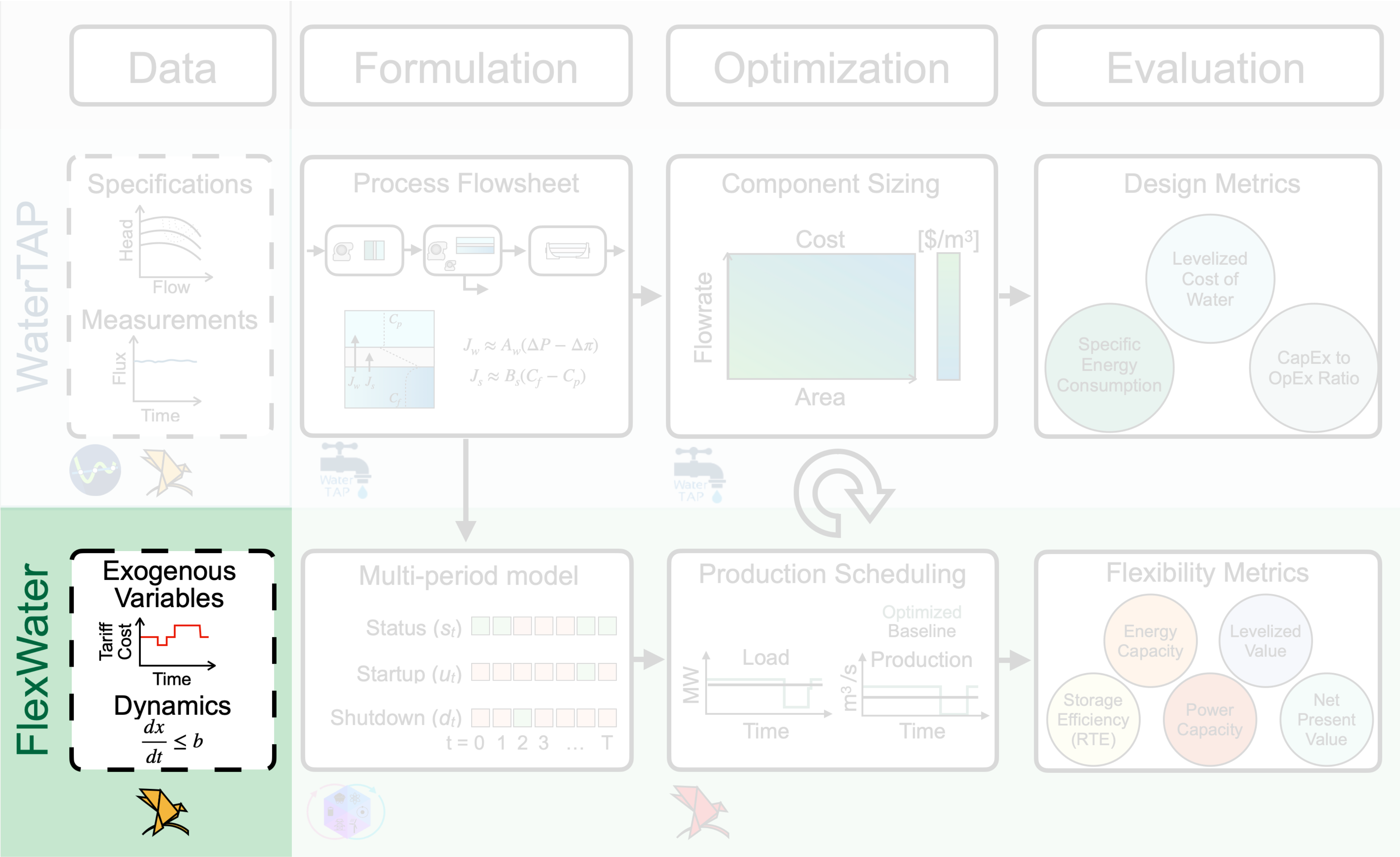


$$SEC_{RO} = ae^{-br} + cr^2 + d$$

Convex on r and low dimensional on $\{a, b, c, d\}$

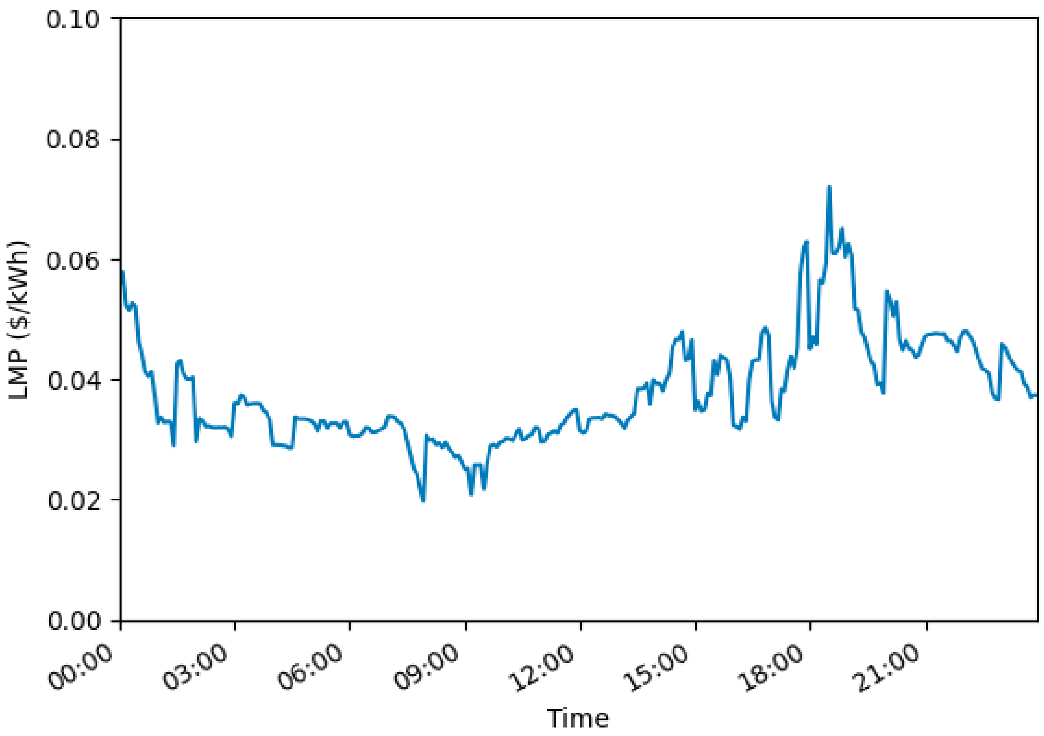
Klise, K., A. et al. (2019). *Computer Aided Chemical Engineering*, 47 (2019): 41-46.

A framework for optimizing & valuing energy flexibility

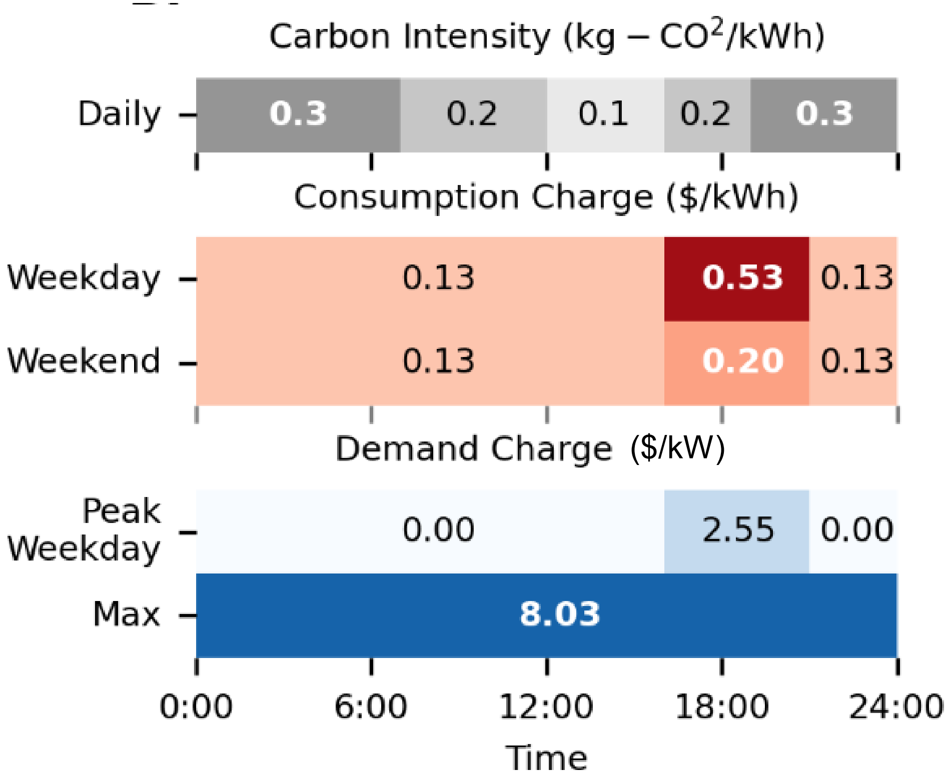


Water facilities don't usually buy wholesale electricity

Locational Marginal Price
(CAISO aggregate example)



