

Degradation-Aware Modeling of Hydrogen Fuel Cells for Hybrid Propulsion

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ABSTRACT No. 1739

This paper presents a degradation-aware quasi-steady-state modeling framework for hydrogen fuel cells in marine hybrid propulsion, developed from sparse manufacturer data without direct end-of-life (EoL) polarization measurements. Polarization parameters are fitted at beginning-of-life (BoL) and at a reconstructed EoL, and a power-law lifetime relation drives cumulative damage. Applied to a proton exchange membrane fuel cell (PEMFC) with a battery energy storage system (BESS) over 25,000 hours, hybridization eliminates power deficit, extends the estimated EoL by 316 hours and saves about 1,269 kg of hydrogen.

I INTRODUCTION

- The International Maritime Organization targets net-zero greenhouse gas emissions from shipping by or around 2050.
- Hybrid fuel cell (FC) systems couple stack performance, energy management system (EMS) and power electronics with aging, necessitating degradation-aware modeling as an EMS baseline.

II MODELING METHODOLOGY

A. Polarization & power

$$V_{\text{stack}}(I) = V_{0,s} - b_s \ln(I) - R_s I \quad (1) \quad T_{\text{EoL}}(L) = a \cdot L^{-b} \quad (4)$$

$$P_{\text{gross}}(I) = I \cdot V_{\text{stack}}(I) \quad (2) \quad \alpha(t) = \int_0^t d\tau / T_{\text{EoL}}(L(\tau)) \quad (5)$$

$$di/dt = k \cdot i, \quad k < 0 \quad (3) \quad V_{0,s}(t) = V_{0,s}^{\text{BoL}} + \alpha(t) \Delta V_{0,s} \quad (6)$$

B. Degradation

Nomenclature

$V_{0,s}$ open-circuit intercept
 b_s activation-loss coefficient
 R_s ohmic resistance
 k degradation scale factor
 L normalized load, 0–1
 T_{EoL} lifetime at load L
 a, b fitted coefficients
 α cumulative damage

- (1): semi-empirical polarization relation [1].
- (3): first-order law for current degradation [2], generalized to the power law (4).
- EoL: BoL voltages scaled by the EoL-to-BoL efficiency ratio.

