Optimal Schedule, Design, and Operation of Solid Oxide Electrolysis Cell Systems Accounting for Long-Term Performance and Health Degradation

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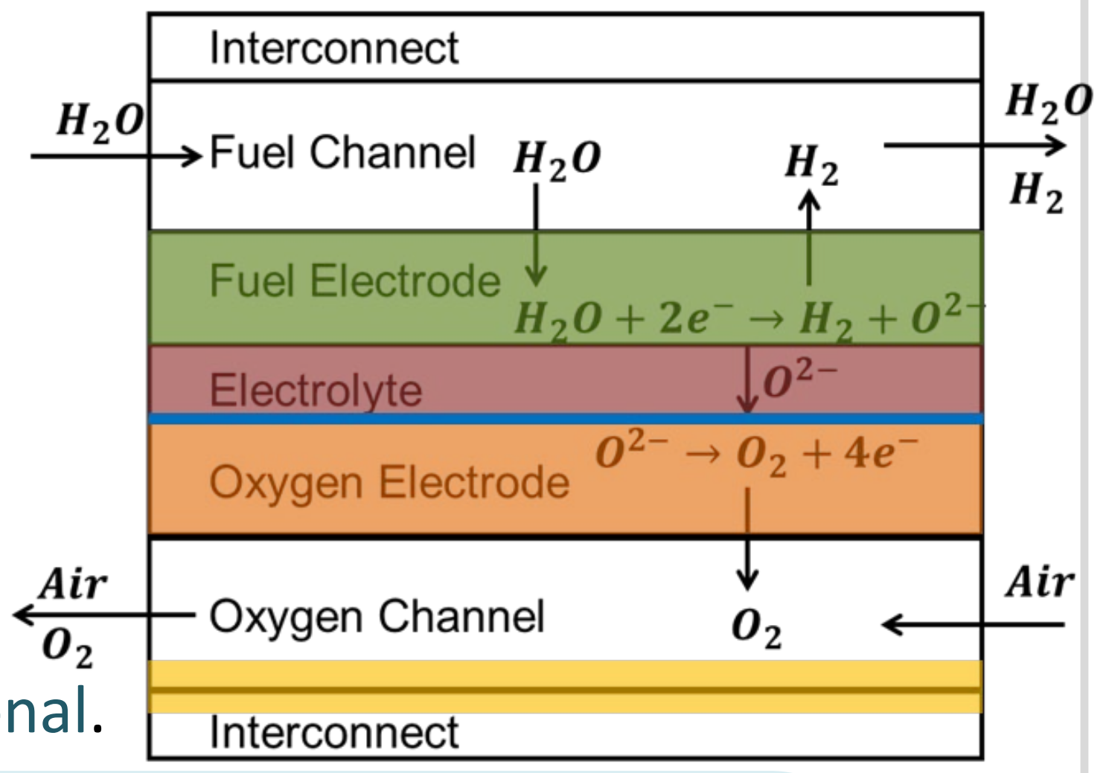
Background

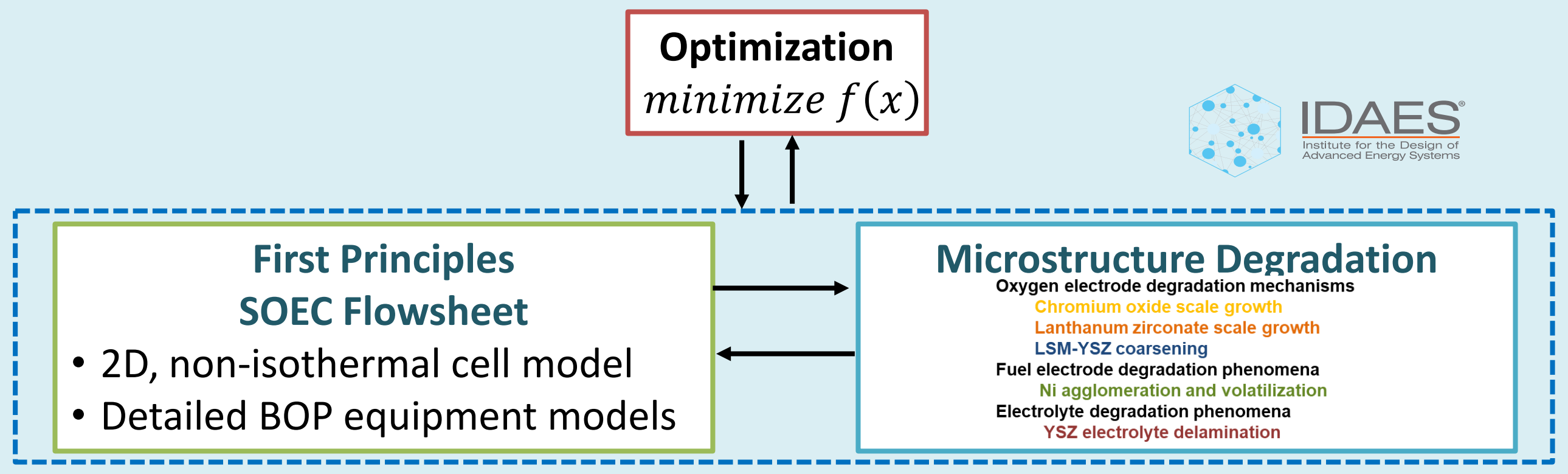
Solid-Oxide Cells (SOC) produce H_2 through steam electrolysis at high theoretical efficiency and low direct emissions.