Industrial Electricity Tariff
(Southern California Edison)



Tariffs may have high geographical variance and complex charge structures

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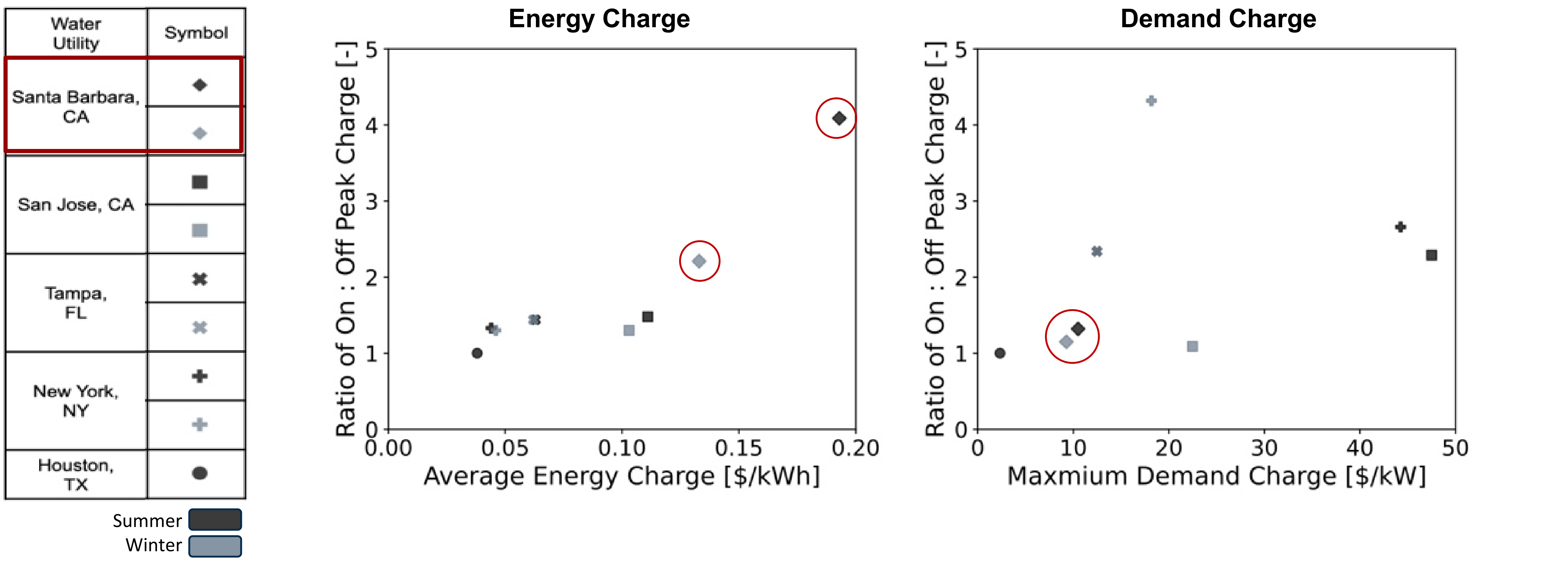
Database for industrial electricity tariffs

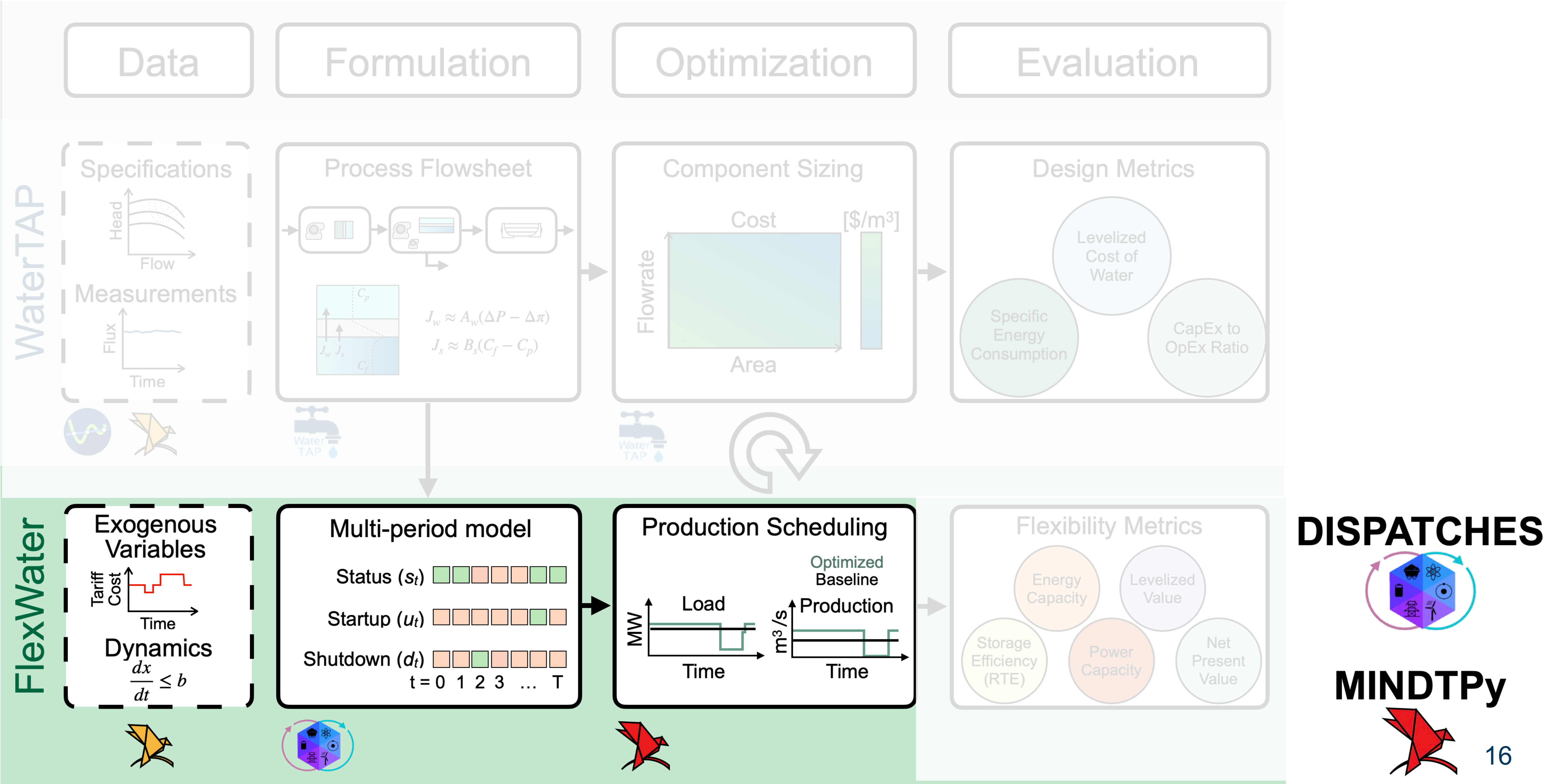


~100 tariffs of water utilities → expanding to 3000+ tariffs relevant to general industrials

