Research on Hydrogen Fuel Cells, Water Electrolysis and Fuel Cell Hybrid Electric System

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Seoul National University
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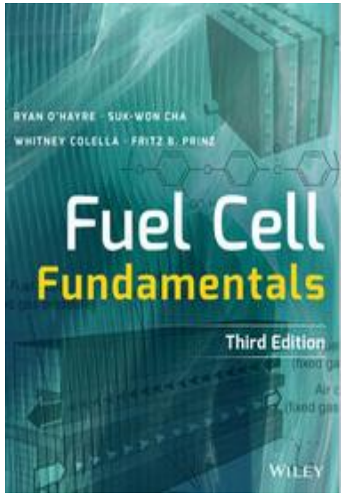
About the Presenter



Education

- Ph.D. in Stanford University (2004)
- M.S. in Stanford University (1999)
- B.S. in Seoul National University (1994)

Experiences

- Professor, Mechanical Engineering, Seoul National University (2005~)
- Co Editors-in-Chief, Int. J. Precision Eng. & Manu-Green Tech (Q1), (2021~)
- President, Advanced Institute of Convergence Technology (2023~2025)
- Director, Institute of Engineering Research, Seoul National University (2025~)
- Co-author of *"Fuel Cell Fundamentals (3rd edition)"*

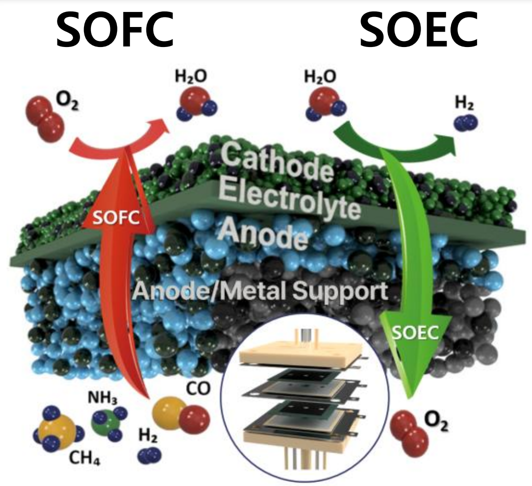
Research Field

- Hydrogen Fuel Cells and Water Electrolysis
- Fuel Cell Hybrid Electric System: Modeling, Simulation, Pre-diagnosis

Outline

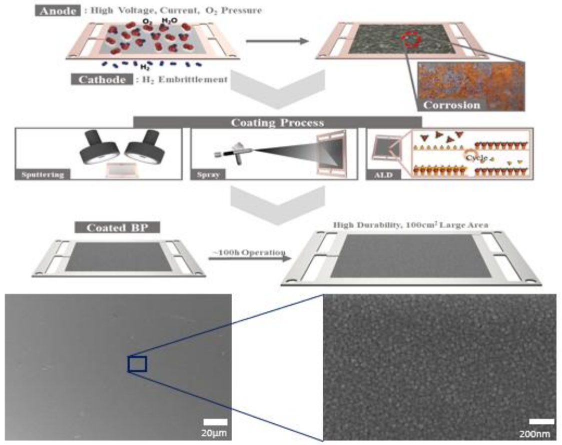
1. Summery of Current Research
2. Low-temperature SOFC/EC
3. PEMFC/WE
4. Fuel Cell System Pre-diagnosis
5. Fuel Cell Hybrid Electric System Management

Summery of Current Research



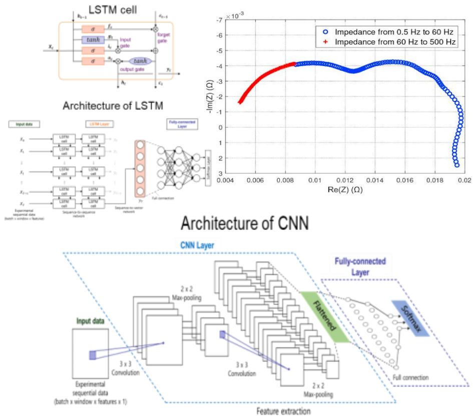
Low-temperature SOFC/EC

- Development of Nanostructured SOFC and SOEC
- Development of Carbon-fueled SOFCs



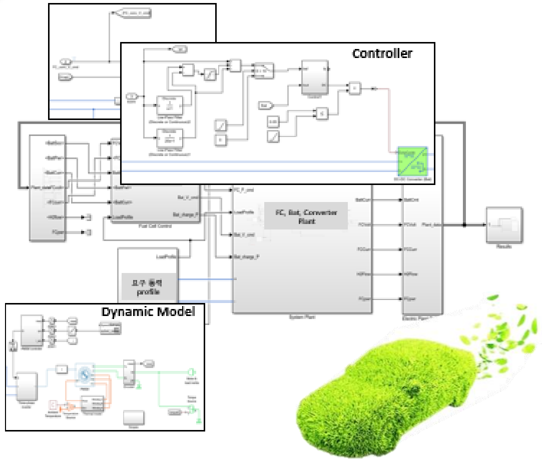
PEMFC/WE

- Analysis of PEMFC Stack Performance and Modeling
- Development of Advanced Low-cost PEMWE Bipolar Plate



Fuel Cell System Pre-diagnosis

- Pre-diagnosis of Condition of FC Energy System Using Fast EIS and AI



Fuel Cell Hybrid Electric System

- Energy Management for FCHEV
- Hybrid Power System Control and Energy Optimization

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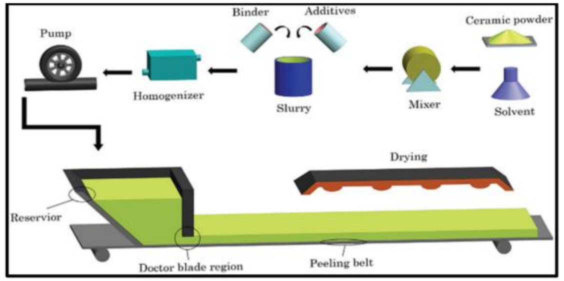
Low-temperature SOFC/EC

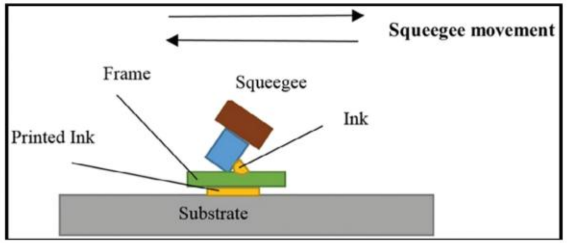
- Thin Film Process
- Various Platforms of Thin Film RSOCs
- Tailoring 3D Structured Electrode
- Thim Film Based Perovskite Deposition

