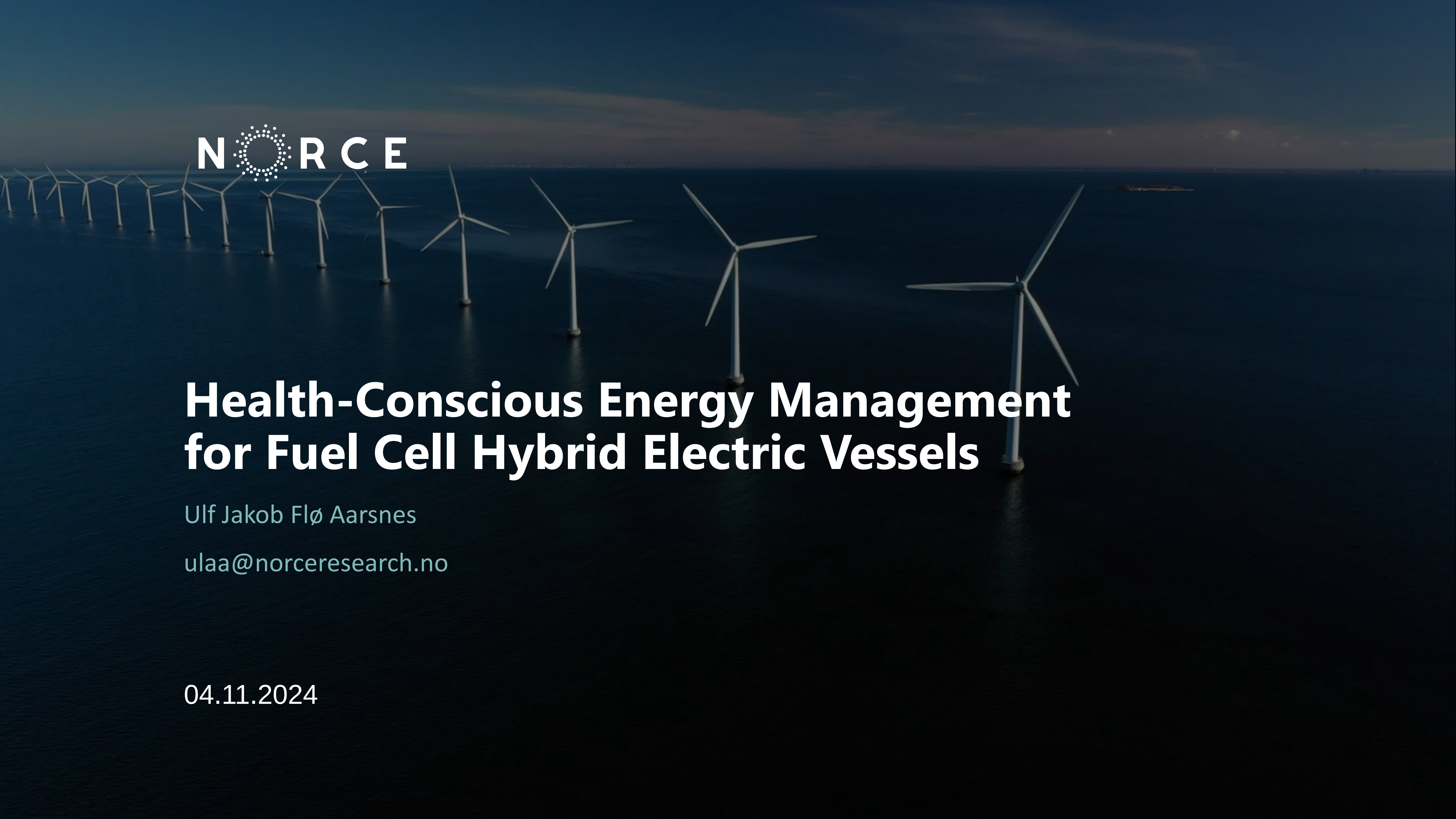

Health-Conscious Energy Management for Fuel Cell Hybrid Electric Vessels

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04.11.2024

- Problem statement
- Case 1: Known demand optimization
- Case 2: Unknown demand

- **Problem statement**
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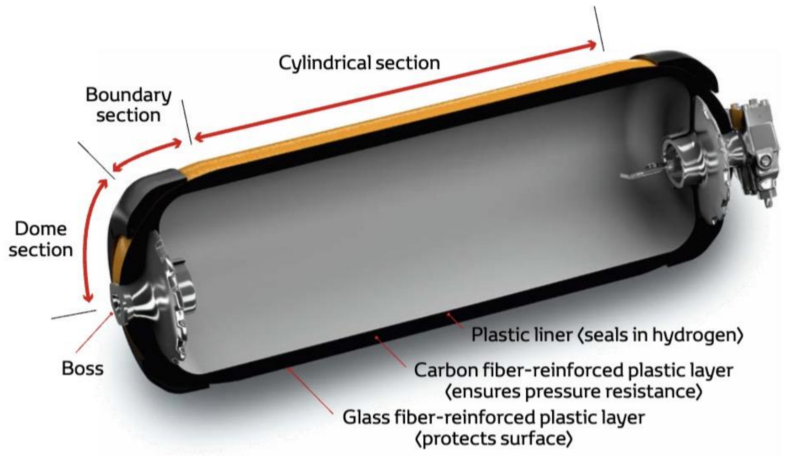
Why Use Fuel Cells?

1. Higher energy and power density than batteries

2. Shorter Refueling/Recharging Time



Downsides of fuel cells

1. Inefficient at certain loads

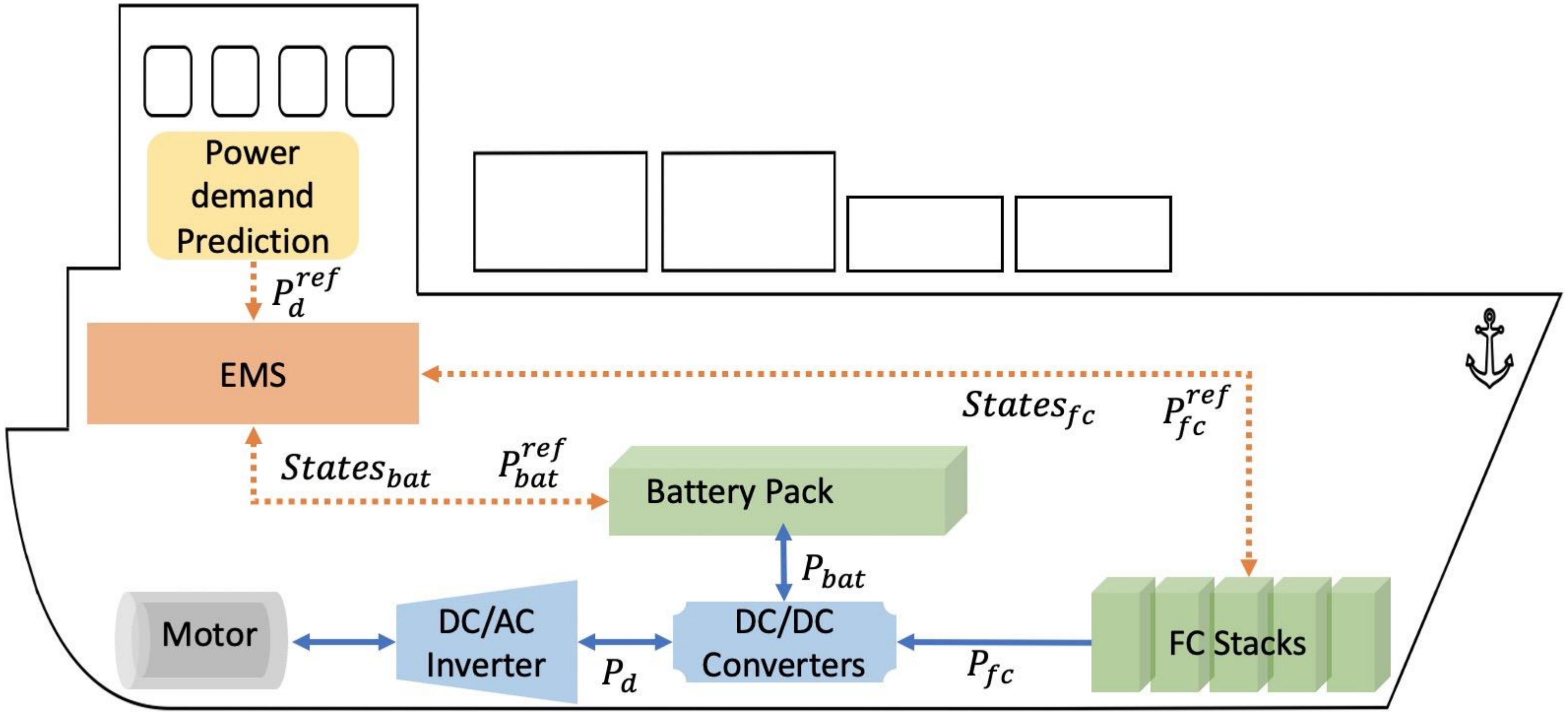
2. Not good at handling transient loads

Problem Statement:

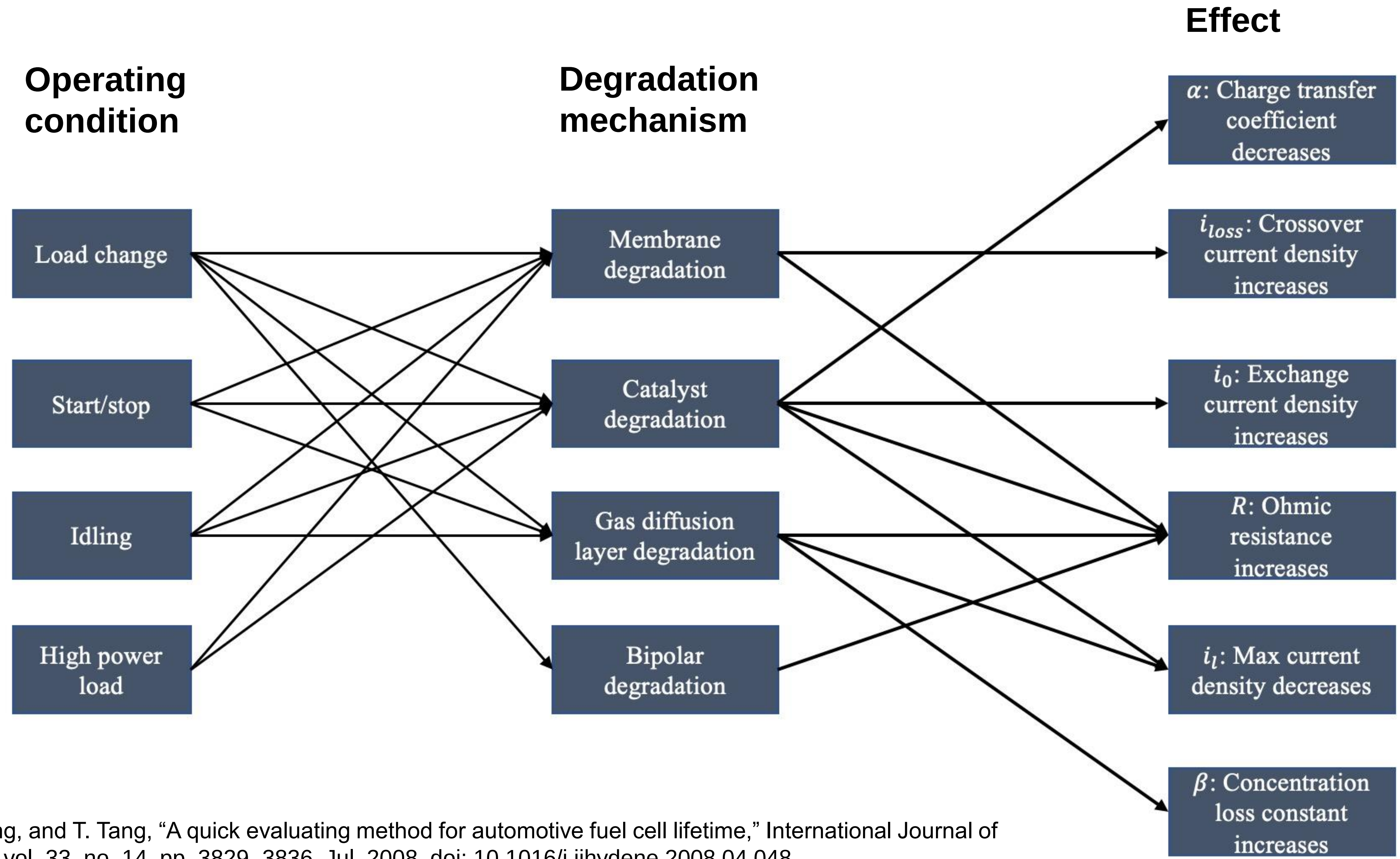
We want an Energy Management System to minimize total cost:

1. Hydrogen fuel consumption
2. Fuel Cell Degradation
3. Battery Degradation

Total Cost = **1**+**2**+**3**



1) Fuel Cell Degradation [1]:



[1] P. Pei, Q. Chang, and T. Tang, "A quick evaluating method for automotive fuel cell lifetime," International Journal of Hydrogen Energy, vol. 33, no. 14, pp. 3829–3836, Jul. 2008, doi: 10.1016/j.ijhydene.2008.04.048.

1) Fuel Cell Degradation:

- Degradation causes cell voltage drop.

"Cost of operation":

$$L_{fc} = C_{fc}\frac{\sum_i \Delta V_i}{V_{drop}^{max}}$$

Voltage drop for operation 'i'

Cost of stack replacement

End of life voltage drop

1) Fuel Cell Degradation:

- Degradation causes cell voltage drop.

“Cost of operation”:

$$L_{fc} = C_{fc} \frac{\sum_i \Delta V_i}{V_{drop}^{max}}$$

Operating condition	Drop rate
High power load	10 µV/h
Idling	8.66 µV/h
Start/stop	0.98 µV
Load change	1.79 µV/h/kW

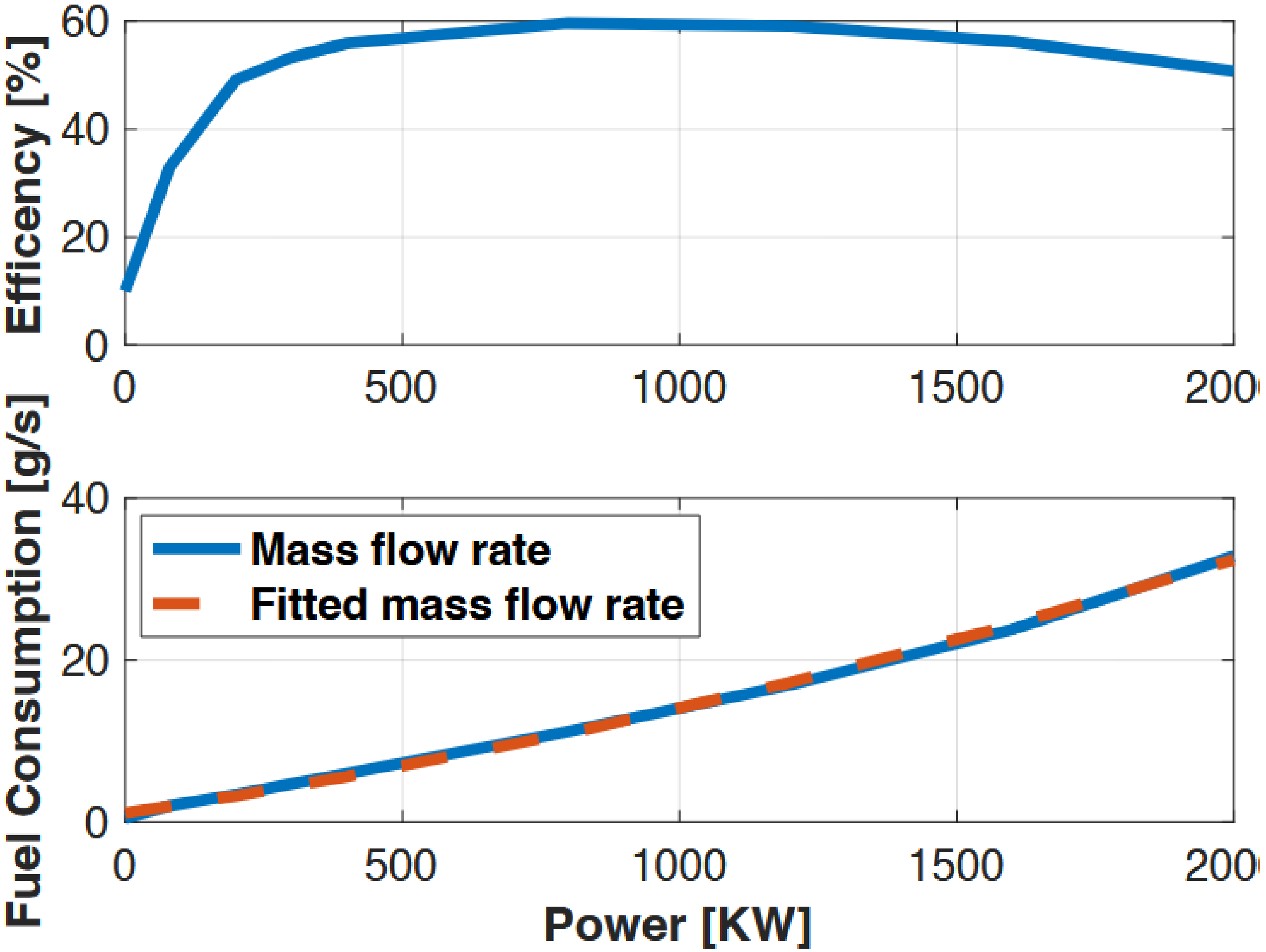
2) Fuel Cell H2 Consumption [2]:

Fuel cost:

FC power

$$\dot{m} = a_m P_{fc}^2 + b_m P_{fc} + c_m$$

Coefficients



[2] T. Markel et al., “ADVISOR: a systems analysis tool for advanced vehicle modeling,” Journal of Power Sources, vol. 110, no. 2, pp. 255–266, Aug. 2002, doi: 10.1016/S0378-7753(02)00189-1.

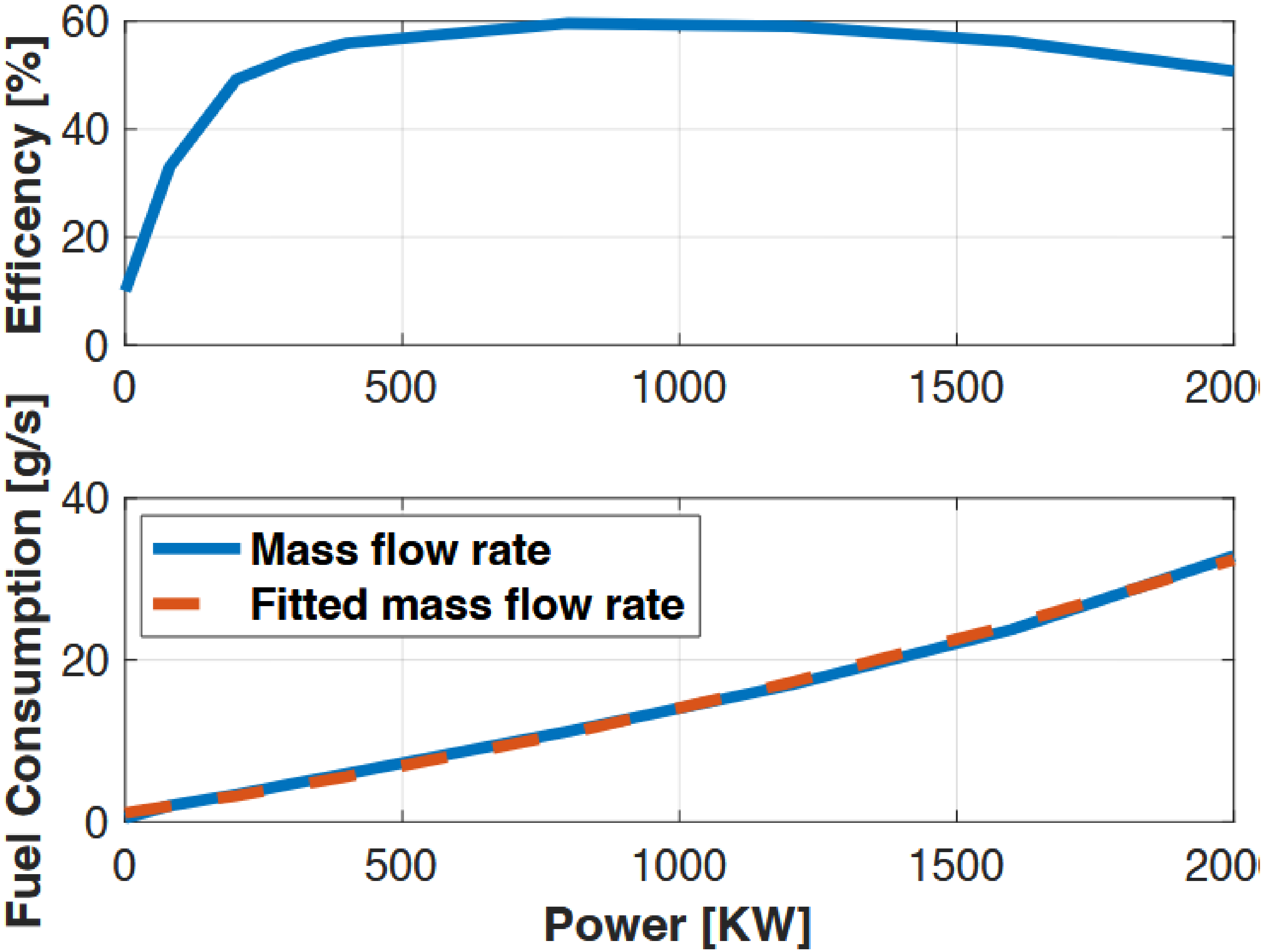
2) Fuel Cell H2 Consumption [2]:

Fuel cost:

$$\dot{m} = a_m P_{fc}^2 + b_m P_{fc} + c_m$$

$$L_{H2} = C_{H2} \dot{m}\, \Delta t$$

Hydrogen cost



[2] T. Markel et al., “ADVISOR: a systems analysis tool for advanced vehicle modeling,” Journal of Power Sources, vol. 110, no. 2, pp. 255–266, Aug. 2002, doi: 10.1016/S0378-7753(02)00189-1.