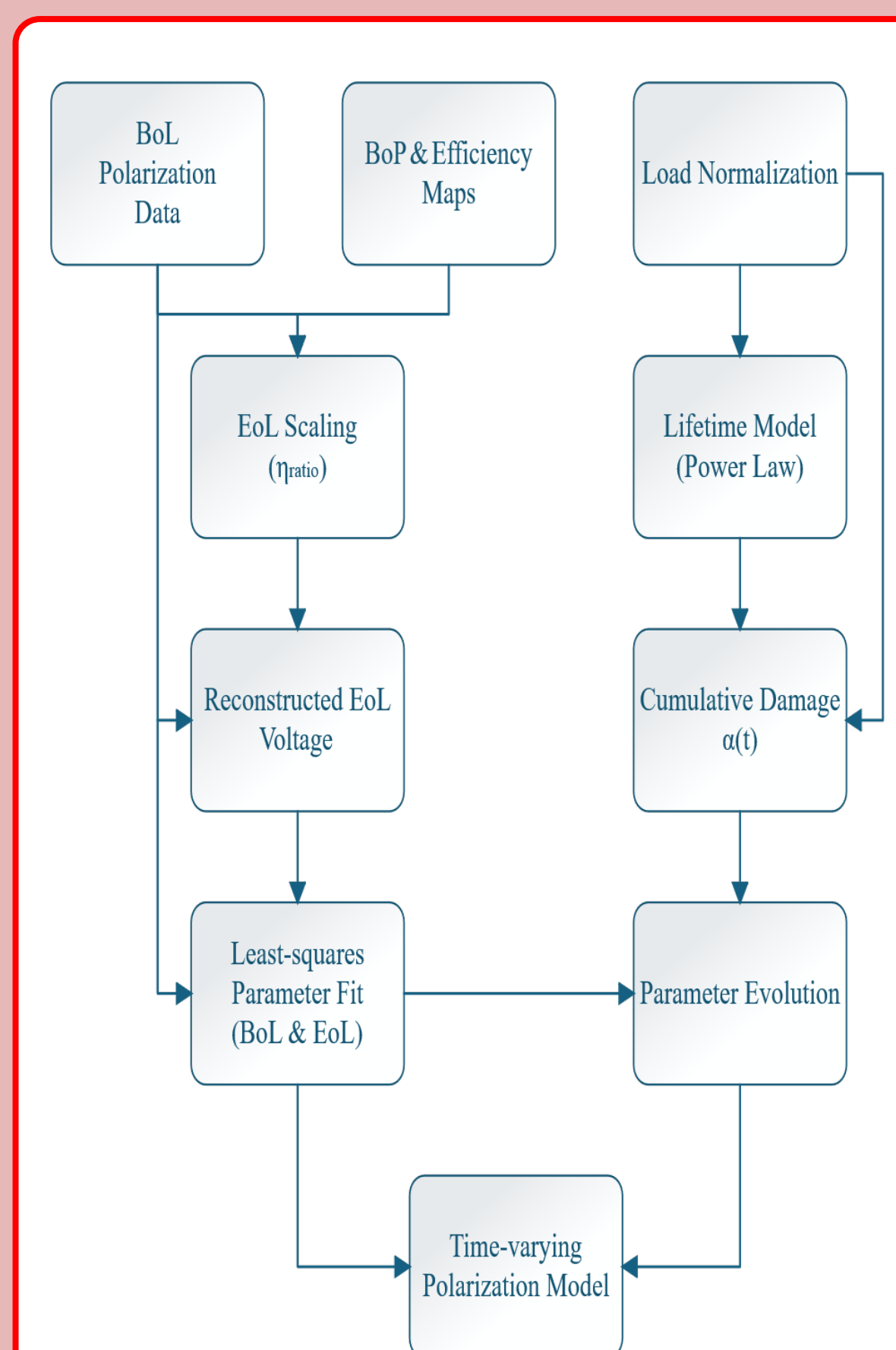


Fig. 1: Degradation-aware modeling flowchart.