Thin Film Process

Conventional Wet-chemical Process

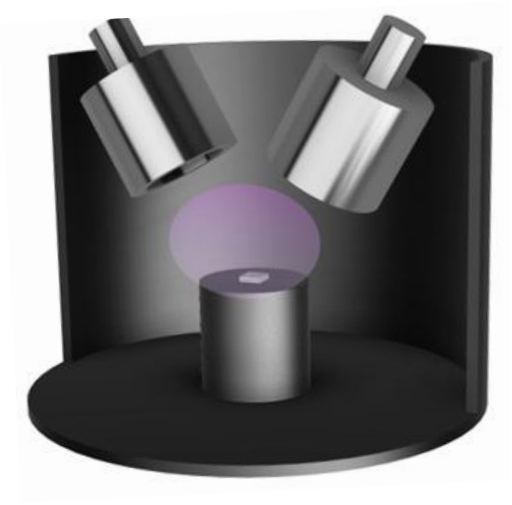


Tape Casting

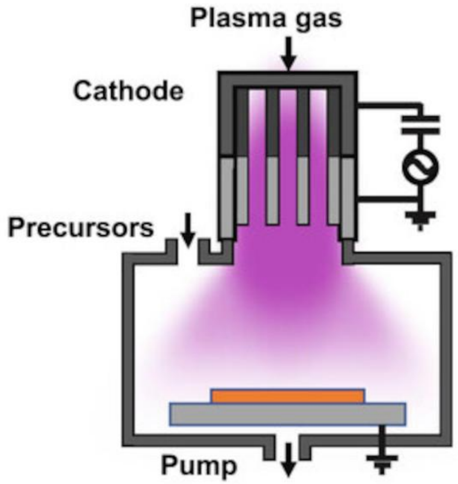


Screen Printing

Thin Film Process



Sputtering



PEALD

Challenges

- **Micro-structure** fabrication → Decreased reaction sites
- **Thick electrolyte** → High Ohmic Resistance
- Operate @ **High Temperature**
- Need **High Temperature heat treatment**

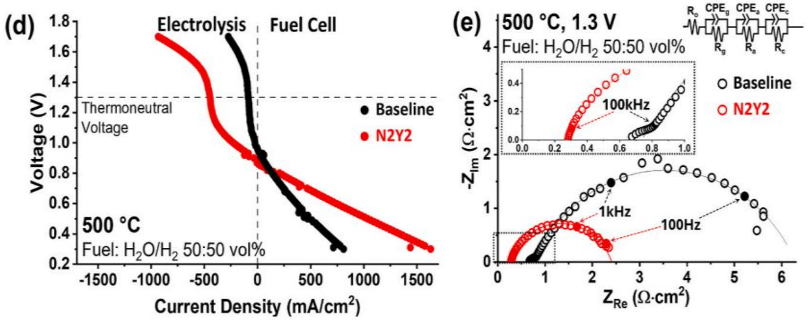
Benefits

- **Nano-structure** deposition → Increased reaction sites
- **Thin electrolyte** → Low Ohmic Resistance
- Operate @ **Intermediate / Low Temperature**
- **Low Temperature** process

Various Platforms of Thin Film RSOCs

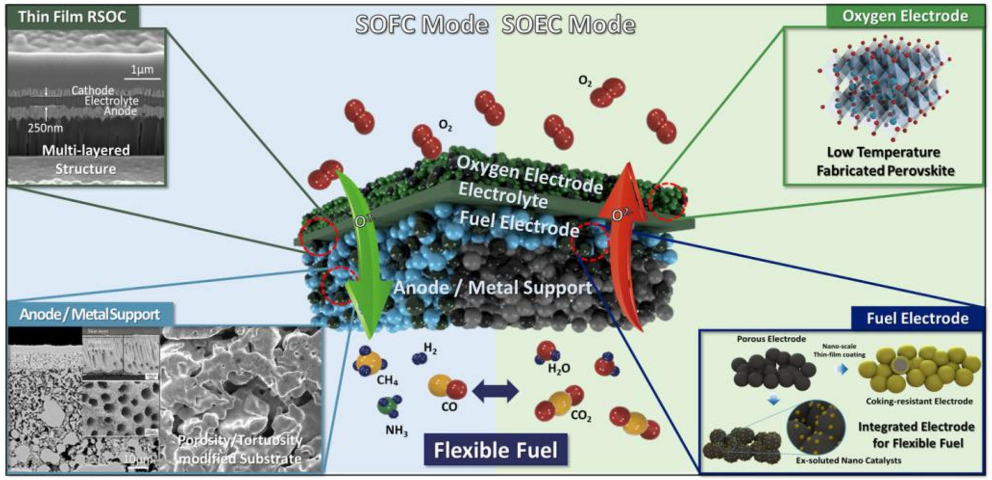
Anodic Aluminum Oxide (AAO)

Successful fabrication of high performance all-sputtered thin-film RSOCs

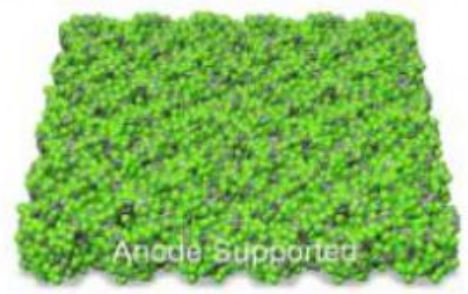


The lowest polarization resistance (2.06 Ω cm²)
An electrolysis current density of 446 mA/cm² at 1.3 V

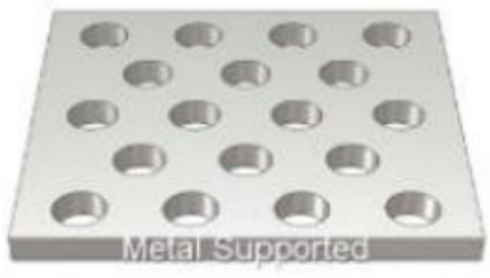
Flexible-fuel Anode / Metal - supported RSOC