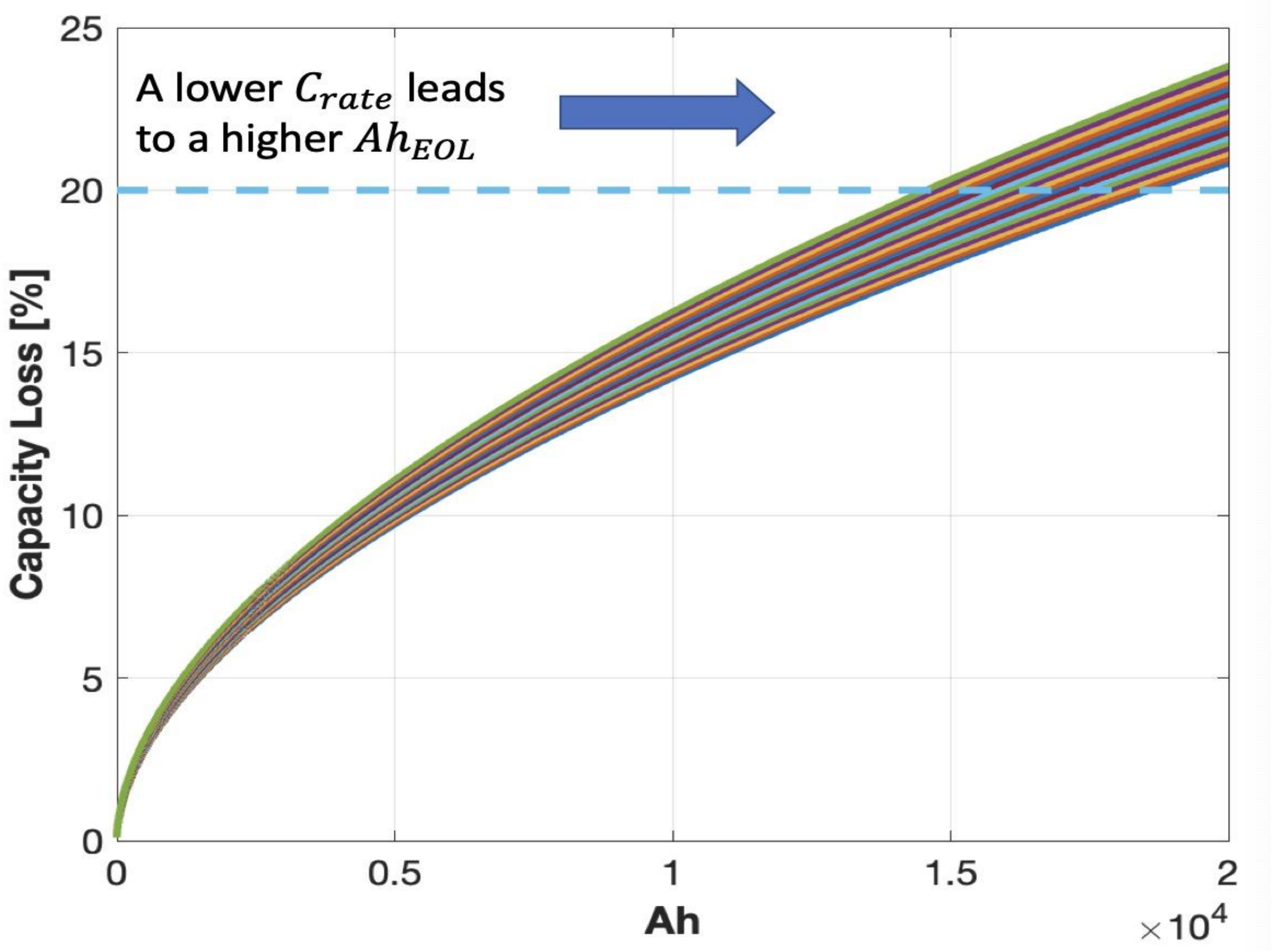
3) Battery Degradation [3]:

Loss of battery capacity.

$$Q_{loss} = M(C_{rate})(Ah)^{0.55}$$

Charging rate

Ampere hours



[3] J. Wang et al., “Cycle-life model for graphite-LiFePO4 cells,” Journal of Power Sources, vol. 196, no. 8, pp. 3942–3948, Apr. 2011, doi: 10.1016/j.jpowsour.2010.11.134

3) Battery Degradation [3]:

Loss of battery capacity.

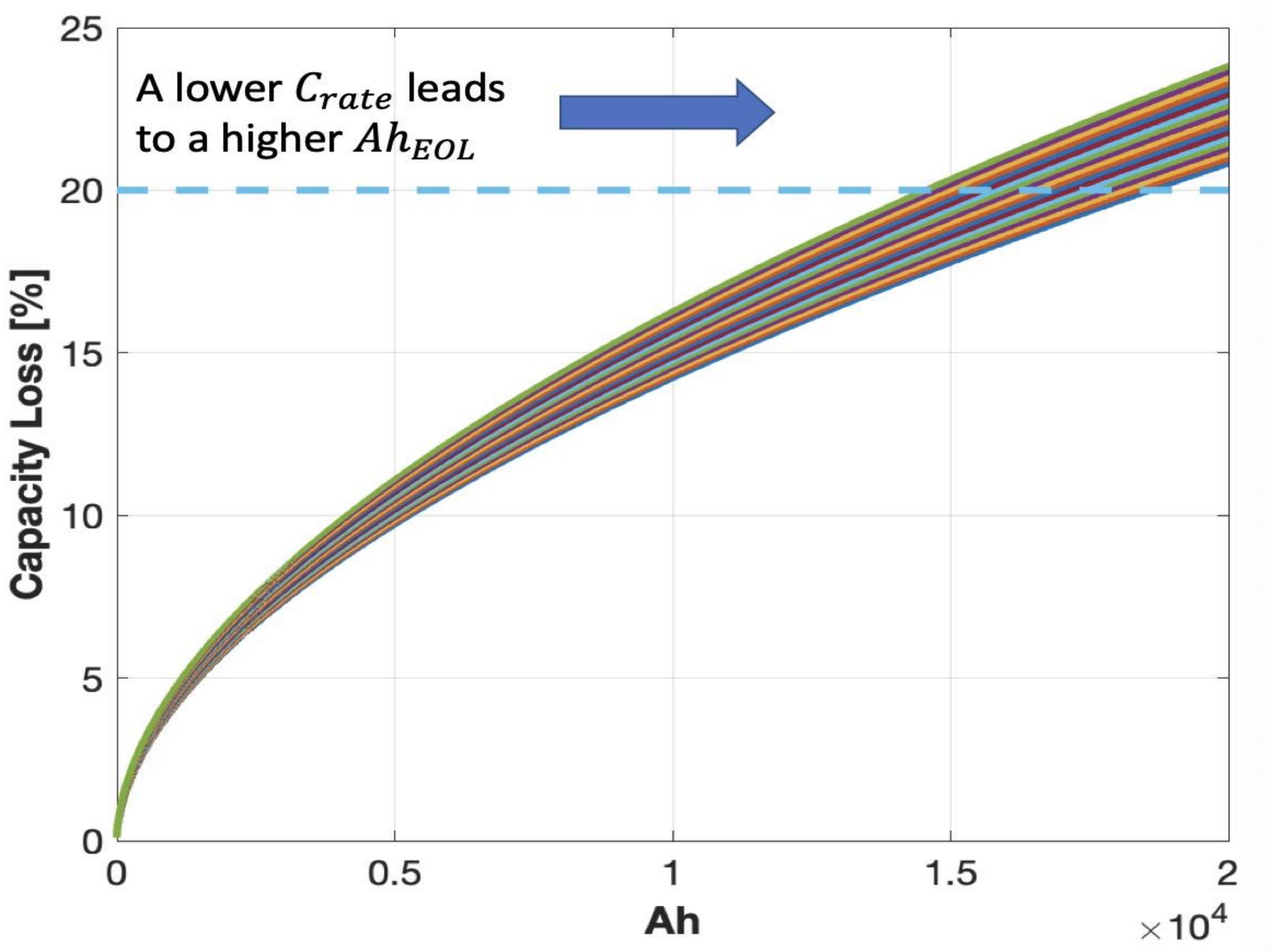
$$Q_{loss} = M(C_{rate})(Ah)^{0.55}$$

$$L_{bat} = C_{bat} \frac{|I|\Delta t}{Ah_{EOL}(C_{rate})}$$

Battery current

Battery rep. cost

Ampere hours to EOL



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Demand Optimization:

Assuming known power demand trend

Determine power distribution between:

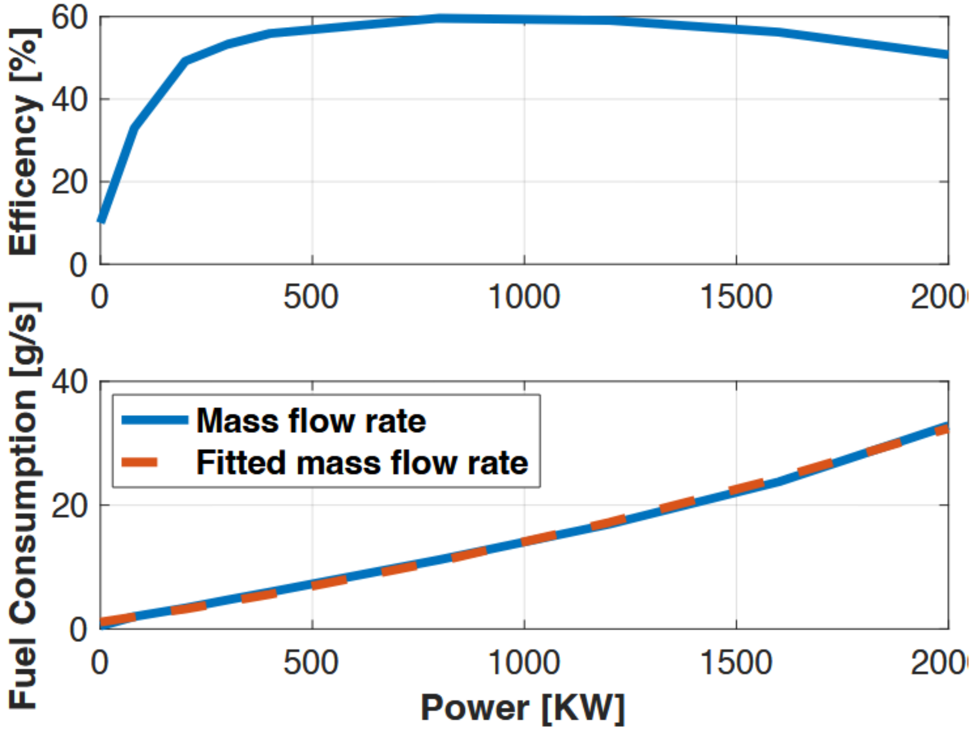
1. Batteries
2. Each fuel cell stack

For each fuel cell, either

1. Turned off
2. Turned on with power $P_{fc}(k,j)$

$$P_d(j) = P_{bat}(j) + \sum_{j=1}^{M} P_{fc}(k,j)$$

Demand — Battery — M Fuel Cell stacks



Optimization problem formulation:

Minimize objective function *J*:

$$J = \sum_{i=1}^{N} l_{bat}(i) + \sum_{j=1}^{M} \left(\dot{m}(k,j)\, \Delta t\, C_{H_2} + l_{fc}(k,j) \right)$$

Sum over time horizon

Sum over fuel cells

Battery degradation

H2 fuel cost

Fuel cell degradation

Optimization problem formulation:

Fuel consumption and degradation constraints:

$$\dot{m}(k,j) = f_{fc-fuel}\left(P_{fc}(k,j)\right)$$

Fuel consumption is nonlinear fcn of FC power

$$l_{fc}(k,j) = l_{on-off}(k,j) + l_{load-change}(k,j) + l_{high-load}(k,j) + l_{idling}(k,j)$$

FC degradation from aging modes

Optimization problem formulation:

Fuel consumption and degradation constraints:

$$\dot{m}(k,j) = f_{fc-fuel}\left(P_{fc}(k,j)\right)$$

Fuel consumption is nonlinear fcn of FC power

$$l_{fc}(k,j) = l_{on-off}(k,j) + l_{load-change}(k,j) + l_{high-load}(k,j) + l_{idling}(k,j)$$

FC degradation from aging modes

Battery dynamic and degradation constraints:

$$I_{bat}(i) = f_{bat-I}(P_{bat}(i), SOC_{bat}(i))$$

Battery power to current relationship

$$I_{bat}^{min} \leq I_{bat}(i) \leq I_{bat}^{max}$$

Battery current Limits

$$SOC_{bat}(i+1) = SOC_{bat}(i) + \frac{100\%\ \Delta t\ I_{bat}(i)}{3600\ Q_{bat}}$$

Battery SOC dynamics

$$SOC_{bat}^{min} \leq SOC_{bat}(i) \leq SOC_{bat}^{max}$$

SOC Limits

$$l_{bat}(i) = f_{bat-loss}\left(I_{bat}(i)\right)$$

Battery degradation

Detailed Formulation of FC and Battery Dynamics and Degradation Equations

Mixed-integer quadratic programming (MIQP) [4]:

$$\dot{m}(k,j) = a_{fc}\, P_{fc}(k,j)^2 + b_{fc}\, P_{fc}(k,j) + c_{fc}\, o_{fc}(k,j)$$
$$o_{fc}(k,j)\, P_{fc}^{min} \leq P_{fc}(k,j)$$
$$P_{fc}(k,j) \leq o_{fc}(k,j)\, P_{fc}^{max}$$

$$l_{load-change}(k,j) = \frac{\Delta V_{load-change}\, C_{fc}}{V_{drop}^{max}} \Delta P_{fc}^{+}(k,j)$$
$$\Delta P_{fc}^{+}(k,j) \geq P_{fc}(k-1,j) - P_{fc}(k,j)$$
$$\Delta P_{fc}^{+}(k,j) \geq P_{fc}(k,j) - P_{fc}(k-1,j)$$

$$l_{on-off}(k,j) = \frac{\Delta V_{on-off}\, C_{fc}}{V_{drop}^{max}} s_{fc}(k,j)$$
$$s_{fc}(k,j) \geq o_{fc}(k,j) - o_{fc}(k-1,j)$$
$$s_{fc}(k,j) \geq o_{fc}(k-1,j) - o_{fc}(k,j)$$

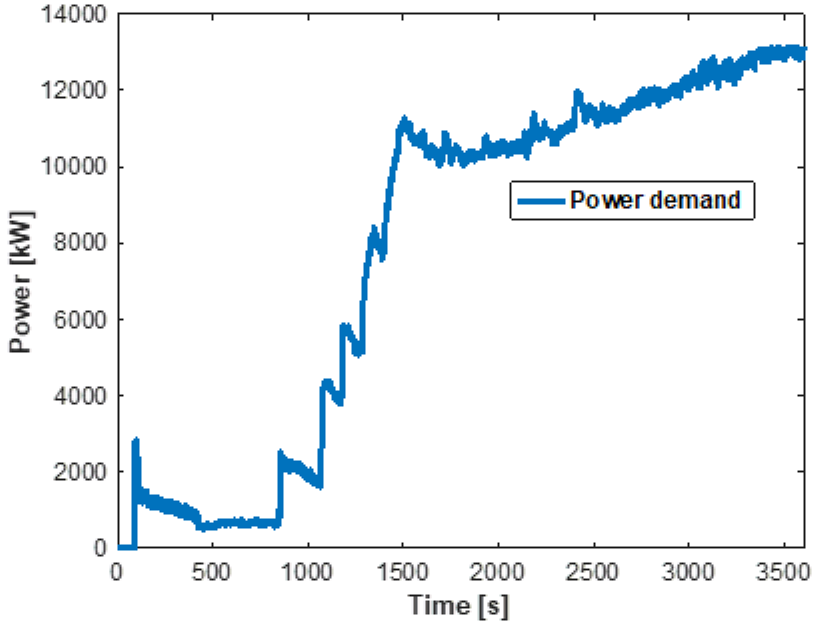
$$l_{idling}(k,j) = \frac{\lambda\, \Delta t\, \Delta V_{idling}\, C_{fc}\, (i_{fc}(k,j) + o_{fc}(k,j) - 1)}{3600\, V_{drop}^{max}}$$
$$\frac{P_{fc}^{low} - P_{fc}(k,j)}{P_{fc}^{low} - P_{fc}^{min}} \leq i_{fc}(k,j)$$
$$i_{fc}(k,j) \leq \frac{P_{fc}^{max} - P_{fc}(k,j)}{P_{fc}^{max} - P_{fc}^{low}}$$

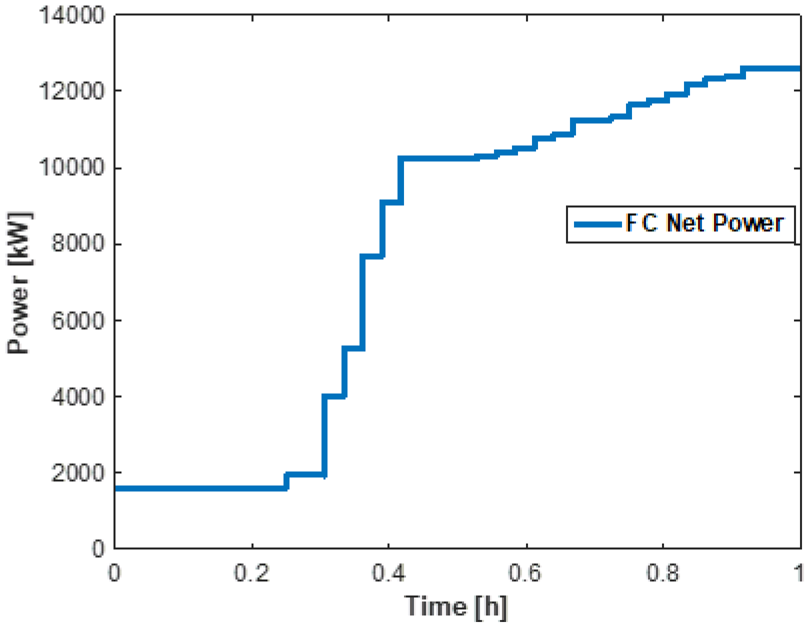
$$l_{high-load}(k,j) = \frac{\lambda\, \Delta t\, \Delta V_{high-load}\, C_{fc}\, h_{fc}(k,j)}{3600\, V_{drop}^{max}}$$
$$\frac{P_{fc}(k,j) - P_{fc}^{high}}{P_{fc}^{max} - P_{fc}^{high}} \leq h_{fc}(k,j)$$
$$h_{fc}(k,j) \leq \frac{P_{fc}(k,j) - P_{fc}^{min}}{P_{fc}^{high} - P_{fc}^{min}}$$

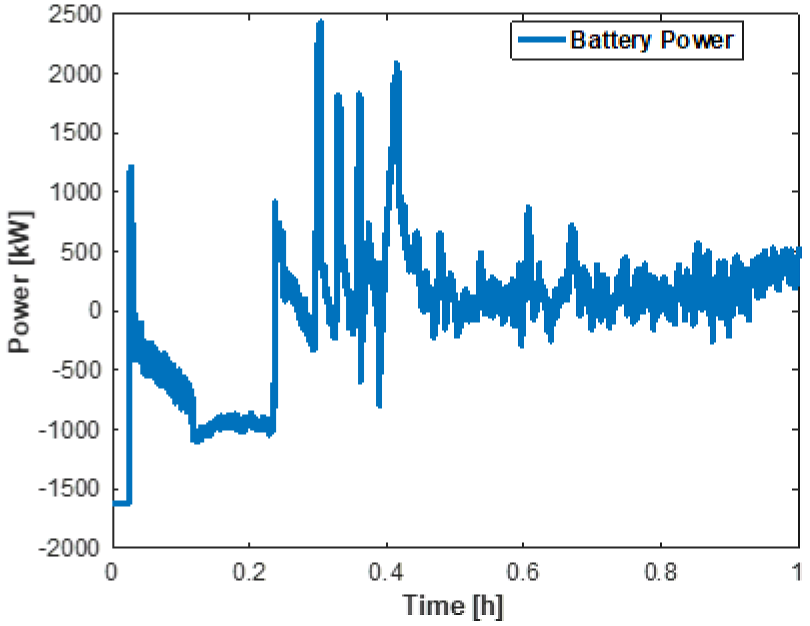
$$I_{bat}(i) = a_{bat}\, P_{bat}(i) + b_{bat}\, SOC_{bat}(i)$$
$$l_{bat}(i) = \left(a_d \frac{I_{bat}^{+}(i)^2}{Q_{bat}} + b_d\, I_{bat}^{+}(i)\right) \frac{\Delta t}{7200} Q_{bat} C_{bat}$$
$$I_{bat}^{+}(i) >= -I_{bat}(i)$$
$$I_{bat}^{+}(i) >= I_{bat}(i)$$

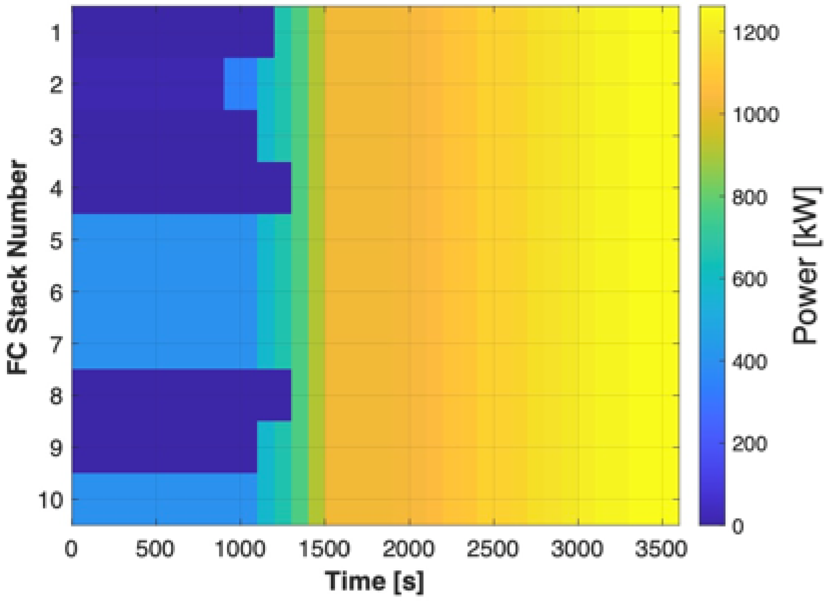
[4] Shi, J., Flø Aarsnes, U. J., Nærheim, D., & Moura, S. (2023). Online energy management system for a fuel cell/battery hybrid system with multiple fuel cell stacks. *arXiv e-prints*, arXiv-2310.