Slow microstructure degradation phenomena decrease efficiency and can require premature replacement of the SOC.

Reducing degradation is often considered a materials design problem, rather than operational.



Combatting degradation through long-term optimization



Optimization
$minimize\ f(x)$

First Principles SOEC Flowsheet
- 2D, non-isothermal cell model
- Detailed BOP equipment models

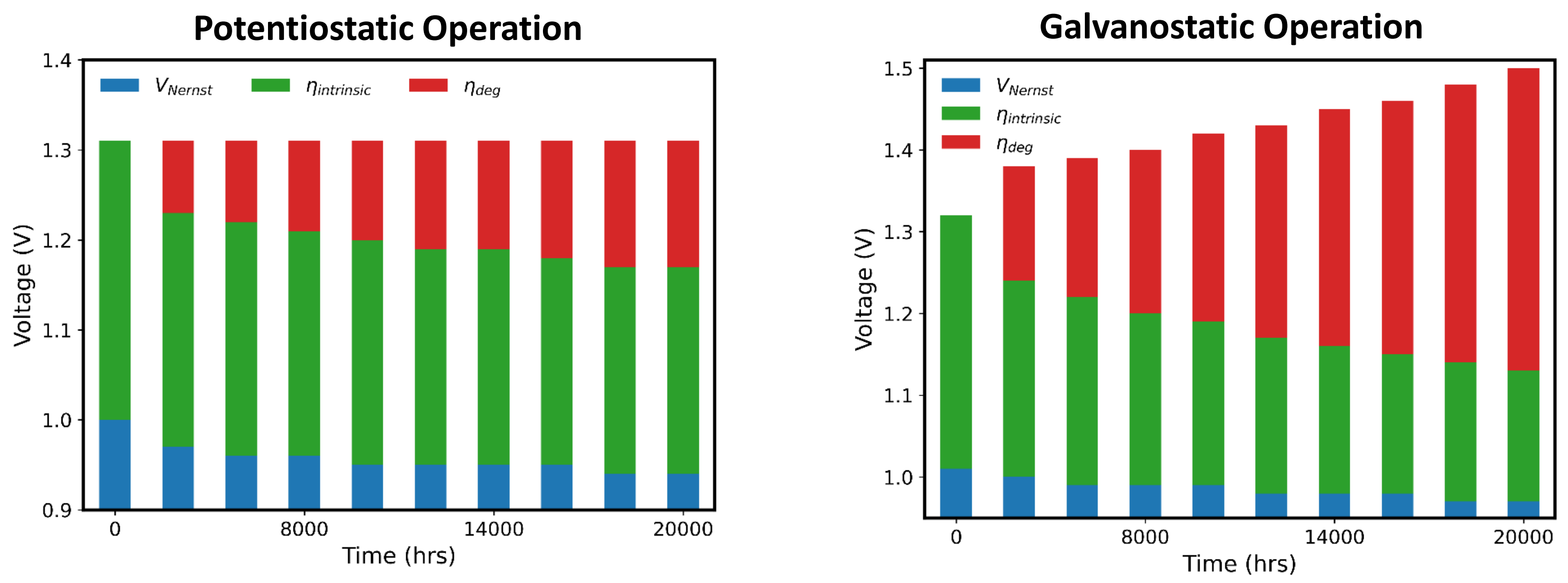
Microstructure Degradation
Oxygen electrode degradation mechanisms
Chromium oxide scale growth
Lanthanum zirconate scale growth
LSM-YSZ coarsening
Fuel electrode degradation phenomena
Ni agglomeration and volatilization
Electrolyte degradation phenomena
YSZ electrolyte delamination