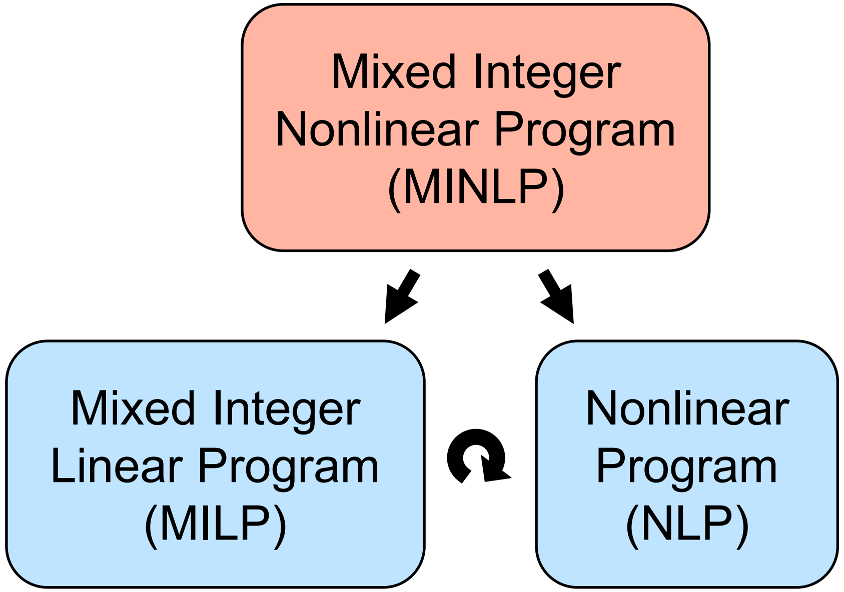
Processed in a modeling-friendly format in CVXPy → expanding for general Pyomo model integration

NAWI Chapin, F.T., Bolorinos, J., & Mauter, M.S. (2024). *Nature Scientific Data*

A framework for optimizing & valuing energy flexibility

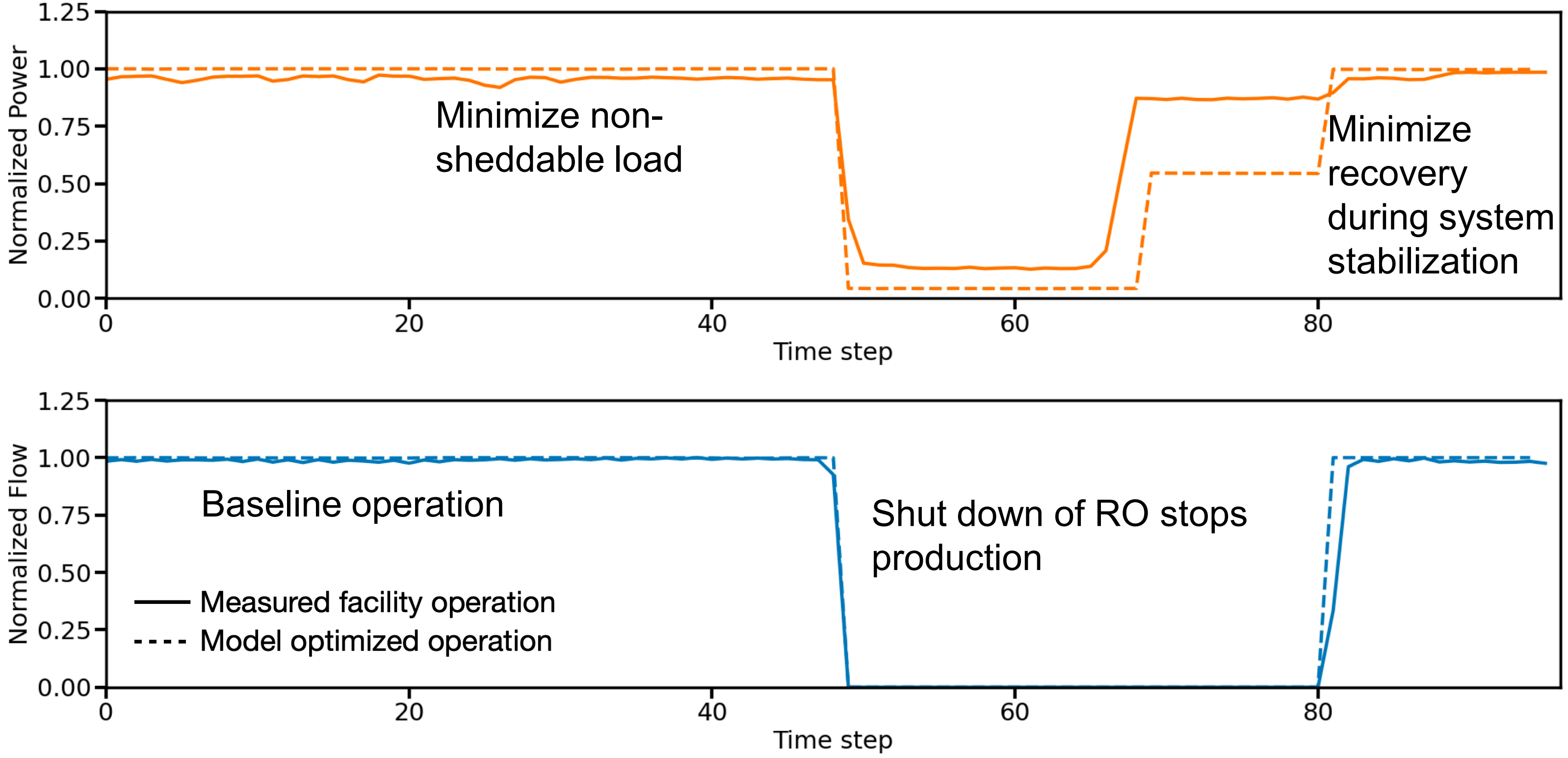


Efficiently solving MINLP scheduling models with MINDTPy



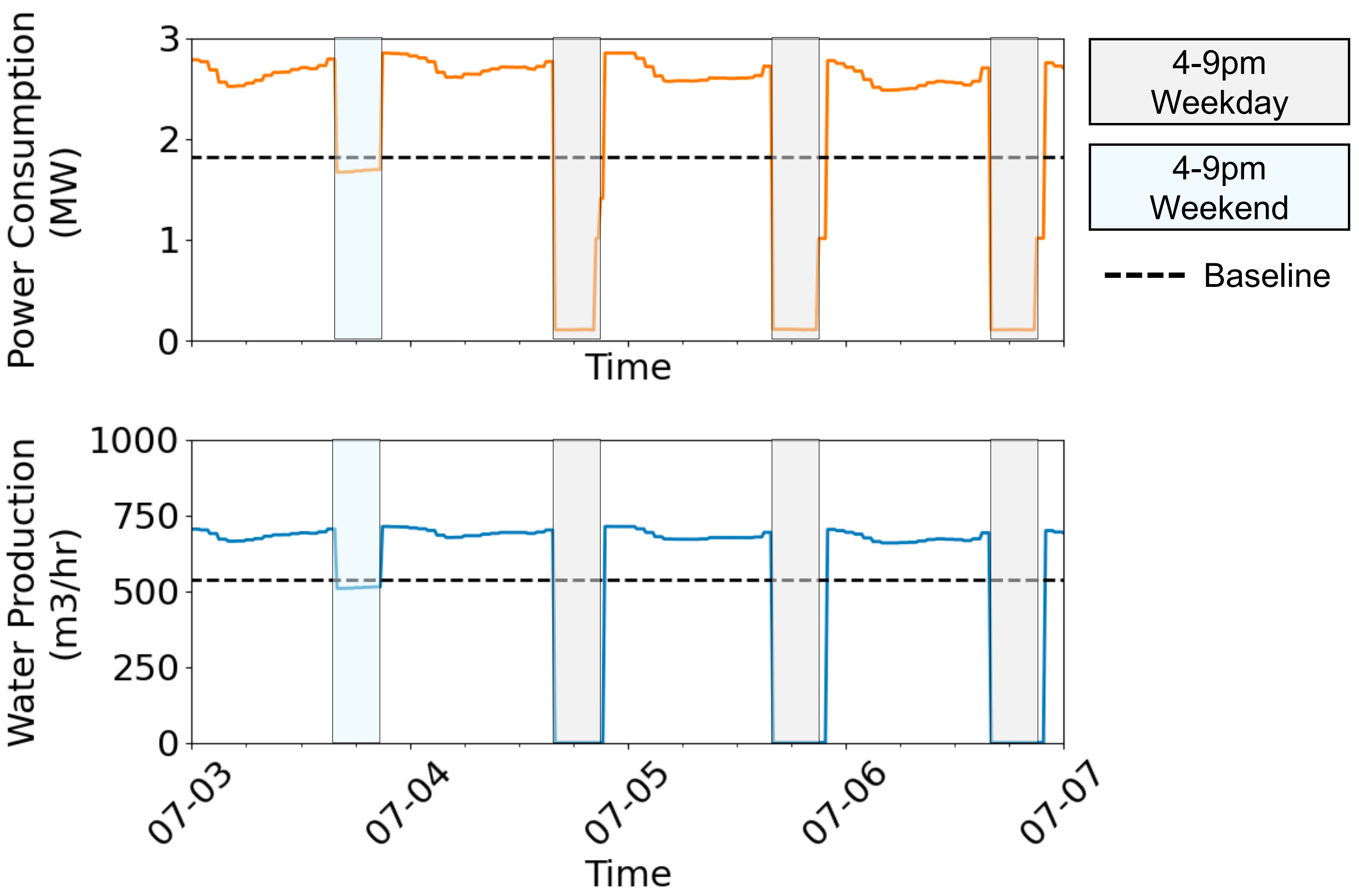

```
solver = SolverFactory('mindtpy') results =
solver.solve(model,
                     strategy='OA',
                     mip_solver='gurobi',
                     nlp_solver='ipopt')
```