III MODEL VALIDATION

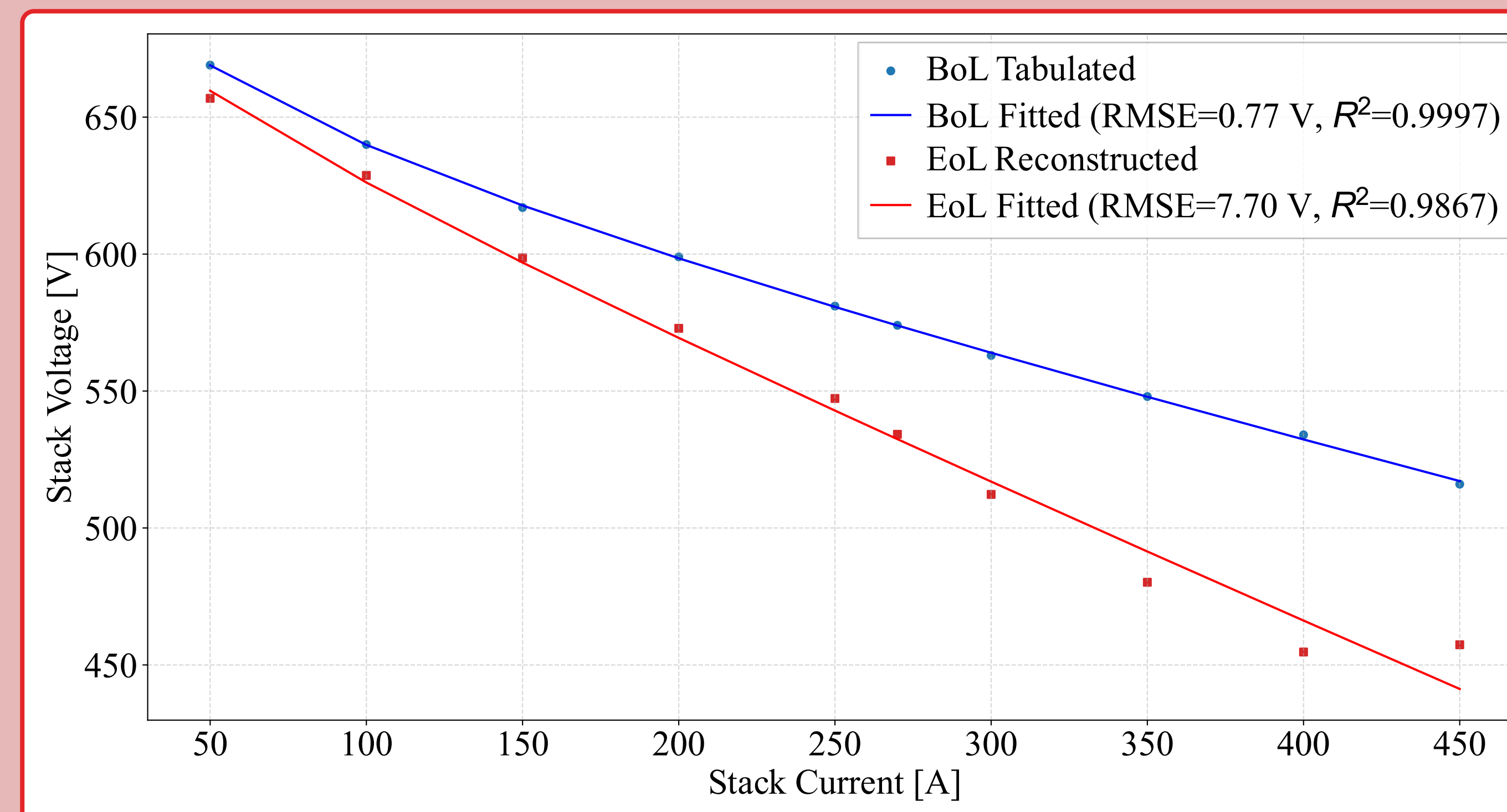


Fig. 2: Polarization curves (BoL tabulated, EoL reconstructed) with semi-empirical fits.

TABLE I: Fitted polarization parameters.

Stack	BoL	EoL	Δ
$V_{0,s}$ (V)	775.5	740.8	−4.5 %
b_s (V)	24.08	14.80	−38.5 %
R_s (Ω)	0.2472	0.4648	+88.0 %

TABLE II: Fit metrics.

Fit	R^2	RMSE
BoL curve	0.9997	0.774 V
EoL curve	0.9867	7.698 V
Lifetime (7)	0.9692	985 h

RMSE: root-mean-square error; R^2 : coefficient of determination.

- The parameter trends (reduced intercept and activation coefficient, increased ohmic resistance) are consistent with established PEMFC catalyst-layer degradation mechanisms.
- Concentration losses and balance-of-plant degradation are not represented.