Detailed Power Split for Independent Control:









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Offline-optimized method:
Cost function for FC module power split

Future power demand is not known:

- Need heuristic for power allocation based on current demand

Assume a constant load, what is the optimal power split?

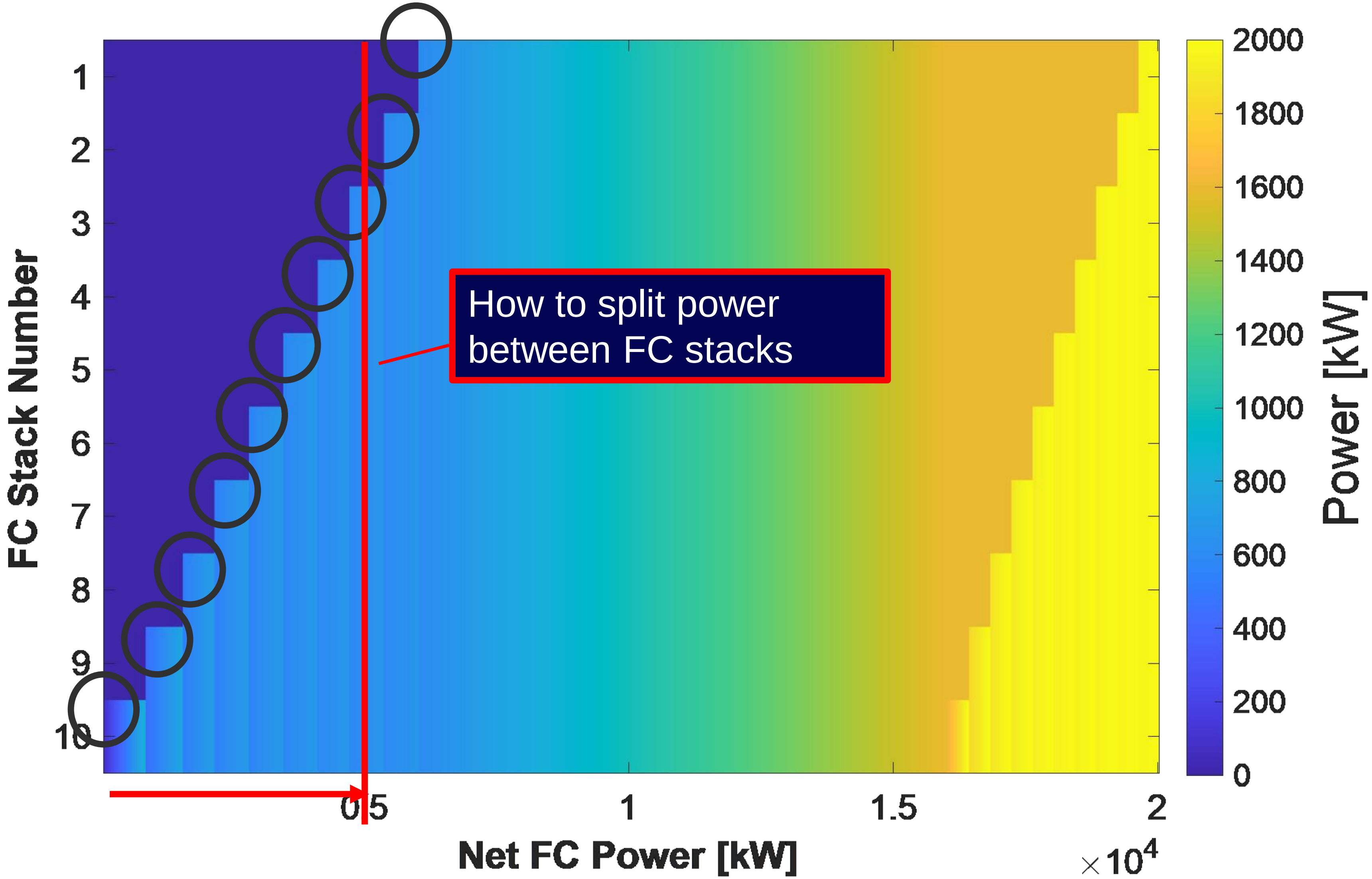
- Only consider:
    1. H2 consumption
    2. FC degradation due to high-load and idling conditions.

Cost function:

$$J = \sum_{j=1}^{M} \dot{m}(j)\Delta t \; + loss_{fc}(j)$$

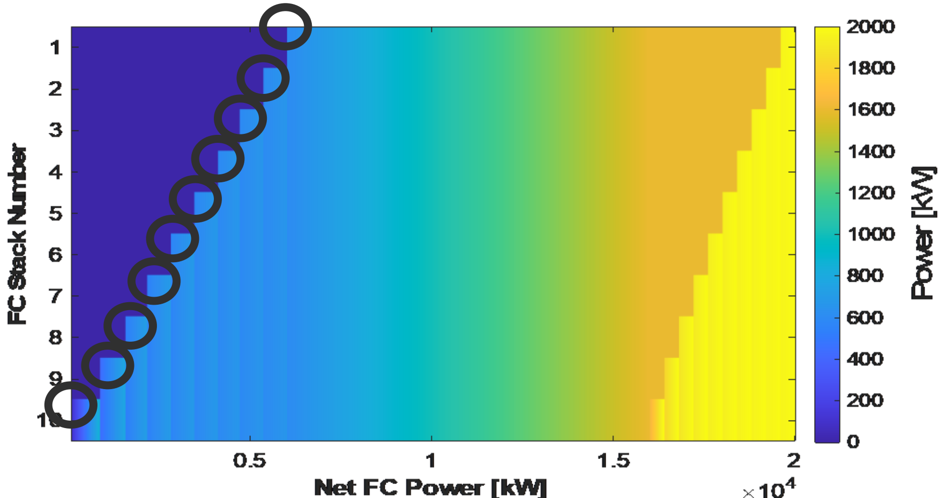
- Determine which FC stacks to keep on and power level.

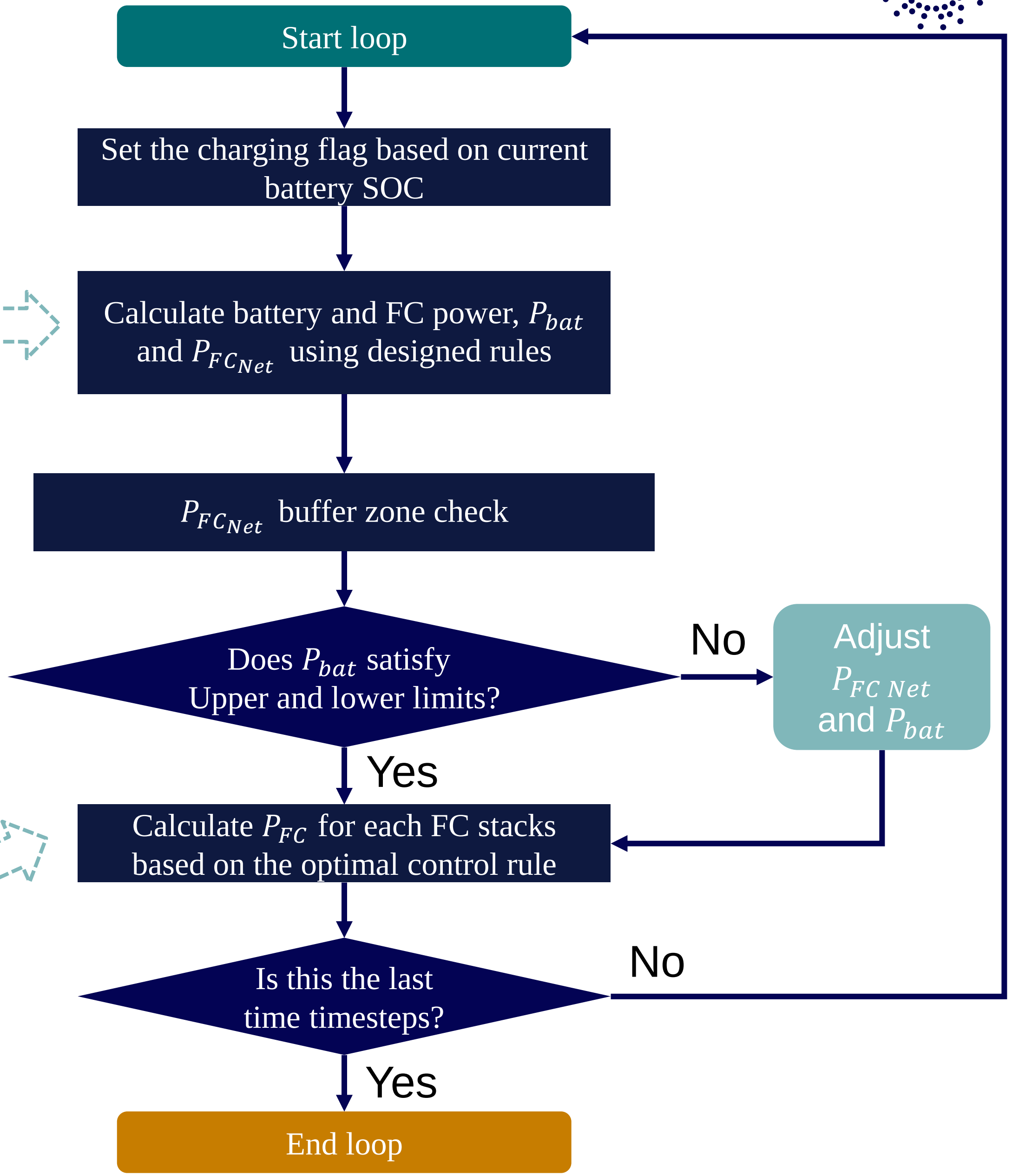
Offline-optimized method: FC module power split rule