Model resolves key features of a facility shut down event



D. Bernal et al. (2018). *Computer Aided Chemical Engineering.*
M. A. Duran & I. E. Grossman (1968). *Mathematical Programming.*

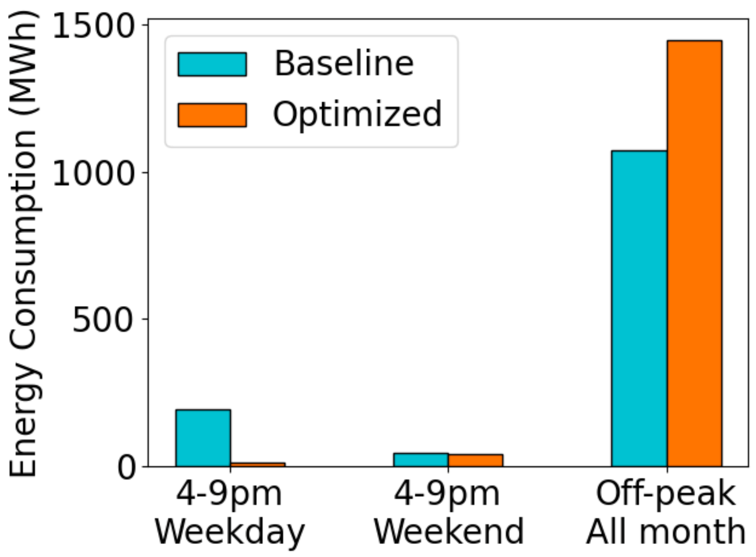
Optimize plant operations for a monthly energy bill



Minimize: Monthly cost

Subject to:

- Facility dynamics
- Monthly water production
- 15-min time steps over 31 days
- $100/ton cost of carbon

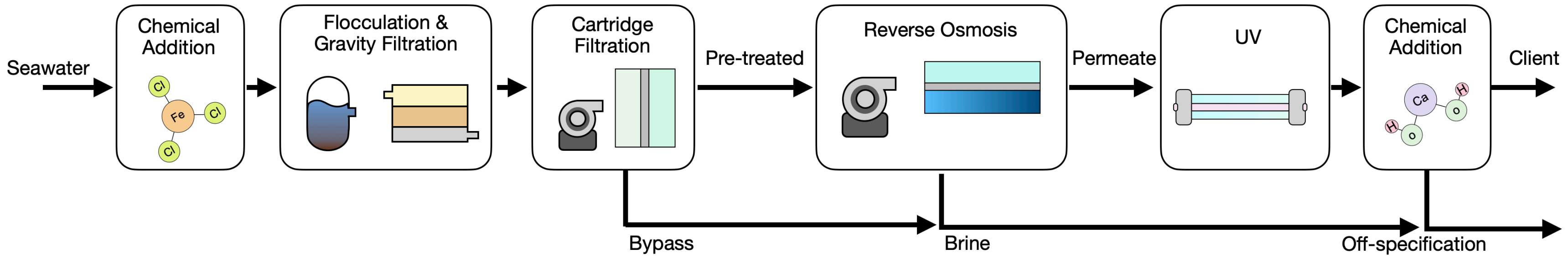


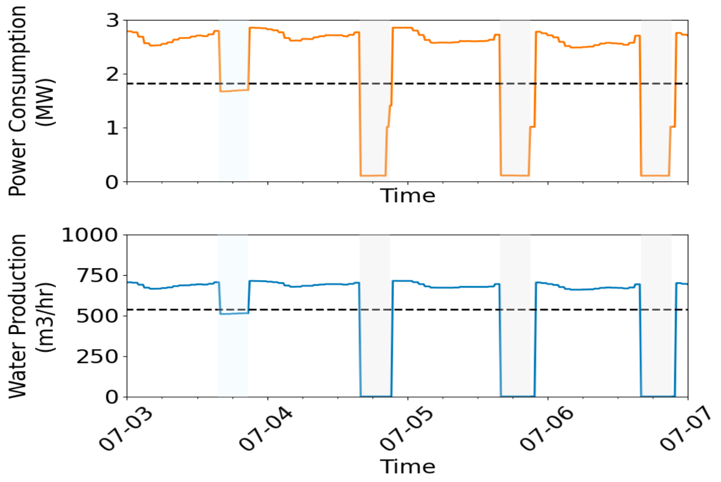
Model projects over 18% cost savings relative to baseline

Flexible formulation enables scenario analysis

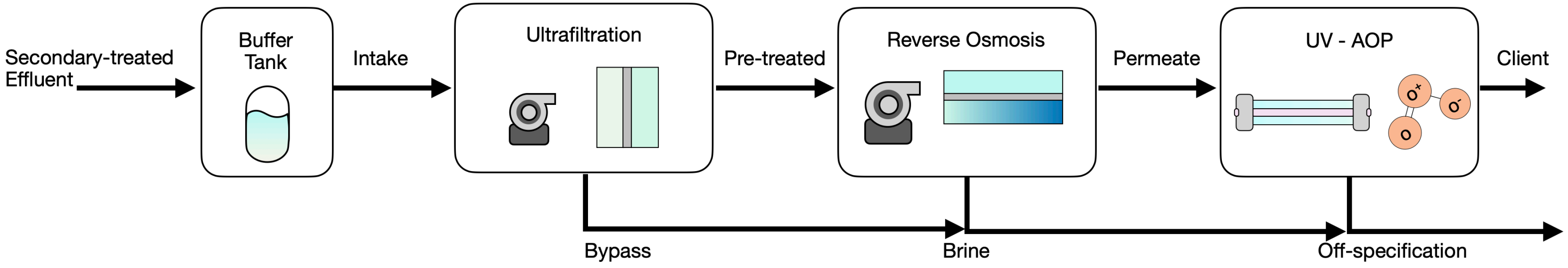
On-Peak
Mid-Peak
Off-Peak
Baseline

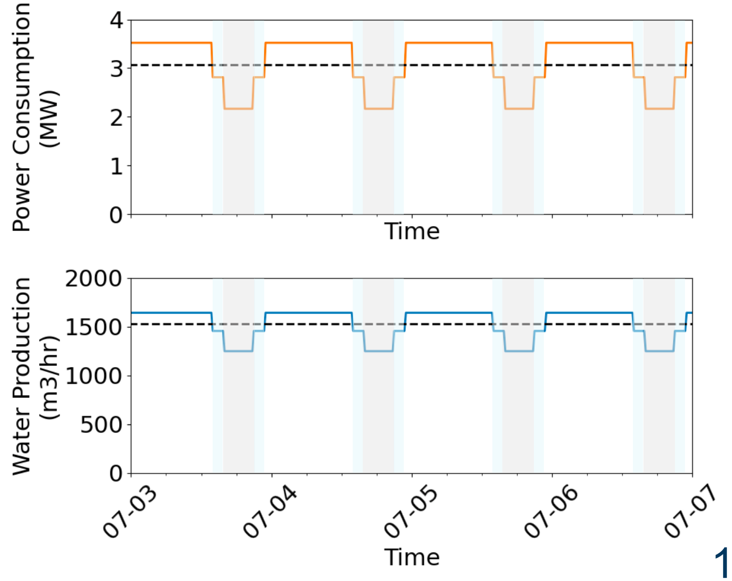
Seawater Desalination – Santa Barbara, CA (existing)