Anode-Supported

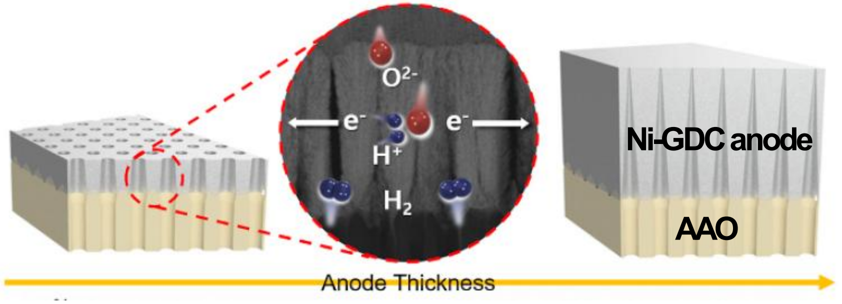


Metal-Supported

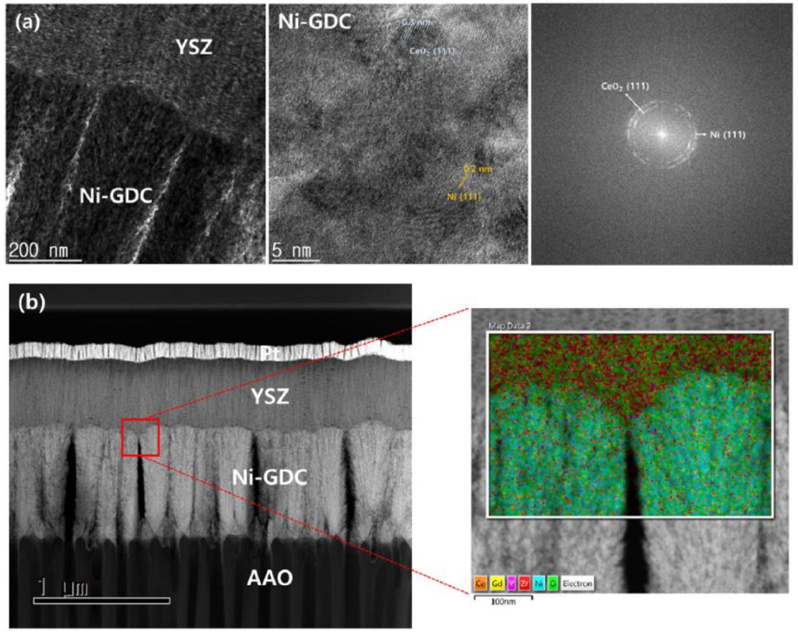


Tailoring 3D Structured Electrode

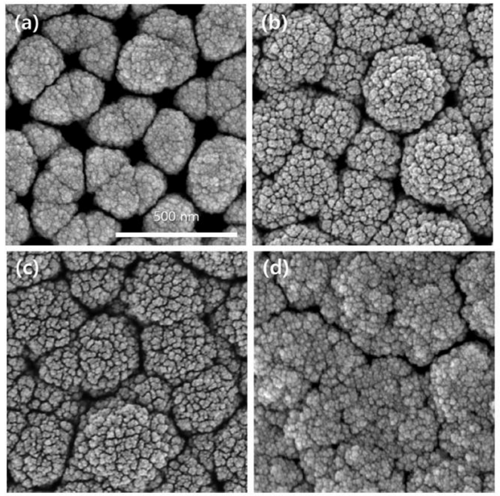
Tailoring 3D structured electrode by Sputtering