IV SYSTEM CONFIGURATION AND SETUP

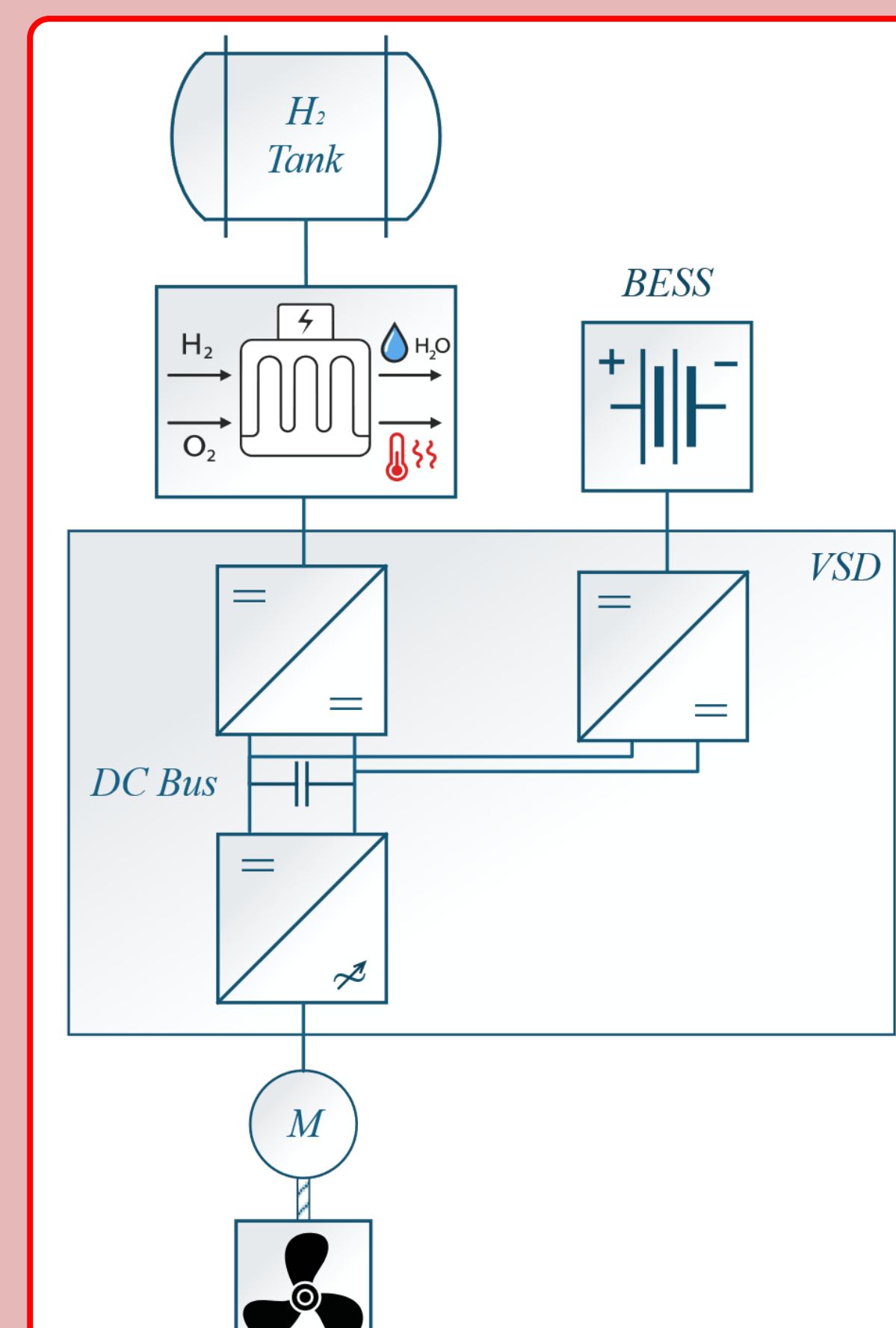


Fig. 3: Hybrid marine drivetrain integrating fuel cell and battery system.

TABLE III: Component Parameters.

Parameter	Value	Unit
FC current ramp limit	20	A/s
Battery capacity	100	kWh
Initial state of charge (SoC)	60	%
SoC limits	20–80	%
Converter efficiency	0.97	–
Time step	1	s

- Each trip spans 4 hours.
- The 25,000-hour horizon corresponds to 6,250 trips with stochastic maneuvering.
- Case 1: FC only. Case 2: FC + BESS with a low-pass-filtered setpoint.

V RESULTS AND DISCUSSION

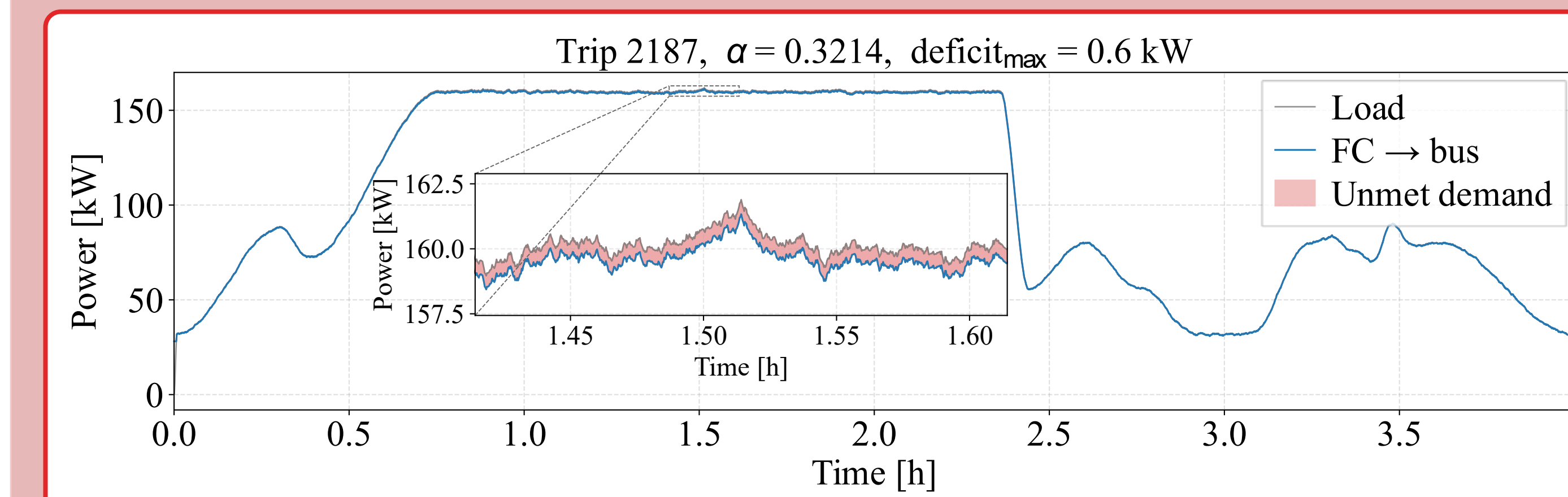


Fig. 4: Case 1 power flow, representative Trip 2187, with inset on the unmet demand.