Indirect Potable Water Reuse – San Jose, CA (hypothetical)





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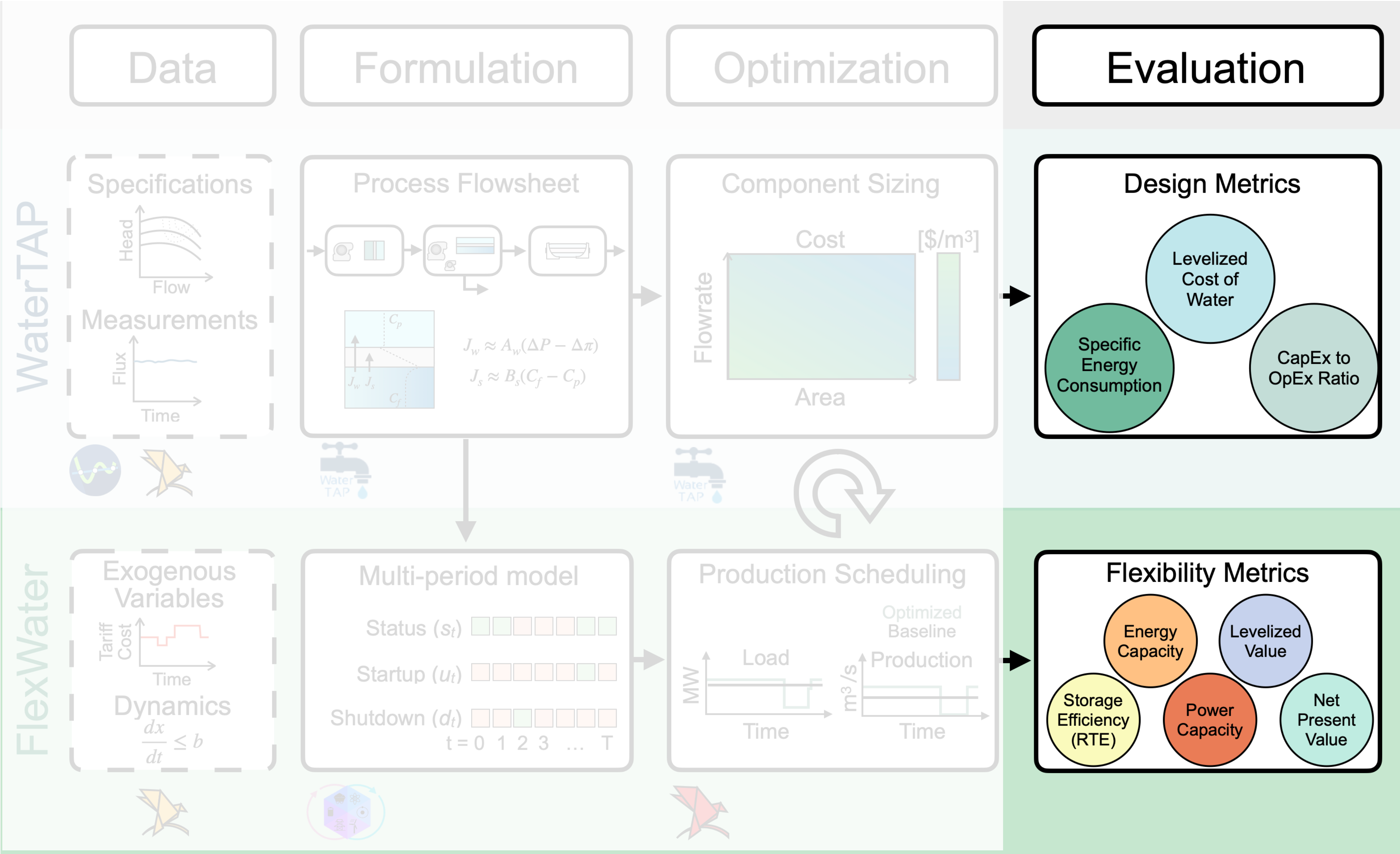
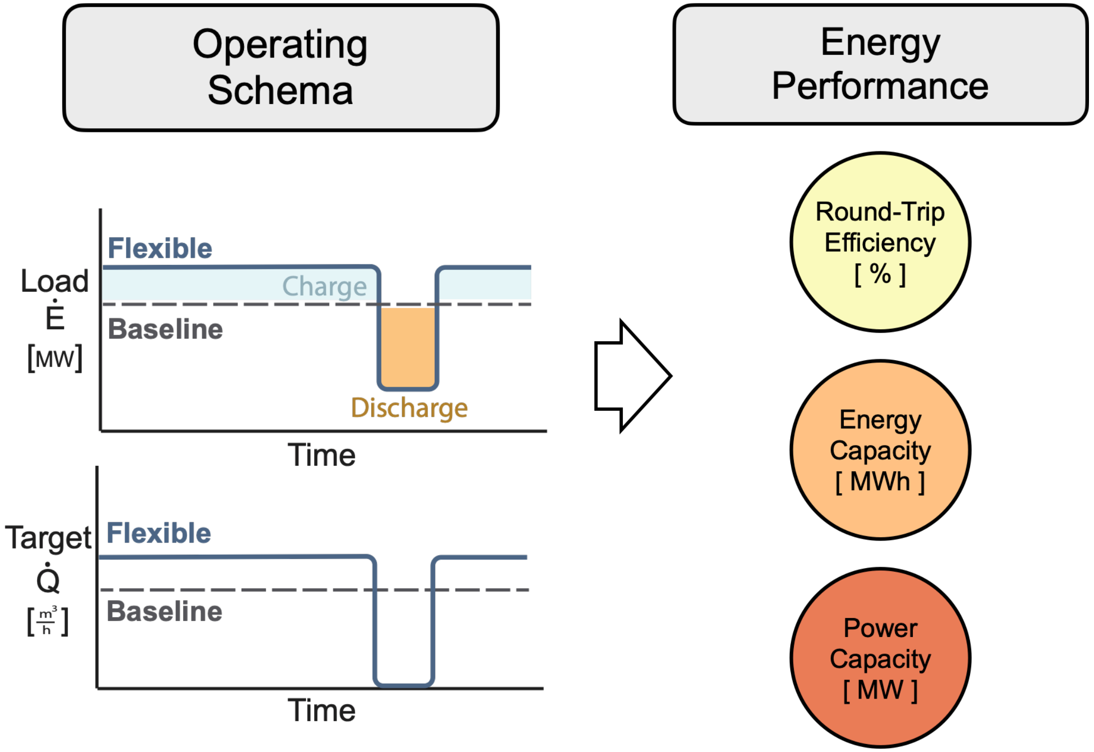
A framework for optimizing & valuing energy flexibility