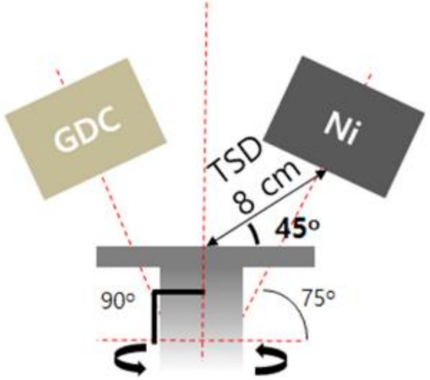


Elemental distribution Ni-GDC anode

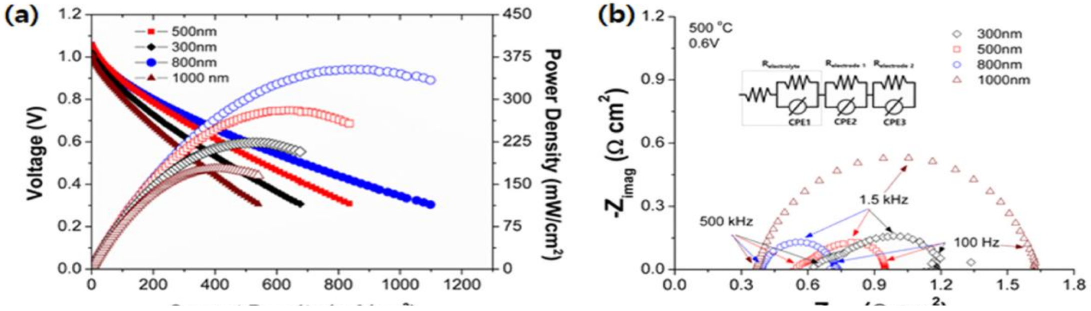


Surface analysis according to anode thickness





Electrochemical performances

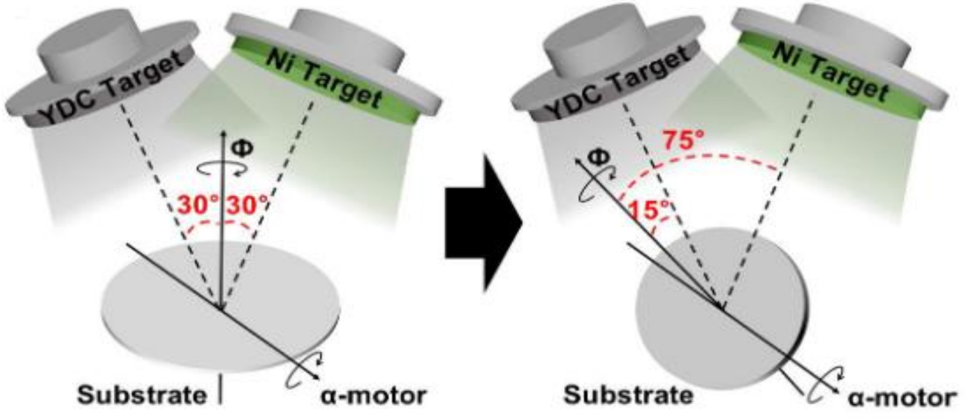


800nm thickness - Maximum power density of 353 mW/cm2 at 500

I. Choi et al. J. Power Sources (2022)

Tailoring 3D Structured Electrode

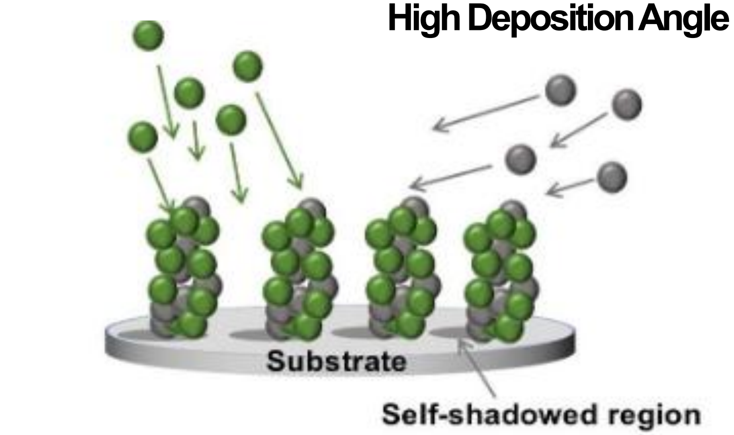
Asymmetric Glancing Angle Co-Sputtering



Symmetric co-sputtering | Asymmetric co-sputtering

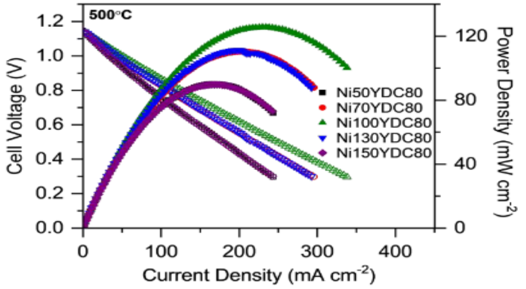
Low Deposition Angle

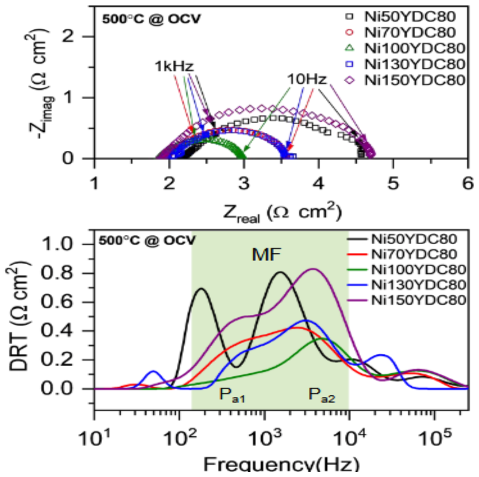
High Deposition Angle



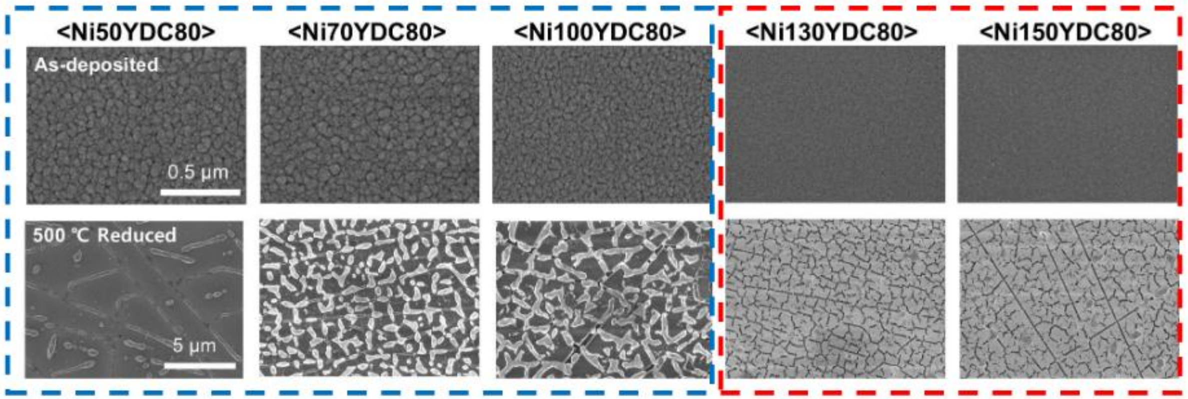
Ni atom/molecule | YDC atom/molecule

Initial performance of ScSZ electrolyte-supported fuel cell





Ostwald ripening | Particle migration and coalescence

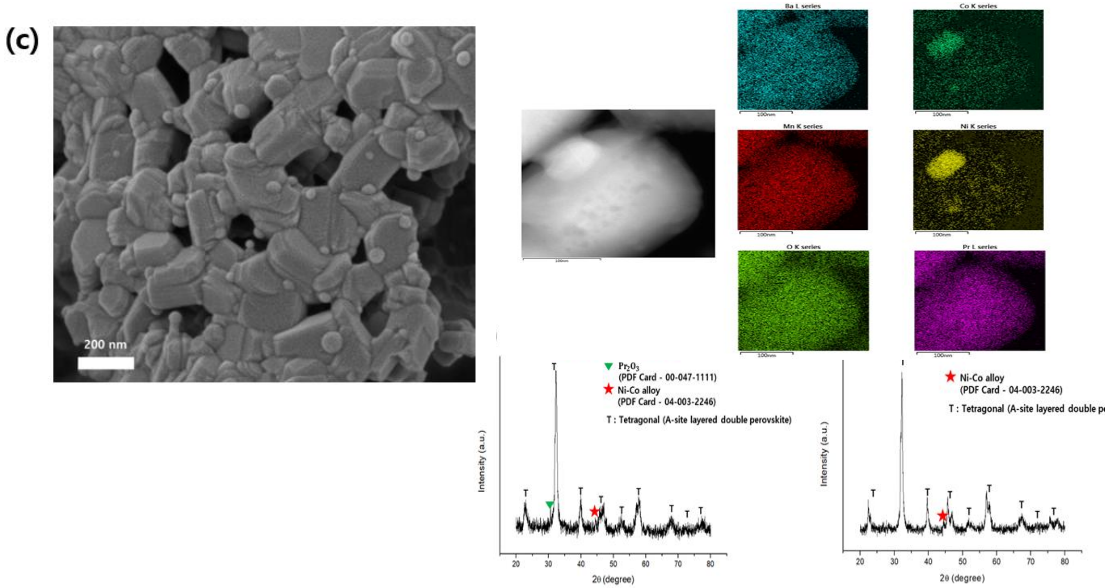


Ostwald ripening due to low Ni content PMC due to the proximity of Ni particles

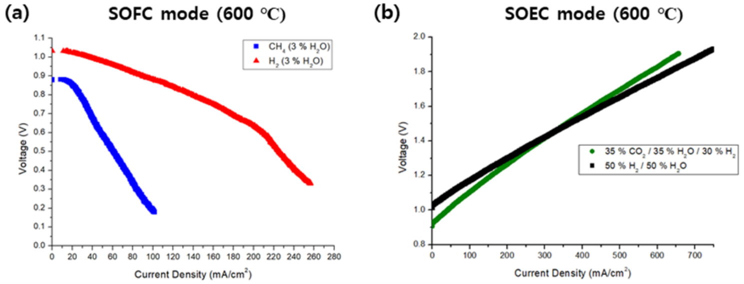
J. Hwang et al. J. Power Sources (2025)

Thin Film Based Perovskite Deposition

Sr-free Perovskite Anode Fabrication

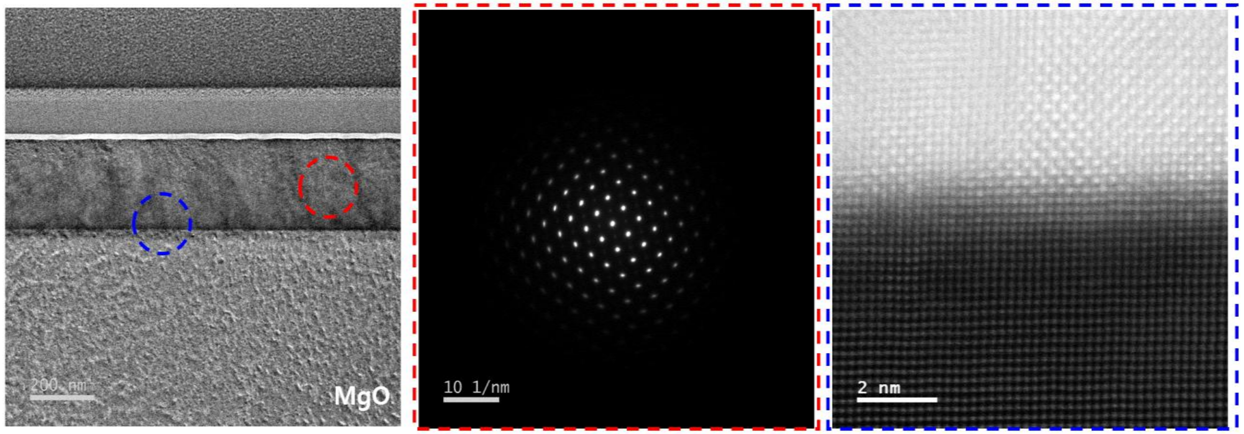


Operation of Electrolyte-supported Cells with Sr-free Perovskite Anode



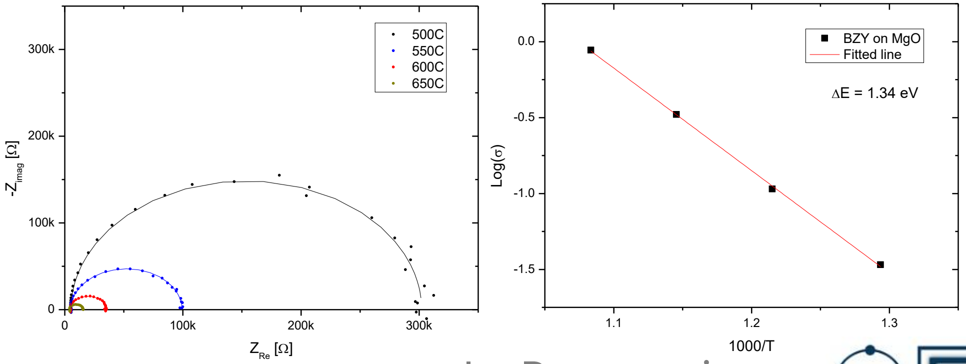
In Preparation

Crystalline BZY electrolyte Fabrication



<CTEM image of BZY thin film> <SAED pattern of BZY thin film> <STEM-HAADF of MgO-BZY interface>