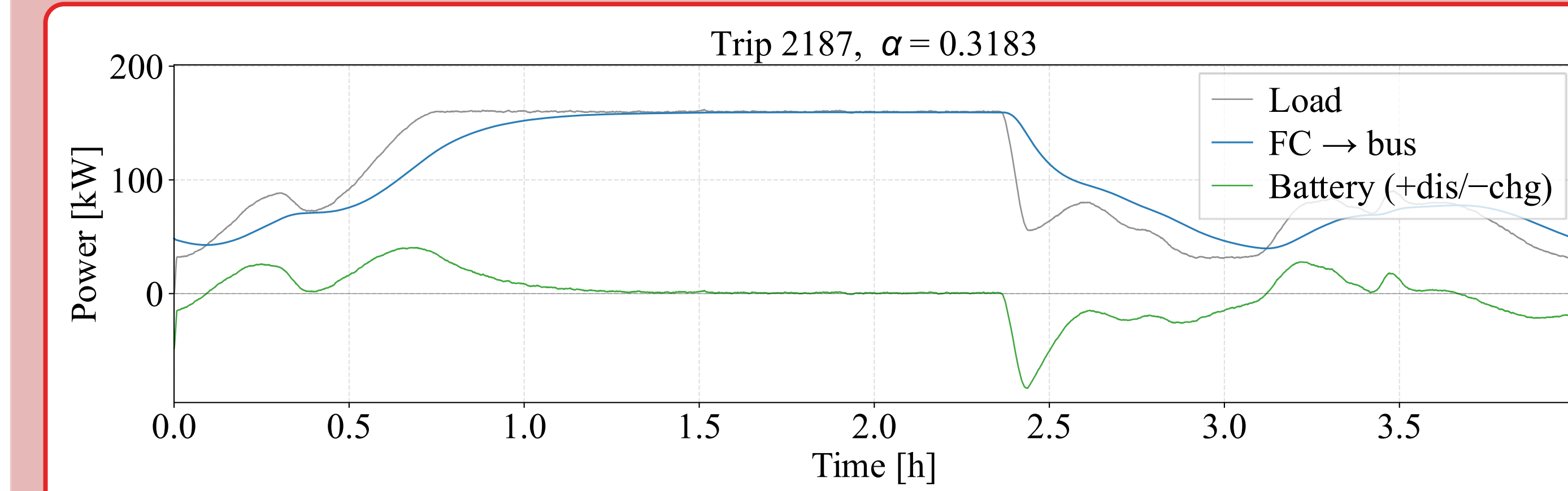


Fig. 5: Case 2 power flow, representative Trip 2187: load demand, FC, and battery power.

TABLE IV: Simulation Results Summary, Case 1 and Case 2.

Quantity	Case 1: FC only	Case 2: FC + BESS
Final α	0.956	0.944
Estimated EoL (h)	26,083	26,399
FC current std. dev. (A)	120.9	111.8
Mean power deficit (kW)	0.21	0.00
Hydrogen used (kg)	164,676	163,407

VI CONCLUSION

+316 h estimated EoL	−7.6 % FC current std. dev.	−1,269 kg hydrogen used	−0.0119 damage $\Delta\alpha$
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- Even a simple load-smoothing strategy yields measurable lifetime benefits; the modest EoL extension is linked to the $\tau = 600$ s low-pass-filtered FC setpoint of Case 2 [3].
- The sensitivity to the energy management strategy and smoothing parameters warrants further investigation.

REFERENCES

- [1] F. Barbir, PEM fuel cells: Theory and practice, 2nd ed. Amsterdam Boston: Elsevier/Academic Press, 2013.
 - [2] P. Pei et al., "Lifetime prediction method of proton exchange membrane fuel cells based on current degradation law," Energy, vol. 265, p. 126341, Feb. 2023.
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CONNECT