Heuristic for splitting power between Battery and FC stacks

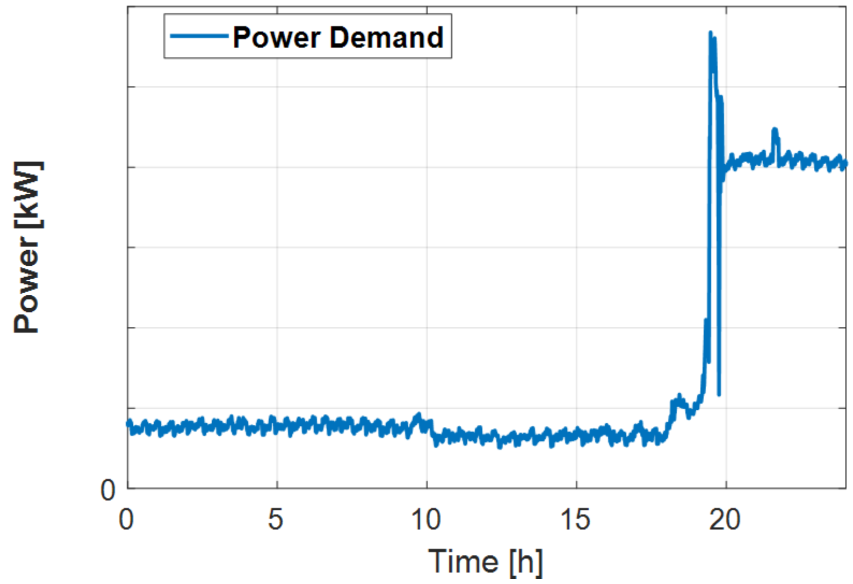
$SOC_{bat} < 15\%$		$flag_{chg} \leftarrow 1$ $P_{FC}^{Net} = \alpha P_d + (1-\alpha) P_{FC}^{Net}$ $P_{bat} = P_d - P_{FC} + K(SOC_{bat} - 85\%)$
$15\% \leq SOC_{bat} \leq 85\%$	$flag_{chg} == 1$	$P_{FC}^{Net} = \alpha P_d + (1-\alpha) P_{FC}^{Net}$ $P_{bat} = P_d - P_{FC}^{Net} + K(SOC_{bat} - 85\%)$
	$flag_{chg} == 0$	$P_{FC}^{Net} = \alpha P_d + (1-\alpha) P_{FC}^{Net}$ $P_{bat} = P_d - P_{FC}^{Net}$
$85\% < SOC_{bat}$		$flag_{chg} \leftarrow 0$ $P_{FC}^{Net} = \alpha P_d + (1-\alpha) P_{FC}^{Net}$ $P_{bat} = P_d - P_{FC}^{Net}$





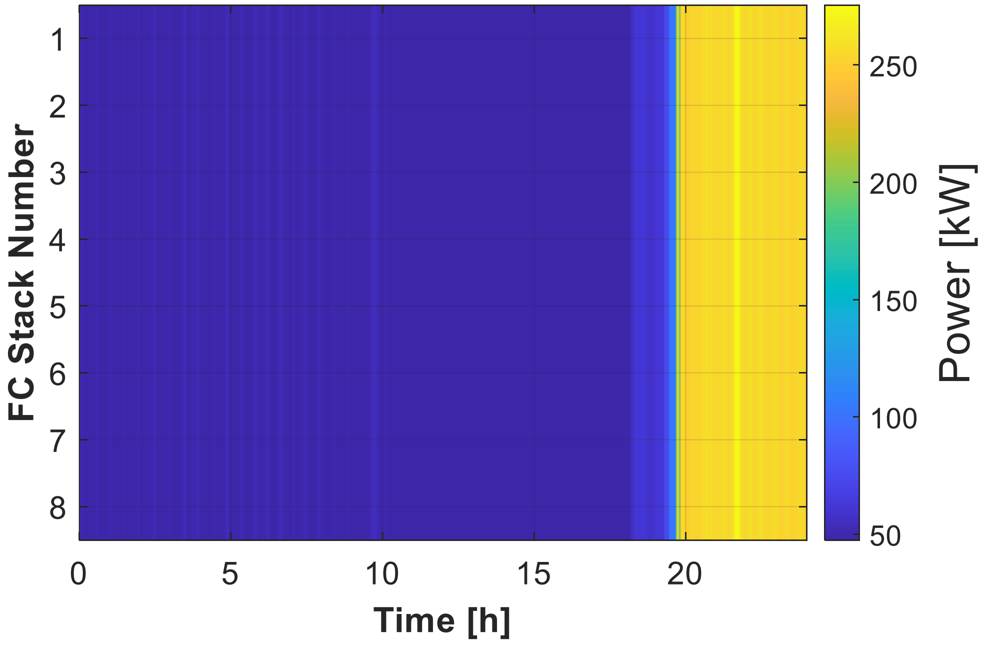
Case Simulation study:

Service Operation Vessel (SOV)

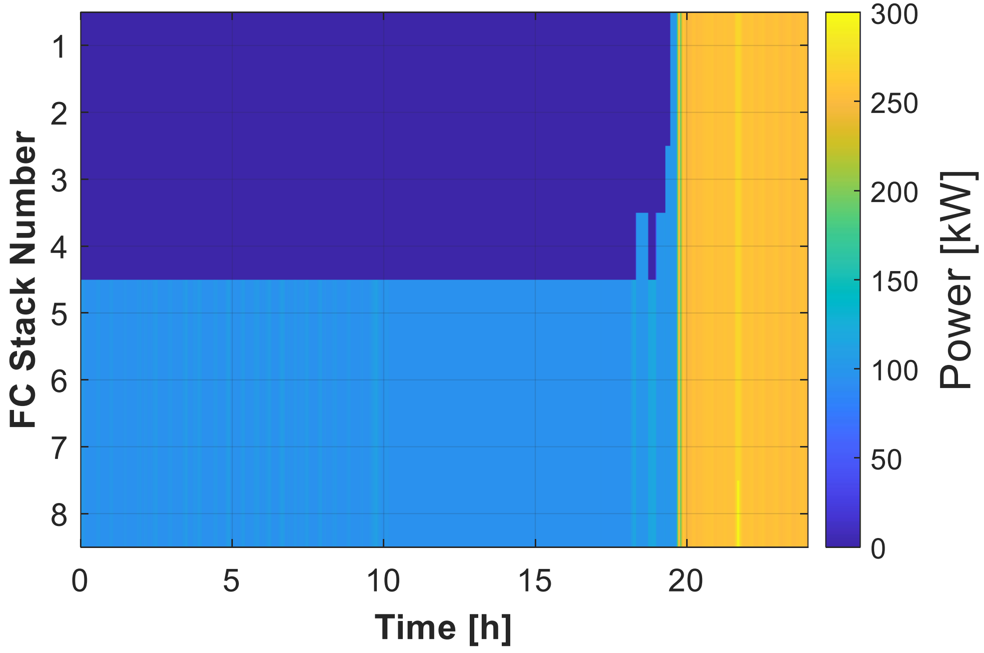


All FC equal

(Significant idling loss)