In-plane Ionic Conductivity of BZY Thin Film



In Preparation

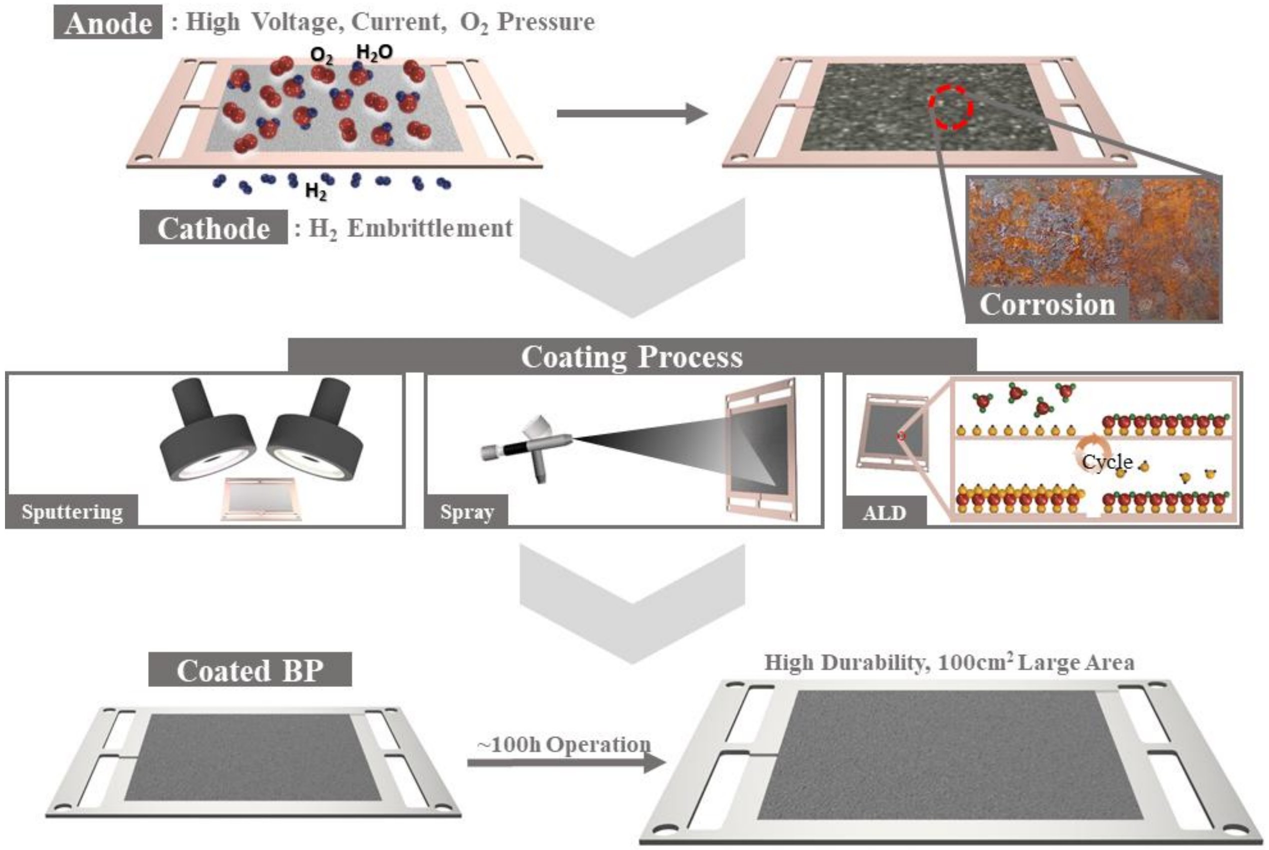
RECL Renewable Energy Conversion Lab.

PEMFC / WE

- Development of Advanced Low-cost PEMWE Bipolar Plate
- Ta/TiN Double-Layer on SUS316L for PEMFC Bipolar Plates
- In-situ potential distribution analysis within PEMWE cells

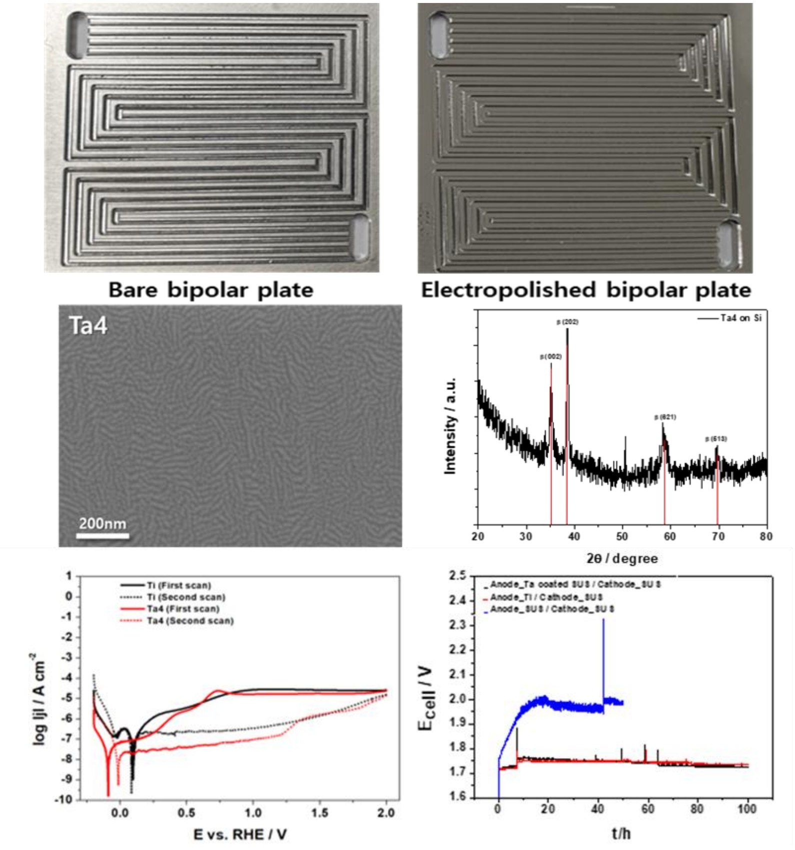
Development of Advanced Low-cost PEMWE Bipolar Plate

Development of durable BP using low-cost material



- **Industry-ready**, **high-throughput** coating route for **durable**, **low-cost** bipolar plates