Interactive web-app

Technoeconomic analysis for dynamic operations

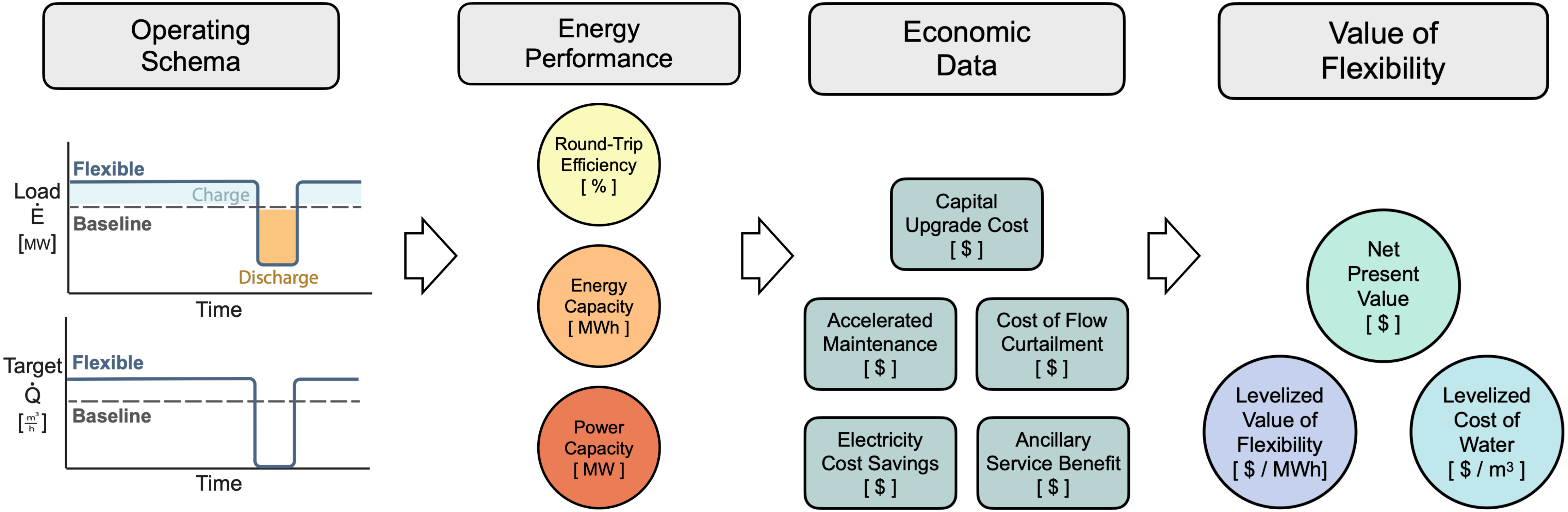


How efficient is the flexibility mechanism?

How much energy is shed/discharged?

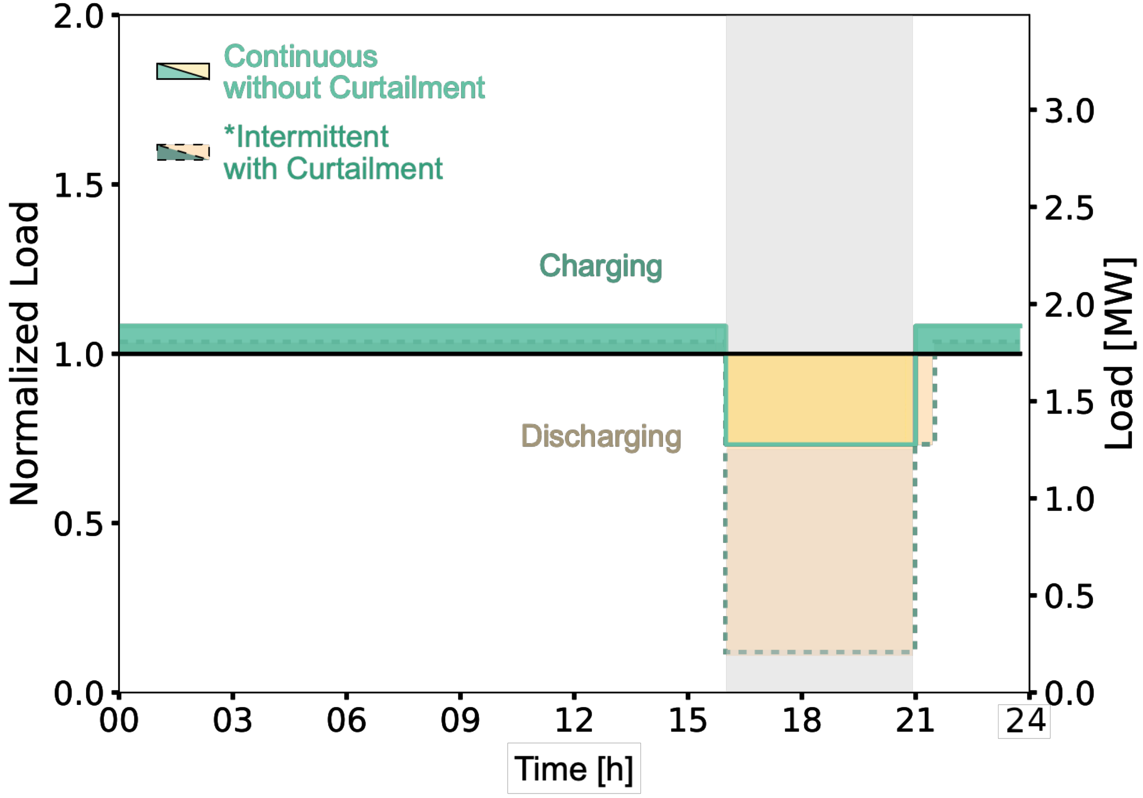
How fast can the facility shed this energy?

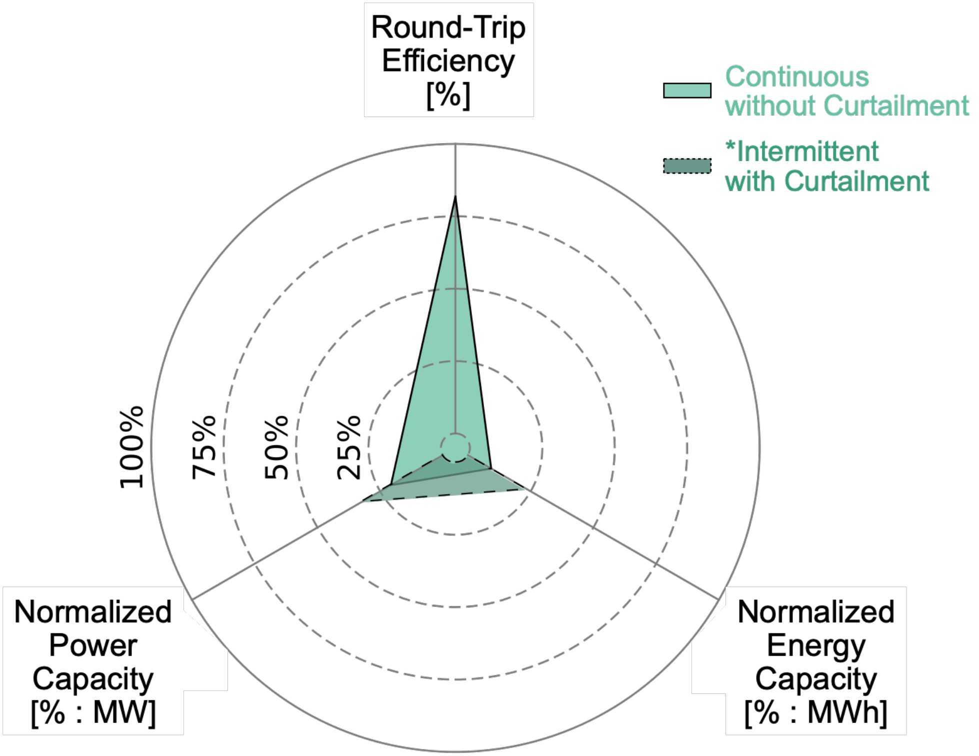
Technoeconomic analysis for dynamic operations



Rao, A., Bolorinos, J., Musabandesu, E., Chapin, F.T., Mauter, M.S. (2024). *Nature Water.*

Operationalizing Energy Flexibility Performance Metrics





Desalination systems can operate continuously with variable recovery for high round-trip efficiency or operate intermittently by shutting down during peak hours to increase load shifting capacity