Long-term Performance Degradation

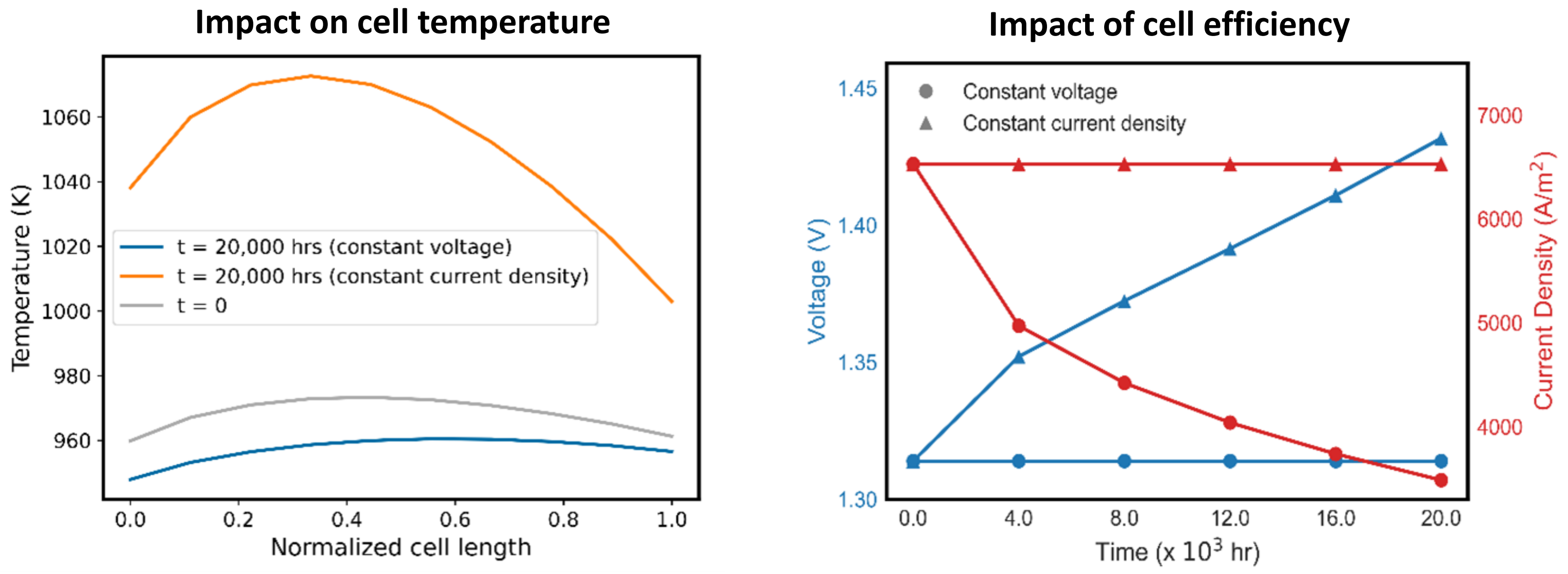
Voltage losses increase the required voltage for electrolysis

$$V_{cell} = \underbrace{V_{Nernst}}_{\text{Thermodynamic Minimum}} + \underbrace{\eta_{activation} + \eta_{Ohmic}}_{\text{Intrinsic Losses}} + \underbrace{\eta_{degradation}}_{\text{Degradation Losses}}$$