Ta coated corrosion resistant BP

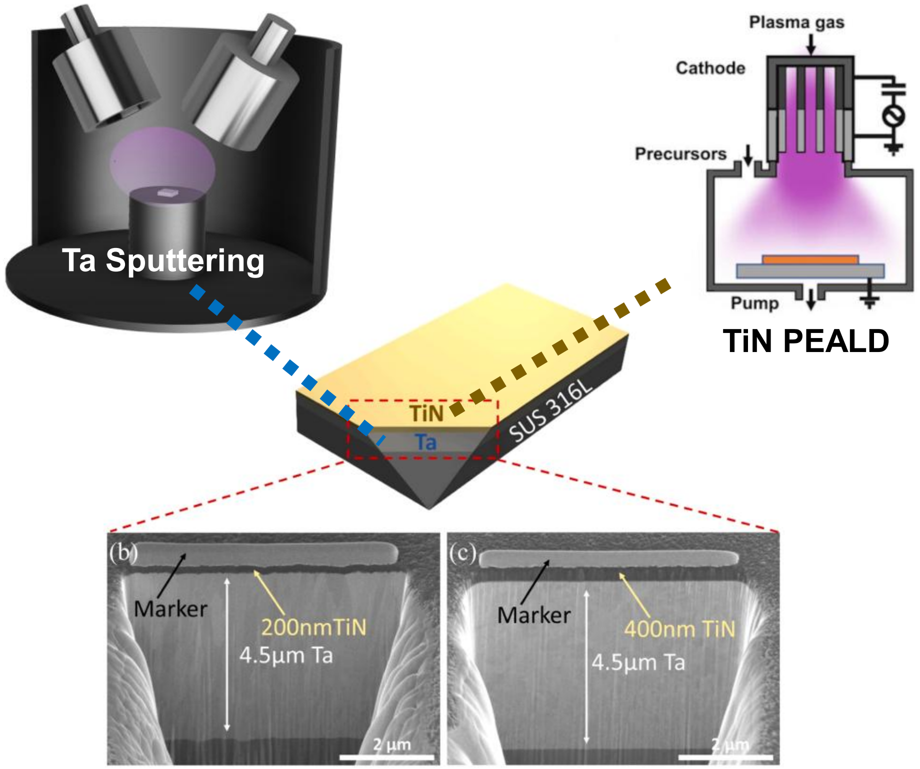


FE-SEM, XRD, Corrosion test

In Preparation

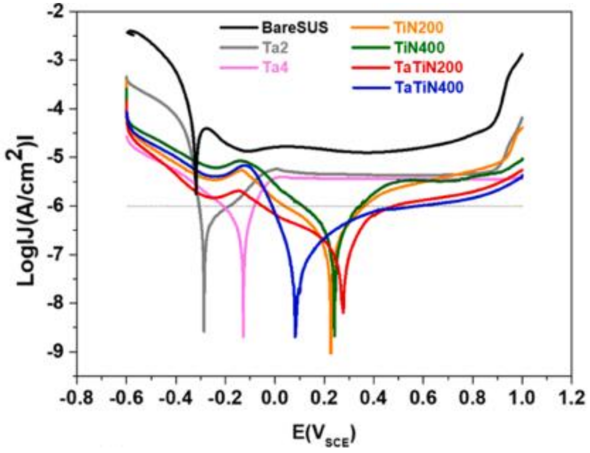
Ta/TiN Double-Layer on SUS316L: Corrosion & ICR Targets Met for PEMFC Bipolar Plates

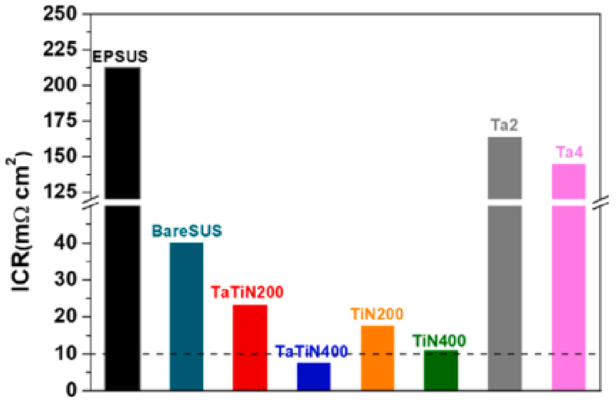
Steel BP Stack-up



- **Sputtering** : 4.5 μm Ta
- **PEALD** : 200~400 nm TiN

Low Corrosion & Low ICR





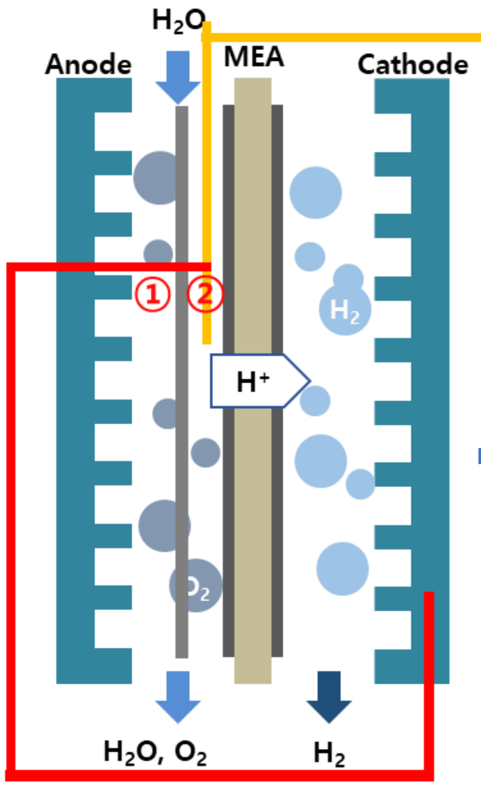
- **Corrosion** @ 0.6V(SCE)
  - BareSUS 16.0 → TaTiN 400 1.0 μA cm^{-2}
- **ICR** @ N cm^{-2}
  - BareSUS 212 → TaTiN 400 7.78 mΩ cm^2

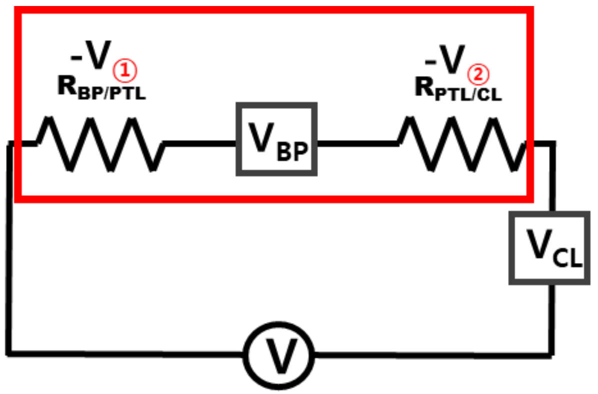
Jang et al., J. Alloys Compd. (2024)

RECL Renewable Energy Conversion Lab.

In-situ potential distribution analysis within cells to identify degradation factors of PEMWE components

Measure in-situ voltage using gold wire





Voltage Measurement @ ①,②

$V_{CL} = V_{applied} - V_{①} - V_{②}$ (Catalyst layer potential)

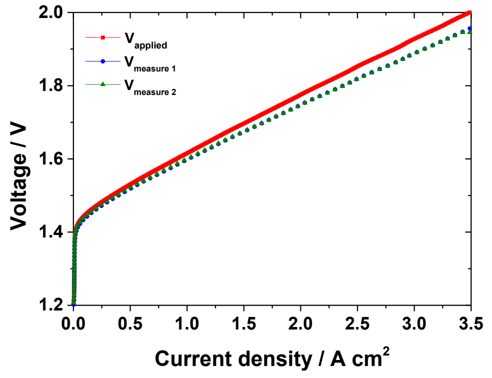
$V_{BP} = V_{applied} - V_{①}$ (PTL potential)