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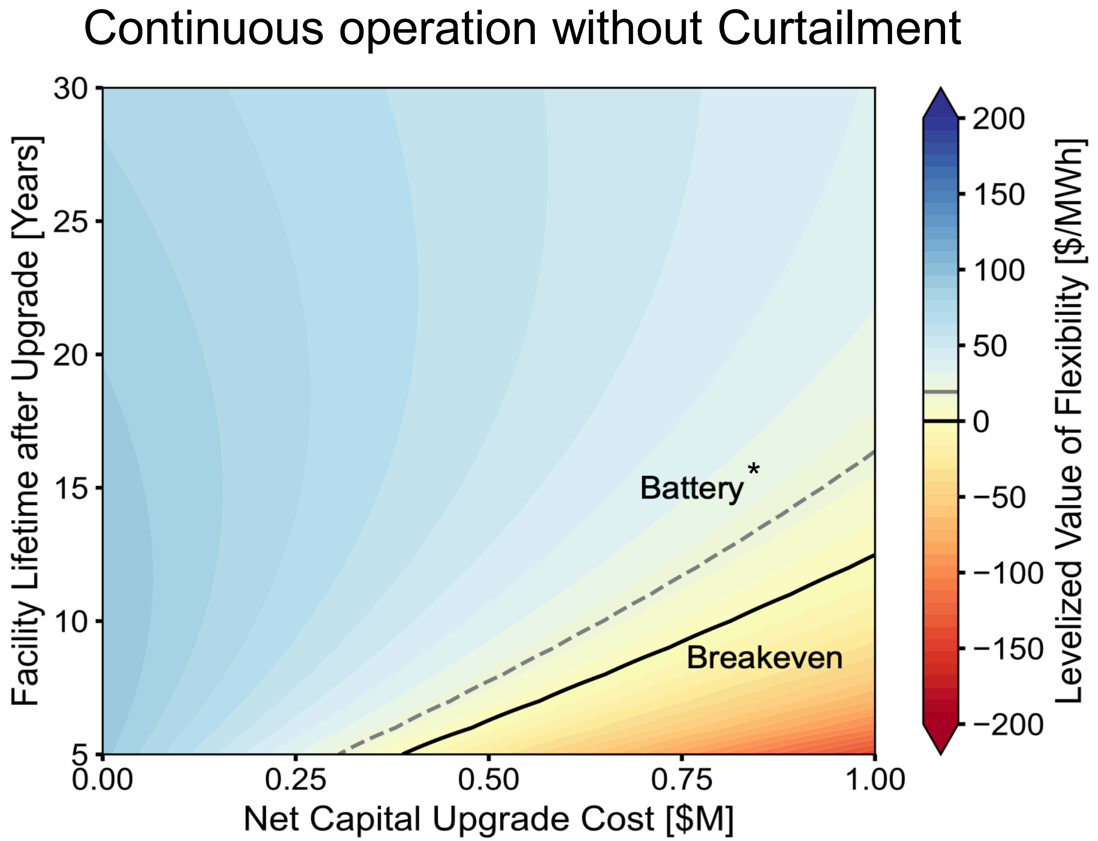
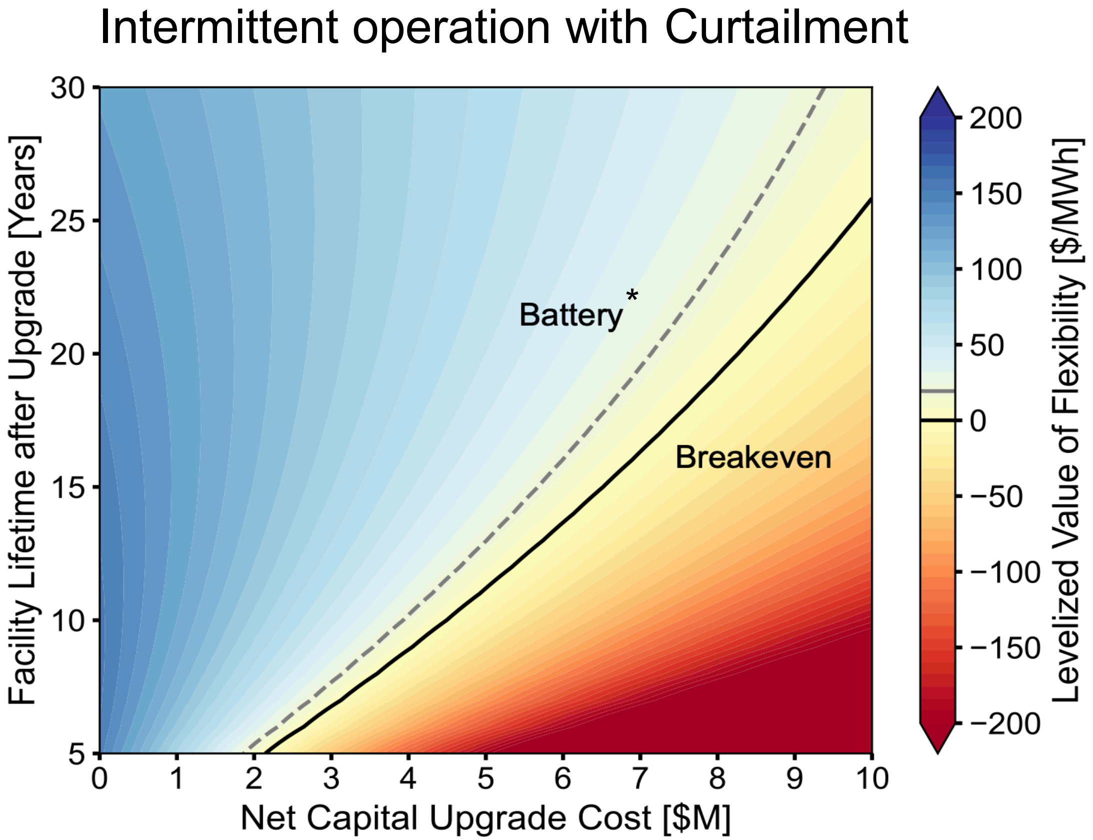
*Round-trip Efficiency is not defined for cases with non-zero curtailment
Base case is represented by a Summer utility tariff structure from SBCE (Santa Barbara)

Capital cost and facility age determine value

How much can a plant afford to spend to upgrade for flexibility?





*The battery is modeled at 1-Load Hour Equivalent and $450/kW CapEx

*Case study assumes SBCE tariff structure

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Rao, A., Bolorinos, J., Musabandesu, E., Chapin, F.T., Mauter, M.S. (2024). *Nature Water.*

Ongoing Work


Carson Tucker

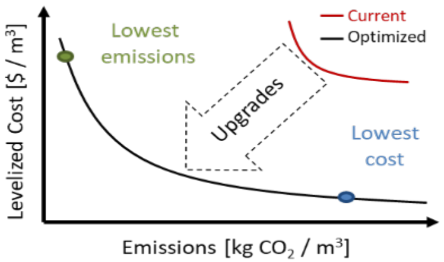

Adhithyan Sakthivelu


Fletcher T. Chapin

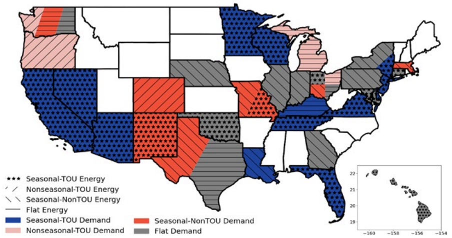
Facility Design

How do we (re) design infrastructure to maximize the benefits of flexibility?

Facility Design Changes

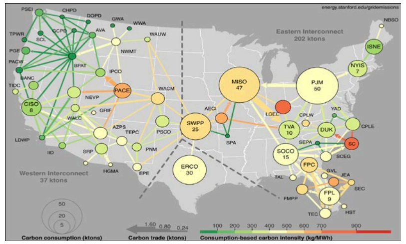


Industrial Tariffs



Chapin et al., (2024). *Scientific Data.*

Grid emissions factors

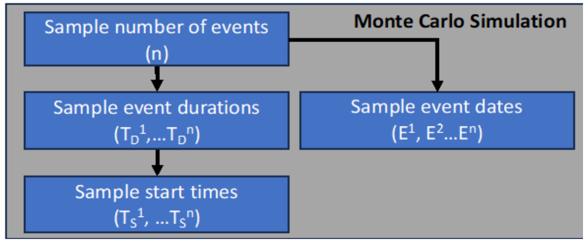


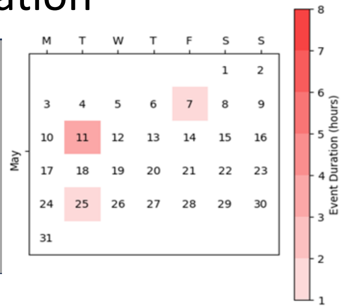
de Chalendar et al., (2019). *PNAS.*

Demand Response (DR)

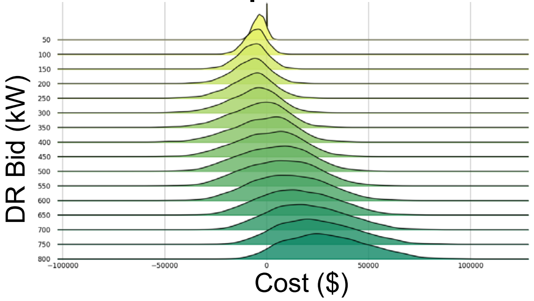
What is the value of DR and how should desalination plants bid into uncertain markets?