Distribution of degradation losses after 20,000 hours of degradation


Potentiostatic Operation
Galvanostatic Operation

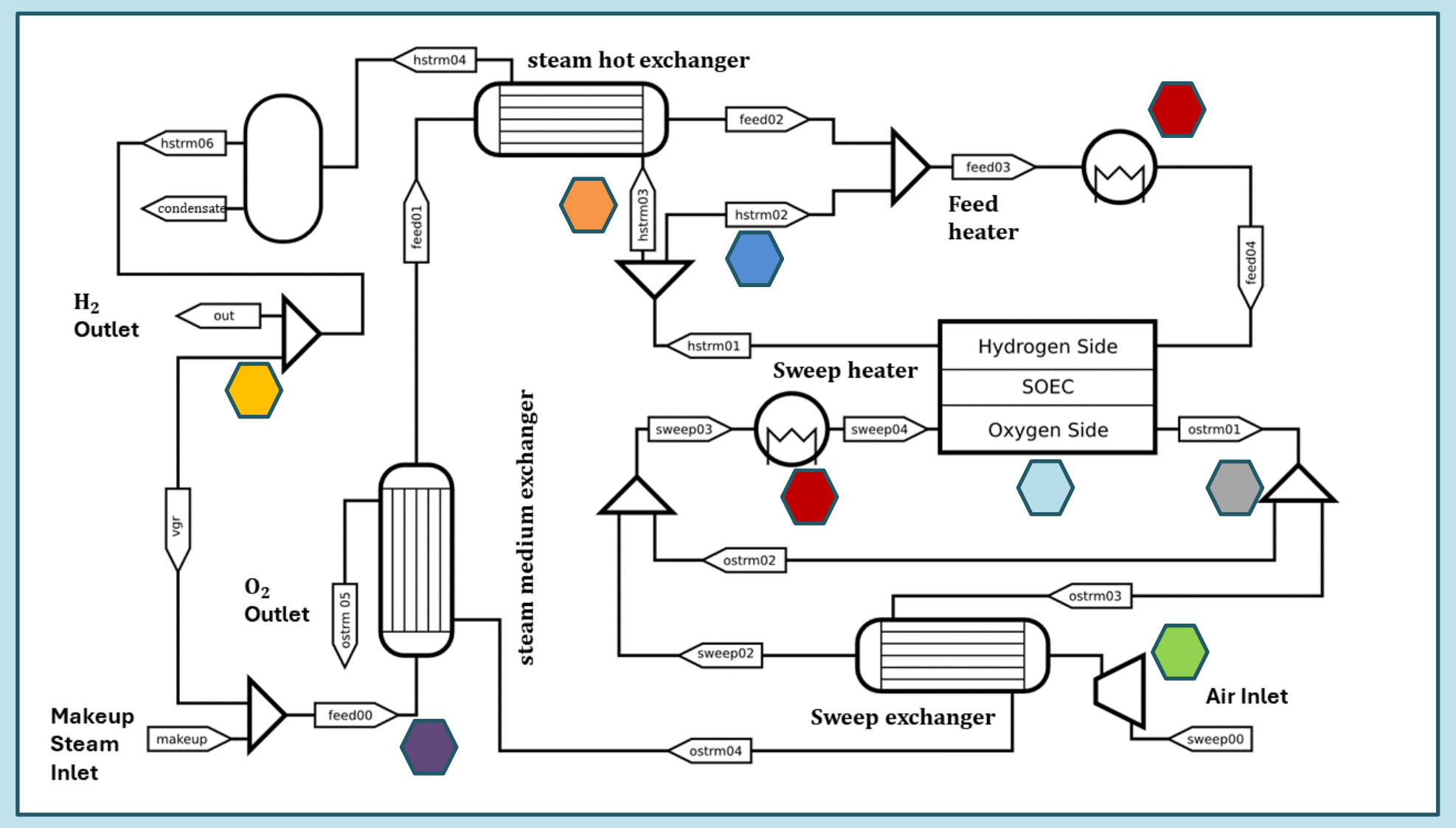
Impact of degradation on cell performance


Impact on cell temperature
Impact of cell efficiency

Operating Decisions

1. Flowsheet and cell level setpoints

Symbol	Decision Variable
⬡	Cell Potential / Current Density
⬢	Feed recycle splitter outlet H_2O mole fraction
⬢	Feed/ Sweep electric heater duties
⬢	Condenser splitter recycle split fraction
⬢	Feed medium exchanger inlet flowrate
⬢	Feed recycle splitter split fraction
⬢	Sweep recycle splitter split fraction
⬢	Sweep blower molar flowrate



Cell degradation impacts the operation of the Balance of Plant (BOP) and decreases system efficiency.

2. Choice of long-term operating mode

Potentiostatic (Constant Voltage)

Galvanostatic (Constant H_2 Production)