$V_{①}$ = Voltage drop across the bipolar plate

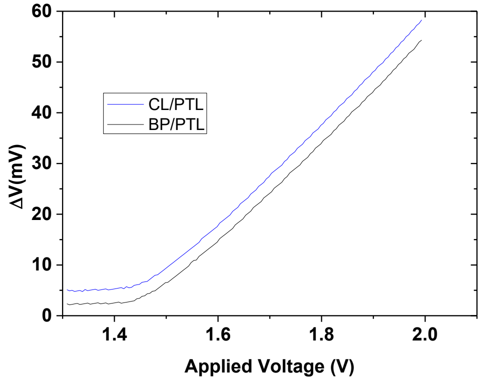
$V_{②}$ = Voltage drop across the PTL

Increase in $V_{①}+V_{②}$ under BP/PTL oxidation

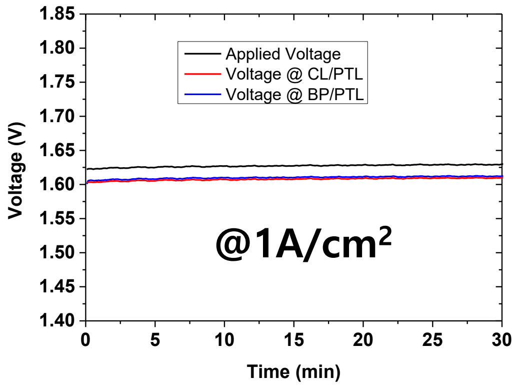
Actual exposure potential

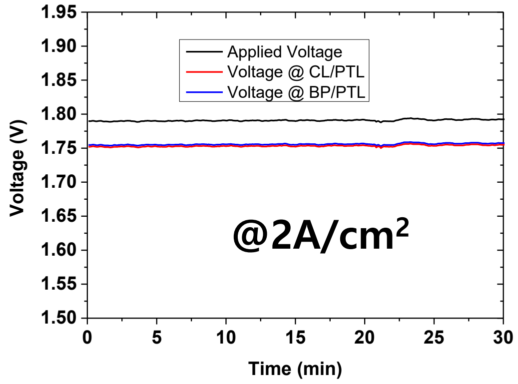


Results under LSV



$V_{①}$ & $V_{②}$ vs. applied Voltage



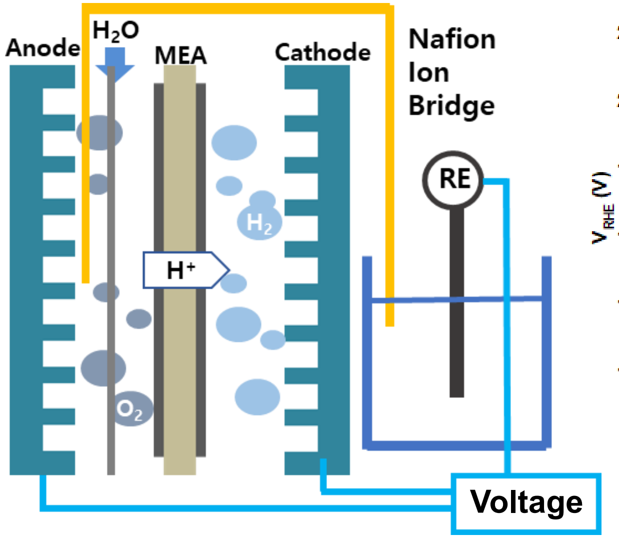


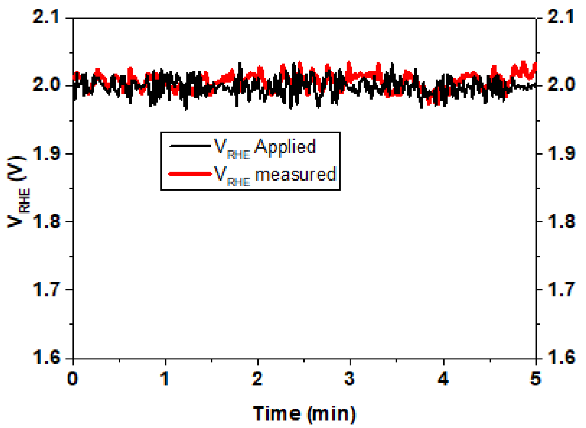
Results from constant-voltage experiments

- <u>In-situ measurement of BP/PTL potential</u> inside the cell, independent of other component effects
- Voltage drops ($V_{①}$&$V_{②}$) at BP/PTL or PTL/CL interfaces reveal voltage losses due to <u>corrosion and resistance inrease</u>

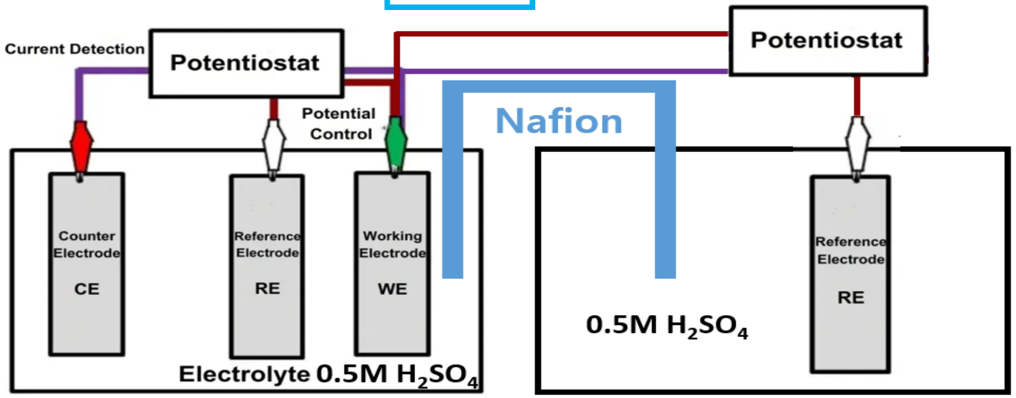
In-situ potential distribution analysis within cells to identify degradation factors of PEMWE components

Measure Electrochemical voltage



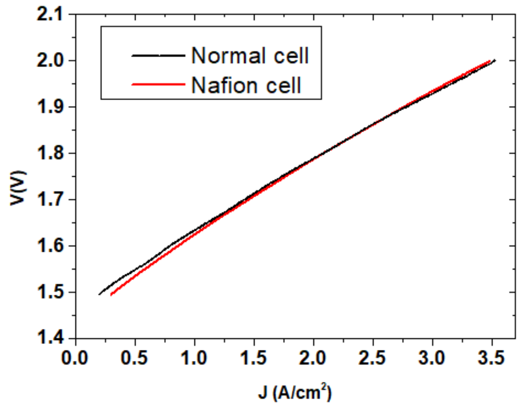


Applied Voltage in 3-electrode test/
Voltage measured inside Nafion-bridge cell

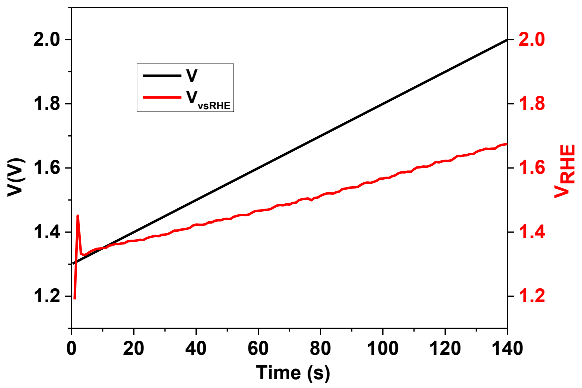


- In-situ electrochemical potential measured by inserting Nafion 212 ion bridge into BP/PTL