Event Simulation





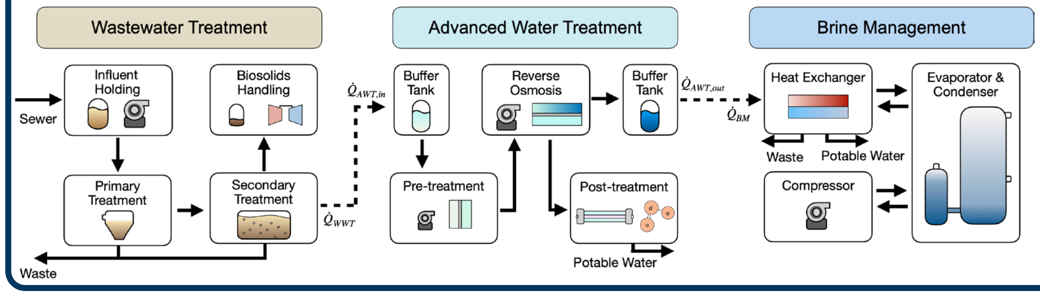
Robust Optimization

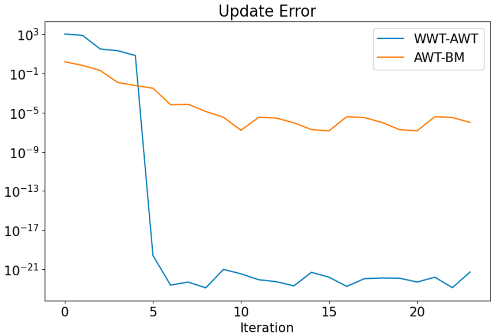


Multi-system Coordination

How does energy flexibility at a facility impact the rest of the network?

Optimization decomposition





Acknowledgements

Please reach out with questions!
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NATIONAL ENERGY TECHNOLOGY LABORATORY

SLAC

Tim Bartholomew
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Marcus Holly
Radhakrishna Gooty

Alex Dudchenko

NAWI

City of SANTA BARBARA

U.S. DEPARTMENT OF ENERGY

Stanford University

WE³ lab

Additional Slides

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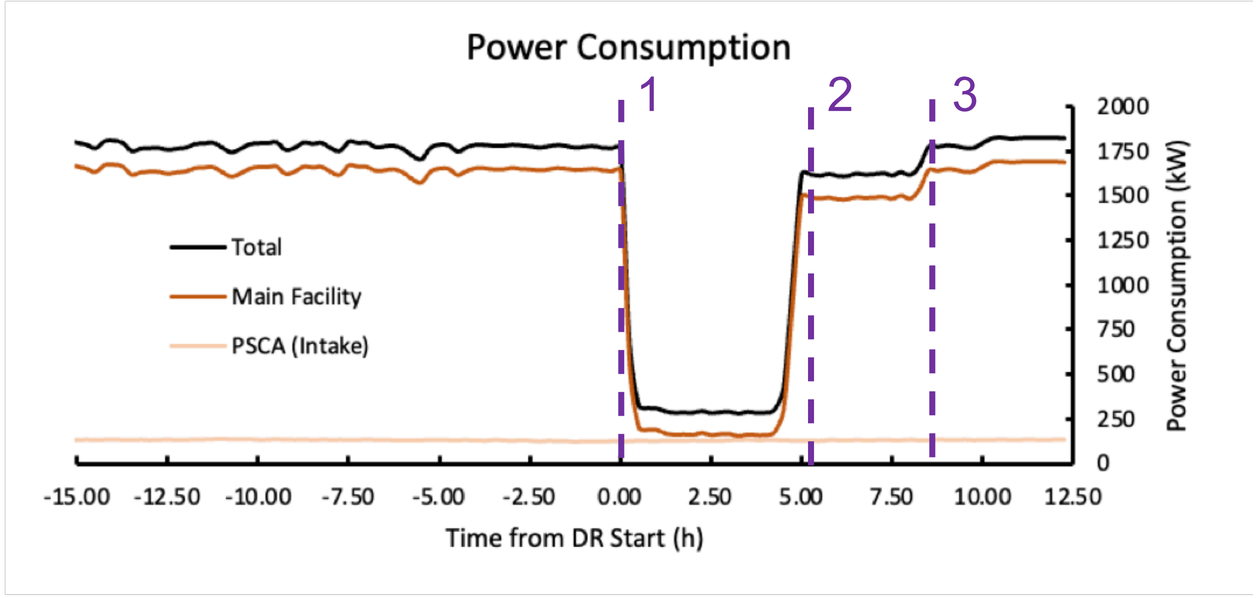
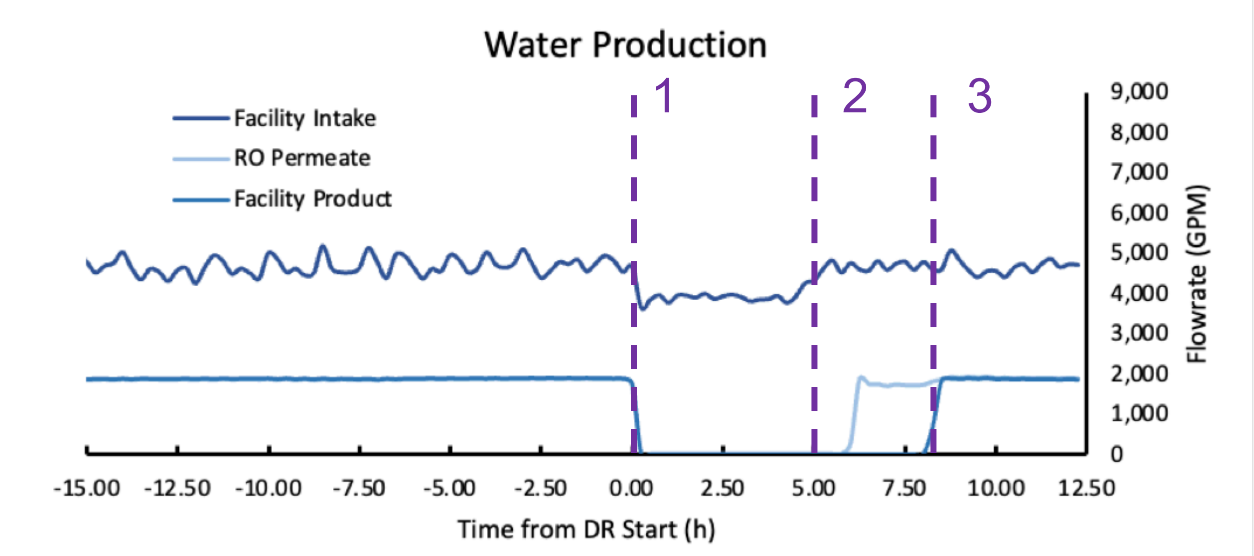
Multi-timestep dynamics: capturing downstream delays





Rao, A.K. et al. (2024). *Under Review.*

Post-treatment stabilization is modeled using a time delay with linear constraints

Shift Matrix ($\tau = 1$) $S_\tau \in \{0,1\}^{T\times T}$ | Start-up $u \in \{0,1\}^T$ | Stabilization $\zeta \in \mathbb{R}^T$

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ & & & \ddots & 0 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

$$\dot{Q}_{product} = (1 - \zeta)\,\dot{Q}_{permeate}$$

1. Facility shuts down
2. RO turns on
3. Permeate quality is stable