Flexible

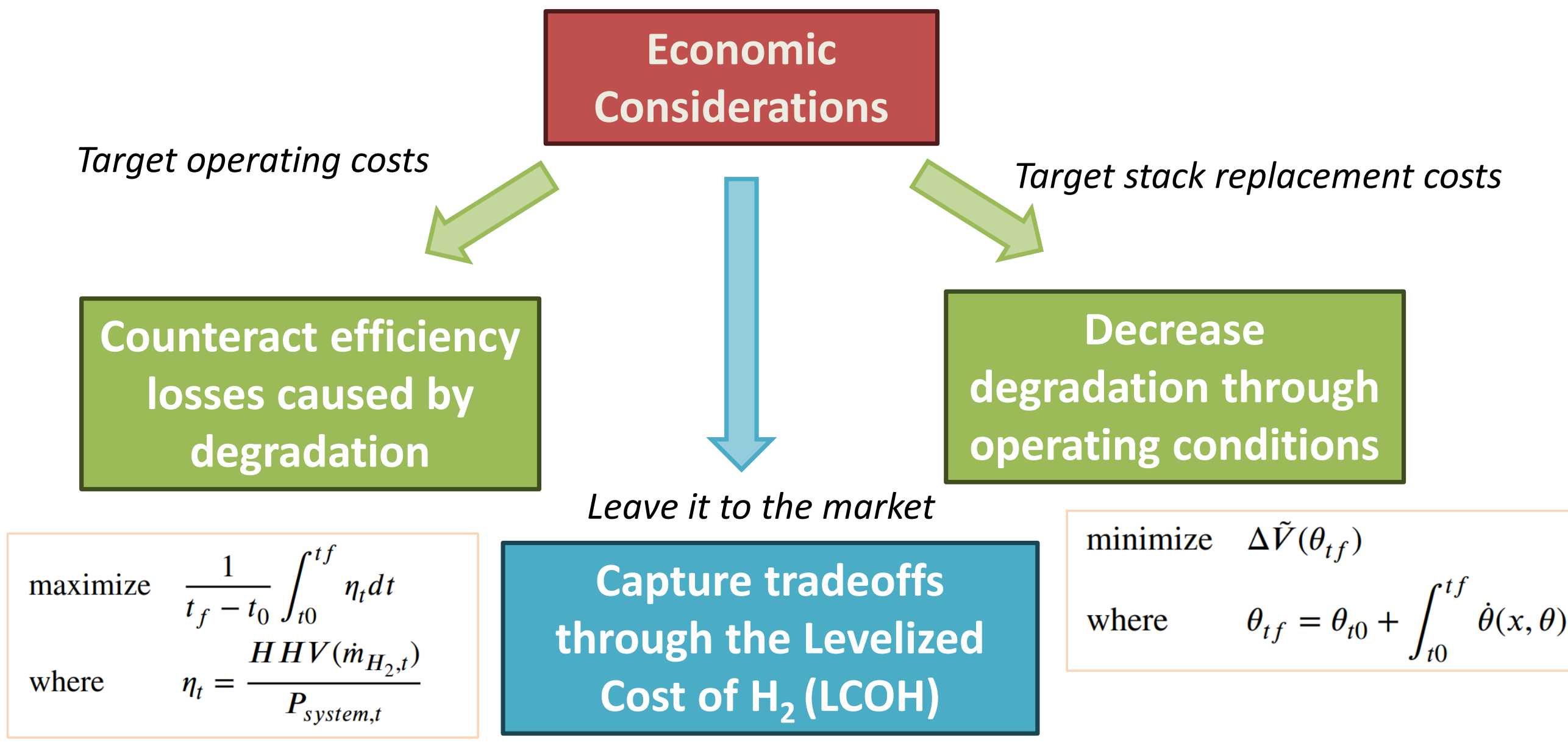
A flexible mode of operation allows both potential and current density to vary simultaneously.

3. Selection of replacement schedule

$$CAPEX = CC_{BOP} + n_{stack}CC_{Stack}$$

Efficiency loss due to degradation can be counteracted by more frequent stack replacements.