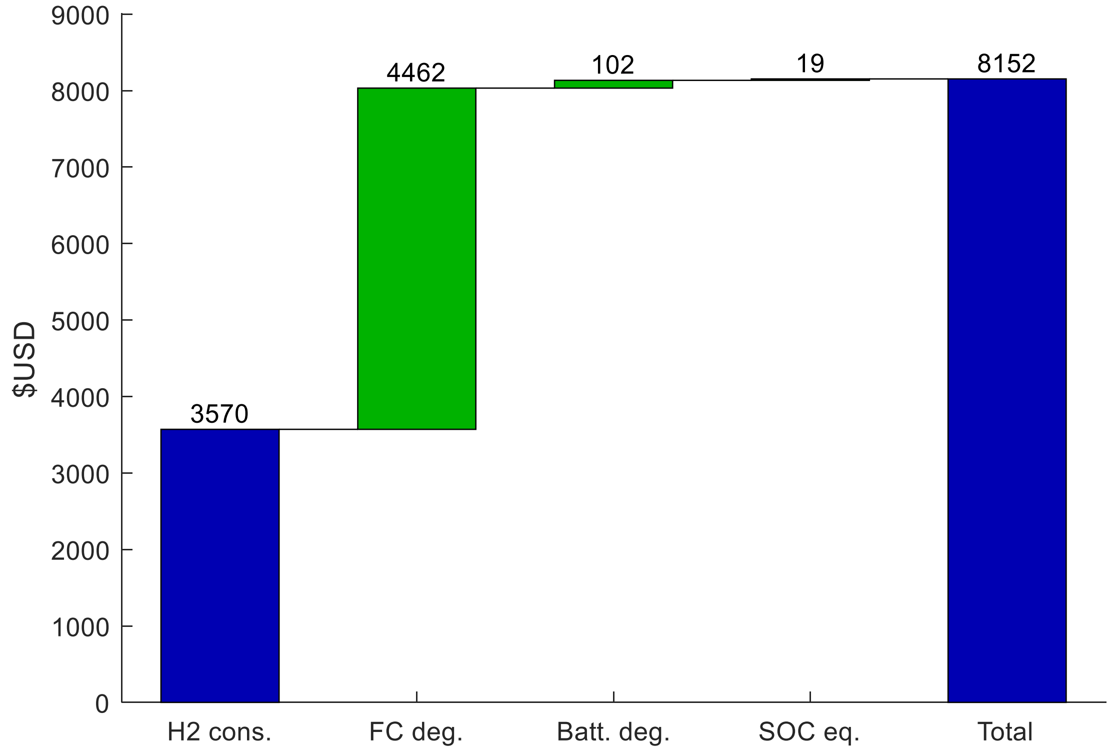


Individual 8-stack FC control

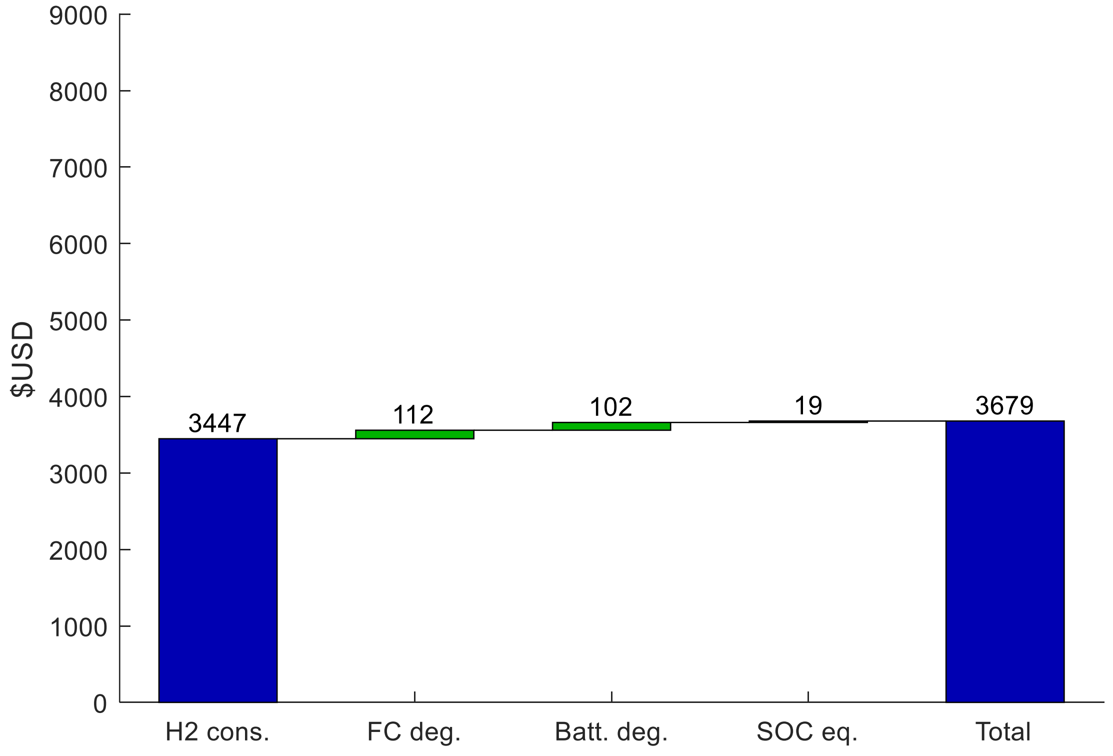


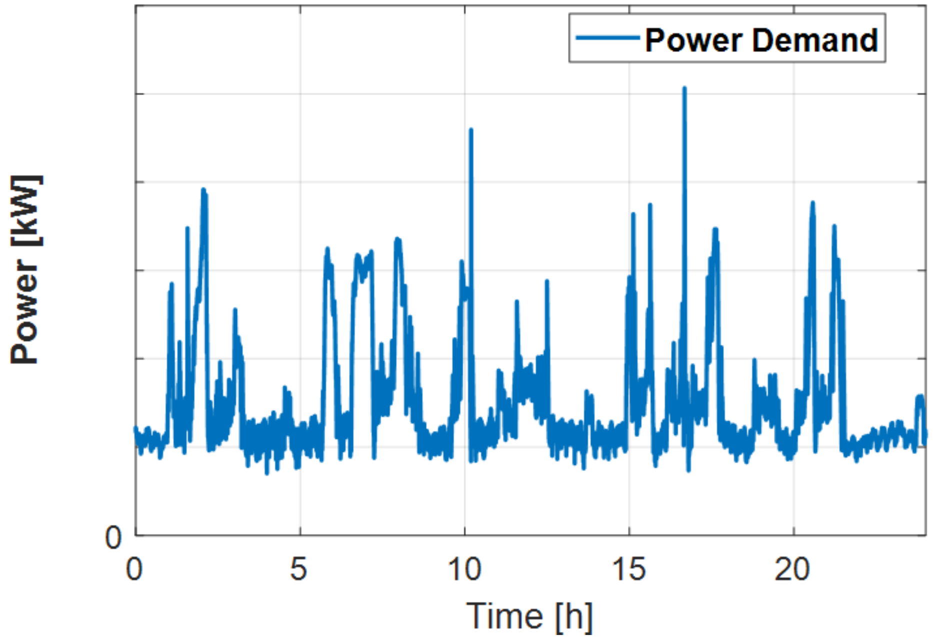
Cost breakdown

All FC equal
(Significant idling loss)