Optimization Formulation



Economic Considerations

Target operating costs

Target stack replacement costs

Counteract efficiency losses caused by degradation

Leave it to the market

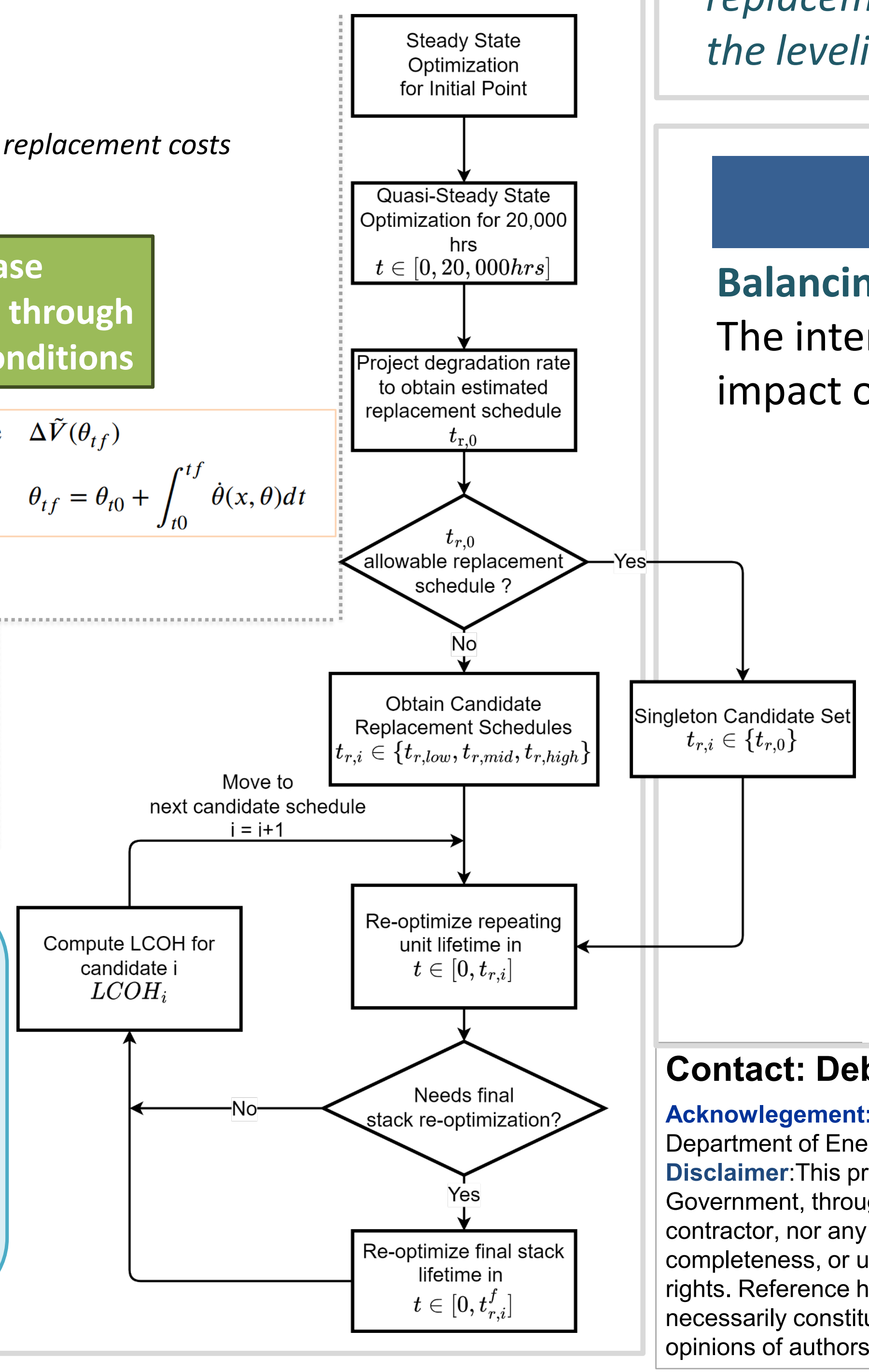
Decrease degradation through operating conditions

Capture tradeoffs through the Levelized Cost of H_2 (LCOH)

$$\text{maximize} \quad \frac{1}{t_f - t_0}\int_{t0}^{tf} \eta_t dt \qquad \text{where} \quad \eta_t = \frac{HHV(\dot{m}_{H_2,t})}{P_{system,t}}$$

$$\text{minimize} \quad \Delta\tilde{V}(\theta_{tf}) \qquad \text{where} \quad \theta_{tf} = \theta_{t0} + \int_{t0}^{tf} \dot{\theta}(x,\theta)dt$$

$$\text{minimize} \quad LCOH$$
$$\text{where} \quad LCOH = \frac{CRF\left(CC_{BOP} + \sum_{i=1}^{R} CC_{stack}FP_i\right) + OC + EC}{m_{H_2,\text{lifetime}}}$$



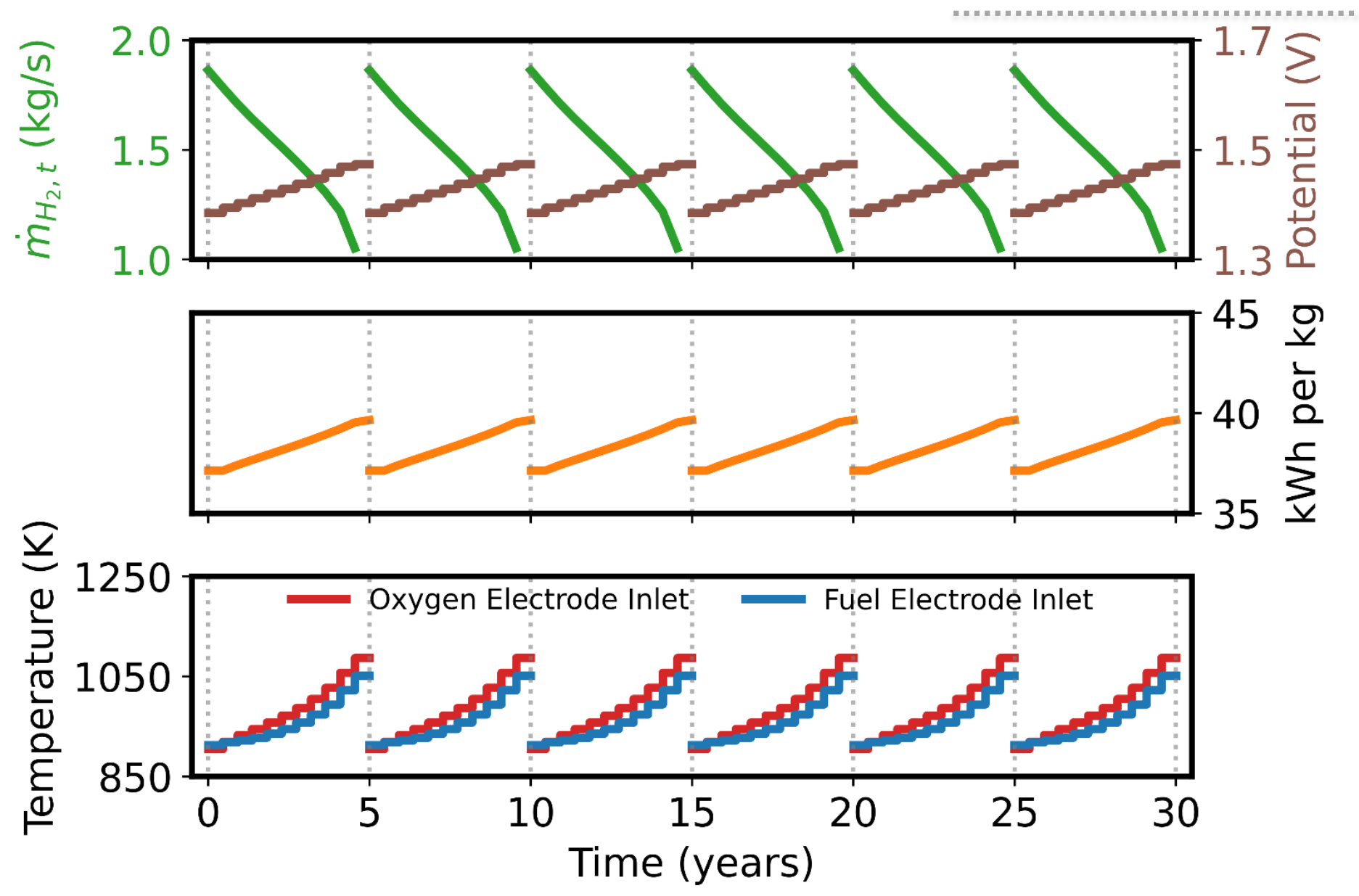
Algorithm to determine optimal replacement schedule

- Re-optimize stack for different candidate replacement schedules, in parallel.
- Avoids binary decision variables.
- Stacks replaced when $\Delta\tilde{V}_{deg} > 50\%$.
- NLP subproblems solved using IPOPT.