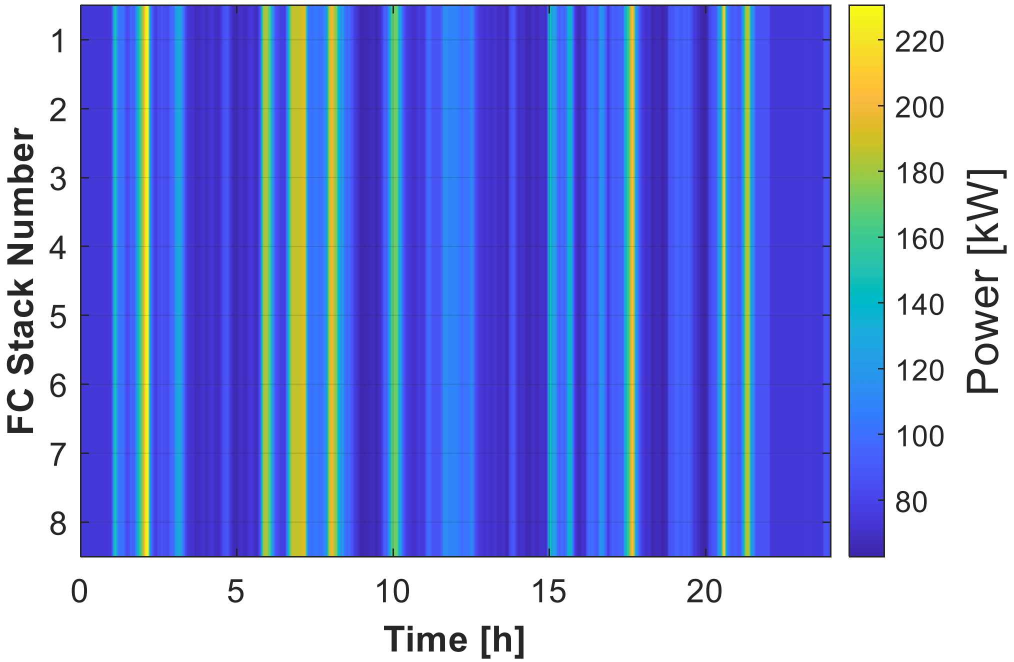


Individual 8-stack FC control

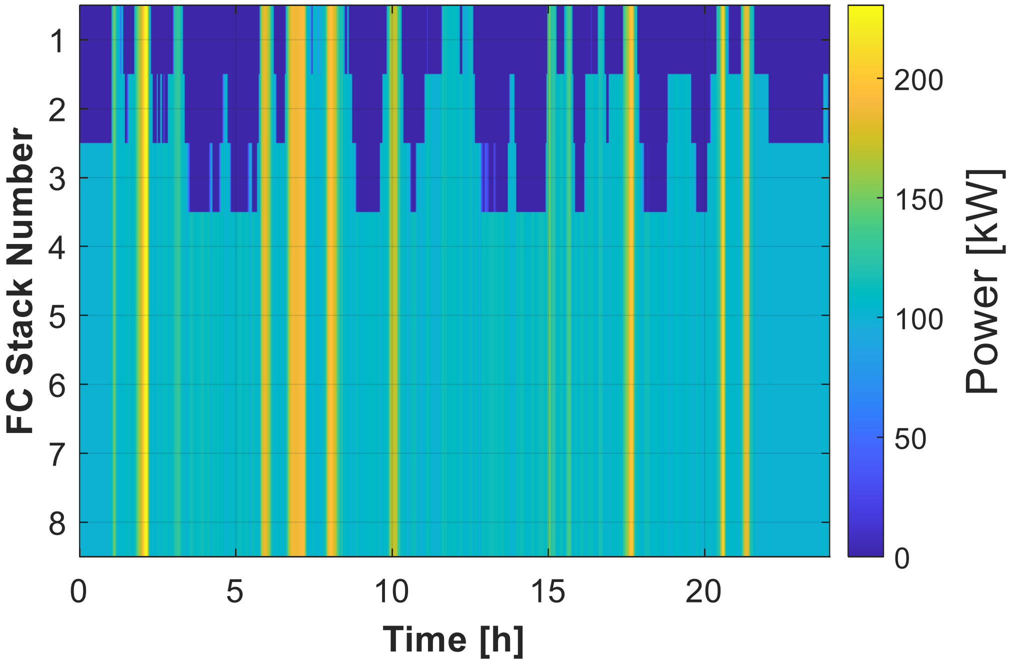




Collective stack control

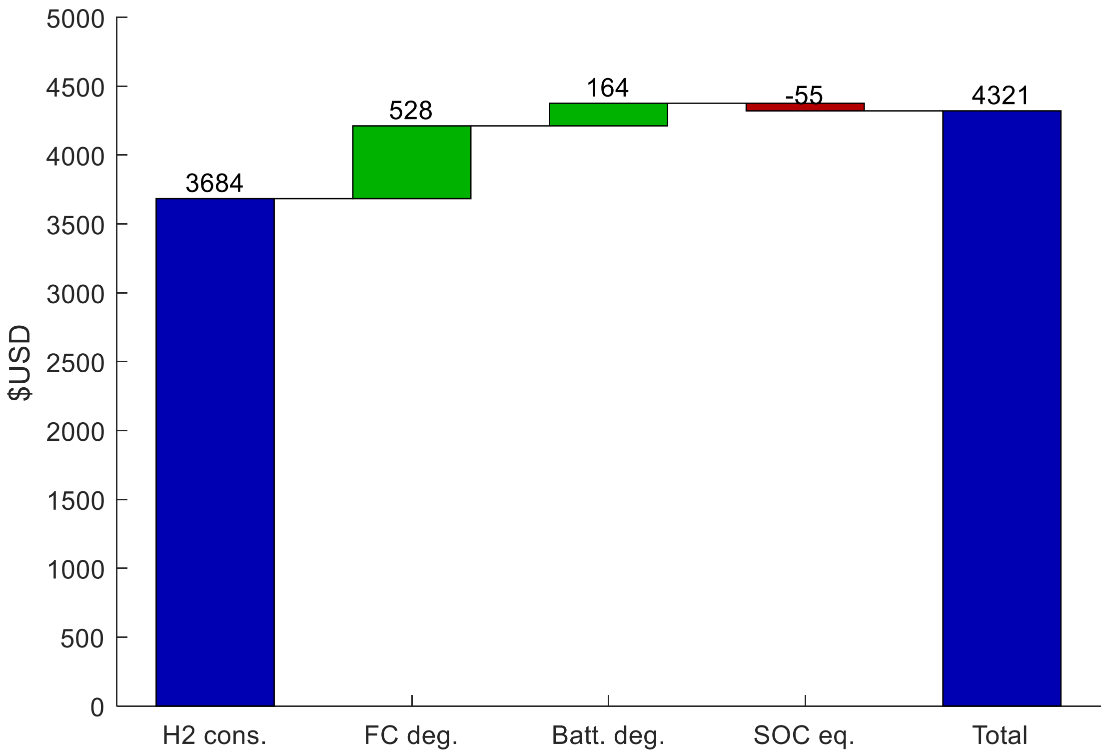


Individual 8-stack FC control

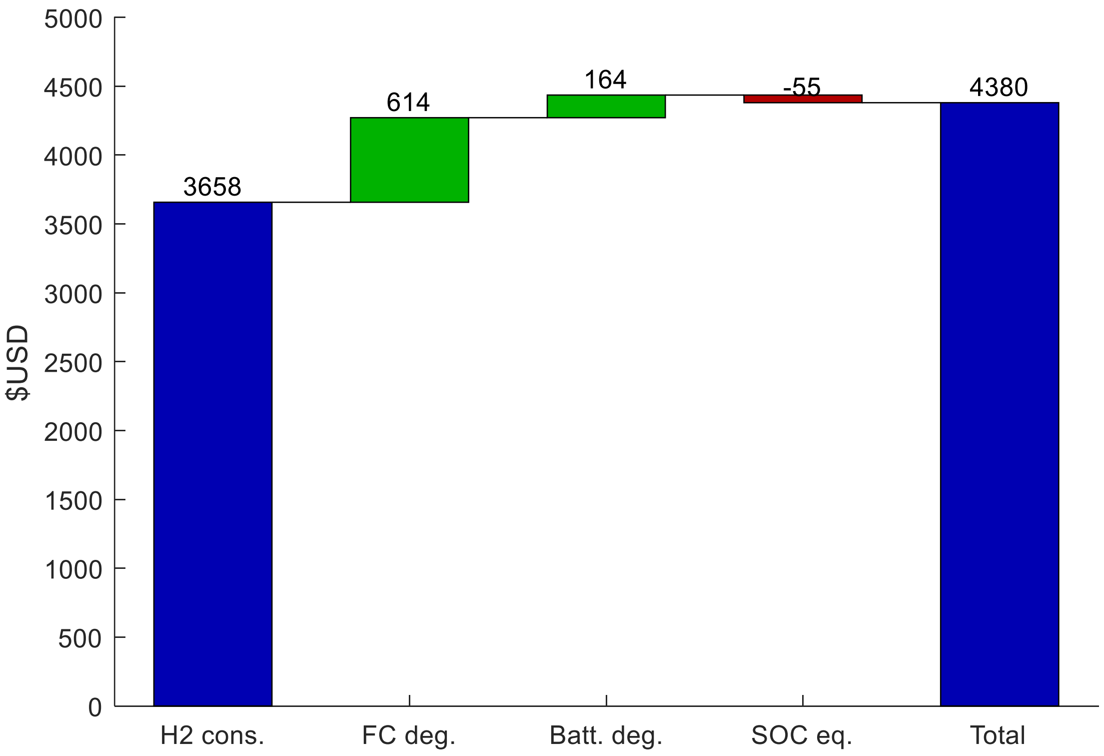


Cost breakdown

Collective stack control

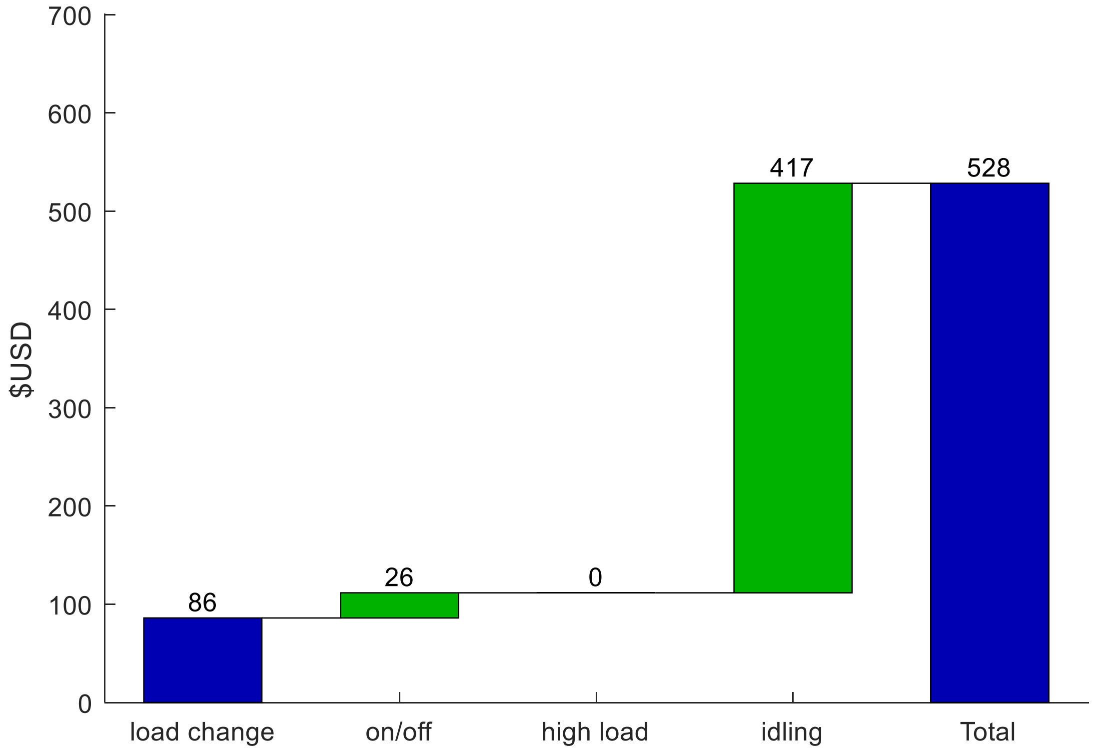


Individual 8-stack FC control

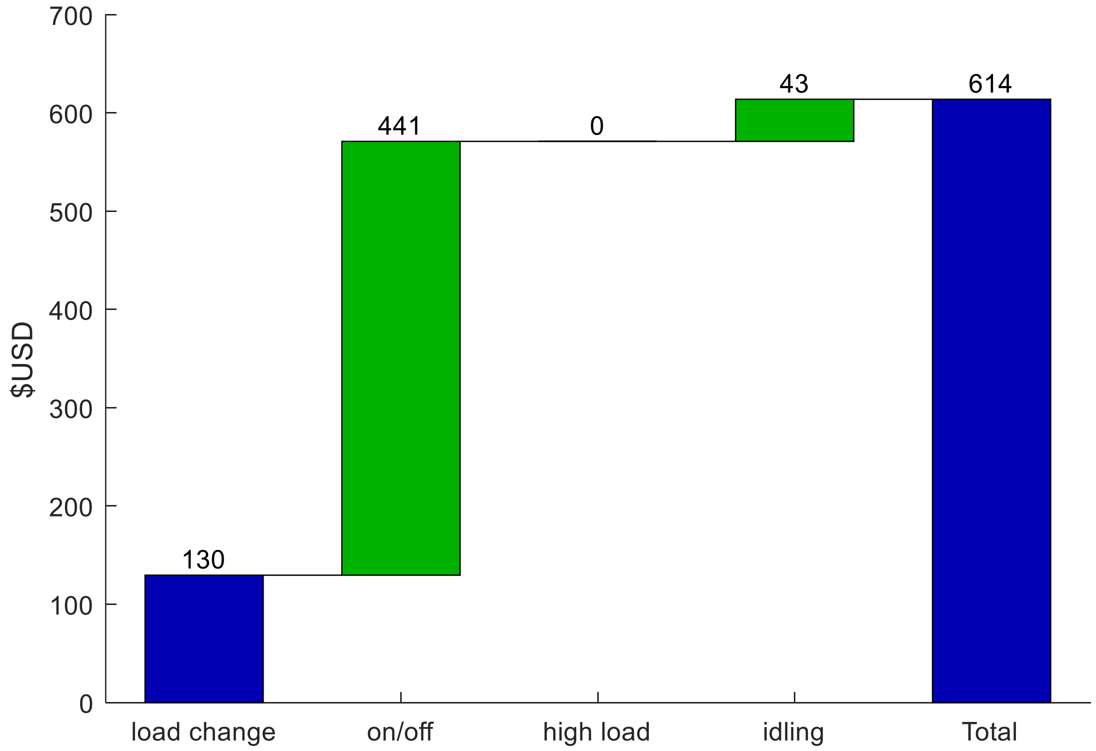


Cost breakdown – FC Degradation

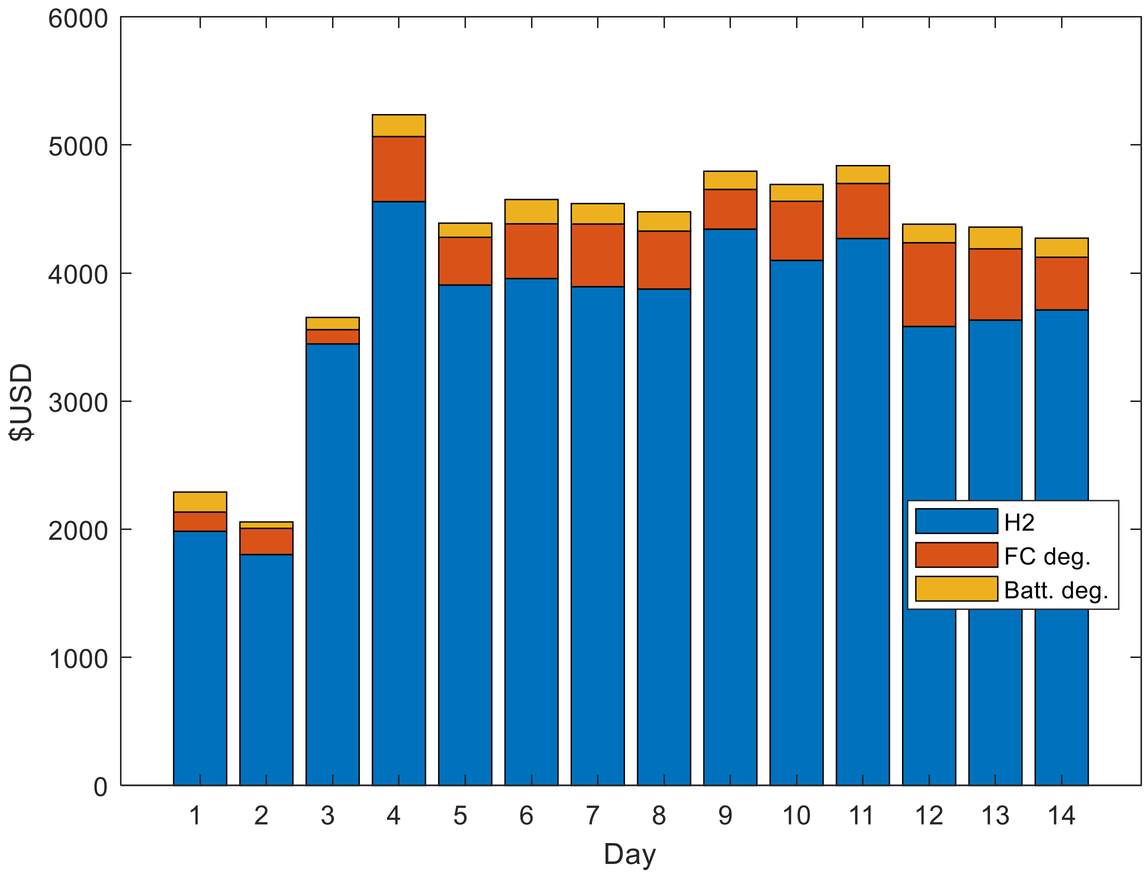
All FC equal
Still ‘idling’, but low ‘on/off’



Individual 8-stack FC control
Too much ‘on/off’ ?



Conclusions and further work



- Independent stack control *needed* for low degradation and efficient H2 use.

- Change control by operation type
- Try to use “predicted” demand

Thank you. Takk.

Merci. Gracias. Obrigado.

NORCE

MARINER Partnership –
Maritime Fuel Cell Degradation Estimation and Reliability

A Clean Energy Transition Partnership

NORCE

IFP Energies nouvelles

MINES PARIS | PSL

BERKELEY LAB

Berkeley UNIVERSITY OF CALIFORNIA

Project Academic Partners

Norway:

- **Norwegian Research Centre (NORCE):** Research institution with expertise in maritime energy and technology. Lead: Ulf Jakob Flø Aarsnes

France:

- **IFP Energies Nouvelles (IFPEN):** Expert in energy transition technologies. Lead: Thomas Leroy
- **Mines Paris PSL:** Renowned engineering school with a focus on industrial processes. Leads: Prof. Florent Di Meglio and Prof. Delphine Bresch-Pietri

USA:

- **Lawrence Berkeley National Laboratory:** Federal research facility advancing energy technologies.
- **University of California, Berkeley:** Top-tier university with extensive research capabilities in engineering and environmental science. Lead: Prof. Scott Moura