Selected Operating Schedules

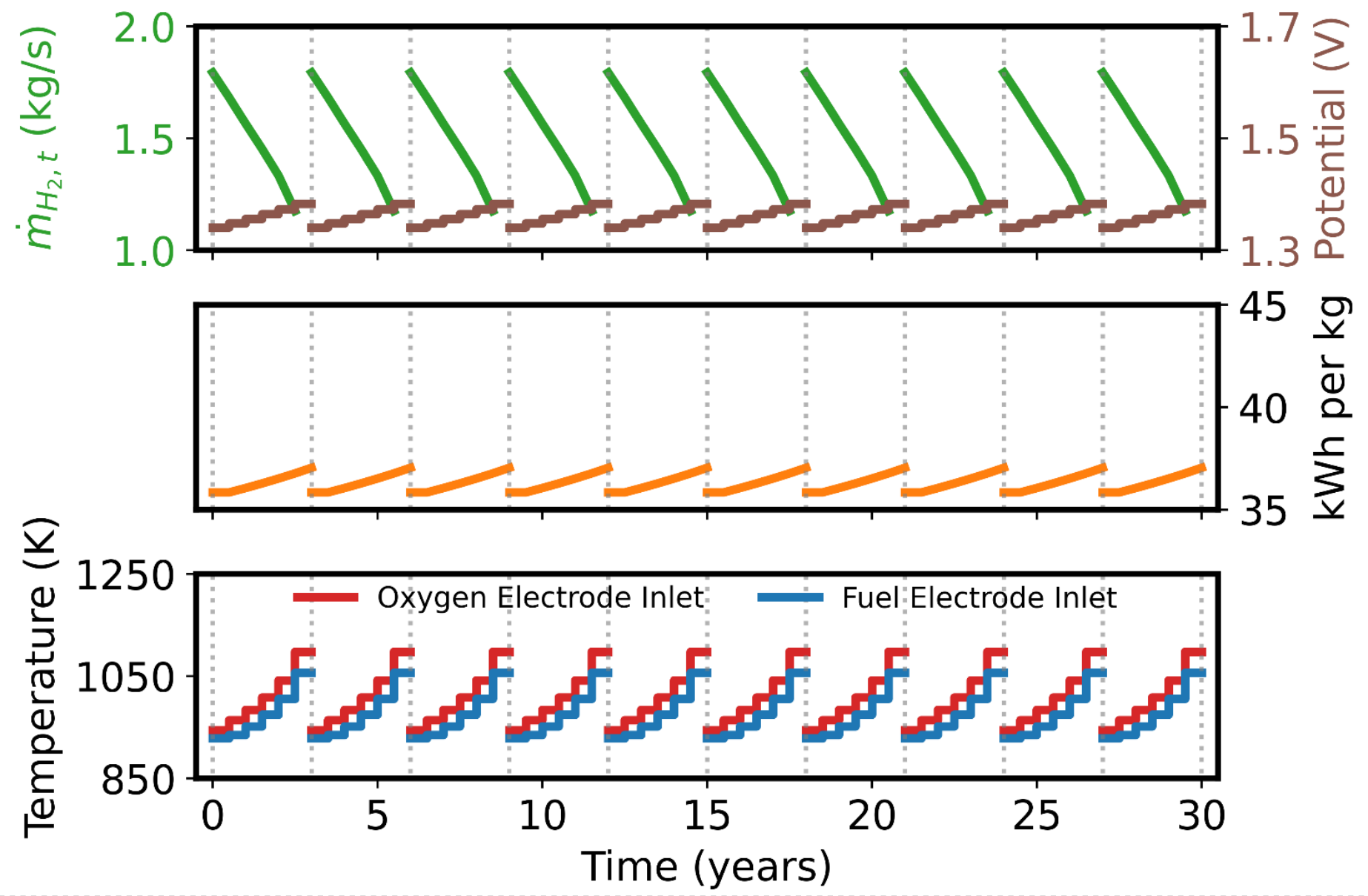
Electricity Price = 0.03 \$/kWh

Replacement time = 5 years
Sp. Energy Consumption = 38.0 $\frac{kWh}{kg\ H_2}$
Degradation rate = 3% /khr



Favor conservative operation

Stack replacement costs are dominant in the LCOH in markets with low energy costs



Electricity Price = 0.3 \$/kWh

Replacement time = 3 years
Sp. Energy Consumption = 35.8 $\frac{kWh}{kg\ H_2}$
Degradation rate = 4% /khr

Favor aggressive operation

Energy costs are dominant in the LCOH in markets with high energy costs

Given electricity market information, this method automatically derives optimal replacement schedules and operating changes within a stack lifetime that minimize the levelized cost of H_2 (LCOH).

Takeaways

Balancing tradeoffs

The interplay of short-term efficiency and long-term degradation has a significant impact on the cost of H_2 production by an SOEC system.

Two distinct consequences of degradation

- Cell degradation impacts both system efficiency and cell thermals.
- Higher temperatures induced by degradation result in accelerated degradation rates and premature failure due to thermal stresses.

Insights from Optimization

- Combatting degradation is both a materials design and an operational optimization problem.
- The tradeoff between efficiency and replacement frequency is captured through the LCOH.
- Flexible long-term operating mode can result in lower LCOH when compared to traditional galvanostatic and potentiostatic operation.

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