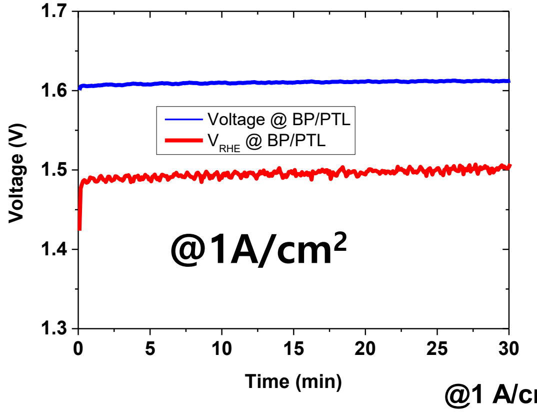
Actual exposure potential

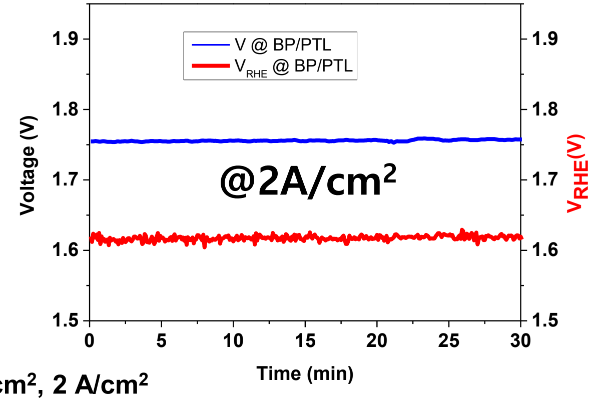


Normal cell/Nafion cell LSV



Voltage in LSV/Electrochemical potential





@1 A/cm², 2 A/cm²
Bipolar plate potential / Electrochemical potential

Observed ~0.2 V decoupling compared with actual exposure potential

BP coating and contamination properties show lower potential than actual exposure

Fuel Cell System Pre-diagnosis

- Online Diagnosis of PEMFC Using Fast-EIS
- Pre-diagnosis of PEMFC Flooding & Drying

Online Diagnosis of PEMFC Using Fast-EIS

1. Necessity of Fast EIS for Fuel Cells

Why Fast EIS is Critical:

- Traditional EIS limitations: Several minutes to hours, incompatible with real-time operation
- Operational challenges: Frequent faults (flooding, drying, air starvation) drastically reduce lifetime
- Diagnostic gaps: Standard sensors only provide limited internal state information
- Cost-benefit: Early fault detection extends lifetime and reduces maintenance costs significantly

Fast EIS Method:

- Technique: Injects Maximum Length Sequence (MLS) disturbance current via Current Pulse Injection (CPI) circuit
- Processing: Continuous Wavelet Transform (CWT) and Maximum Likelihood Estimation
- Time reduction: Complete measurement in ~16 seconds (vs. traditional methods taking minutes)

* Lu, H., et al. (2019). Journal of Power Sources

Online Diagnosis of PEMFC Using Fast-EIS

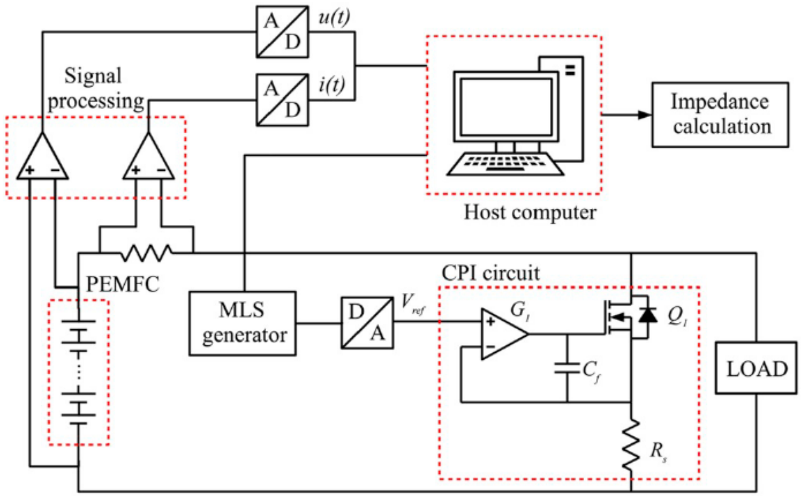
2. Fast-EIS Using Maximum Length Sequence

MLS Properties:

- Pseudo-Random Binary Sequence (PRBS) type
- White-noise-like frequency characteristics
- Generated via n-stage shift register: $a_n = (\sum_{i=1}^{n} c_i a_i) mod(2)$

Frequency Specifications:

- Spectral spacing: $\Delta f = \frac{f_s}{2^n - 1}$
- Bandwidth: $f_{min} = \frac{f_s}{2^n - 1}$ to $f_{max} = \frac{f_s}{3}$, $T = \frac{2^{11}-1}{200} + \frac{2^{13}-1}{1500} \approx 16\ s$.



Schematic of the fast EIS measurement system

MLS	n-bits	f_s	Coverage	Duration
1	11	200Hz	0.5-60Hz	10.2s
2	13	1500Hz	60-500Hz	5.5s

Online Diagnosis of PEMFC Using Fast-EIS

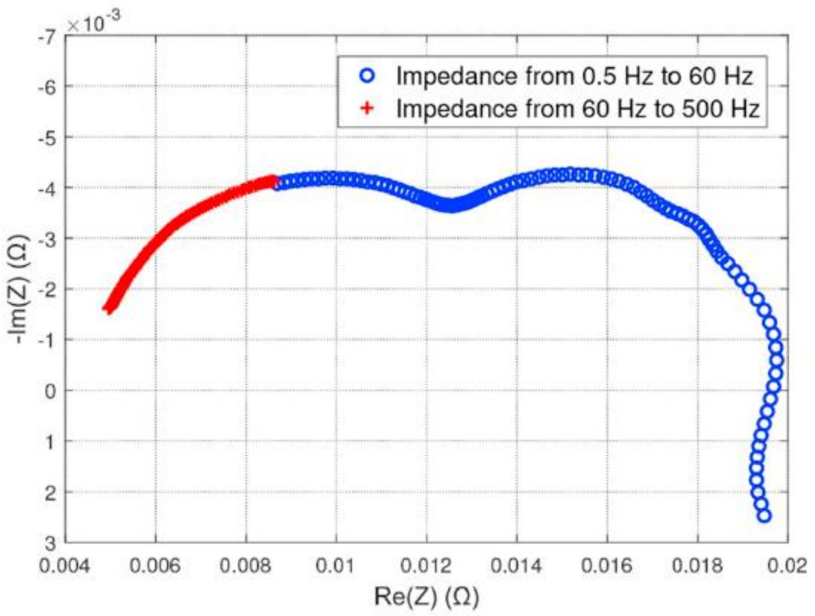
3. Fuel Cell Diagnosis and Fault Detection

Diagnostic Parameters from ECM:

- R_m (Ohmic Resistance):Indicates membrane hydration state
- R_p (Polarization Resistance): Reflects charge transfer/oxygen reduction reaction
- R_w (Warburg Resistance): Represents mass transfer limitations

Fault Detection Capabilities:

- Drying: Increased R_m (membrane dehydration)
- Flooding: Increased R_p and R_w (blocked gas diffusion)
- Air Starvation: Significantly increased R_w (limited reactant supply)

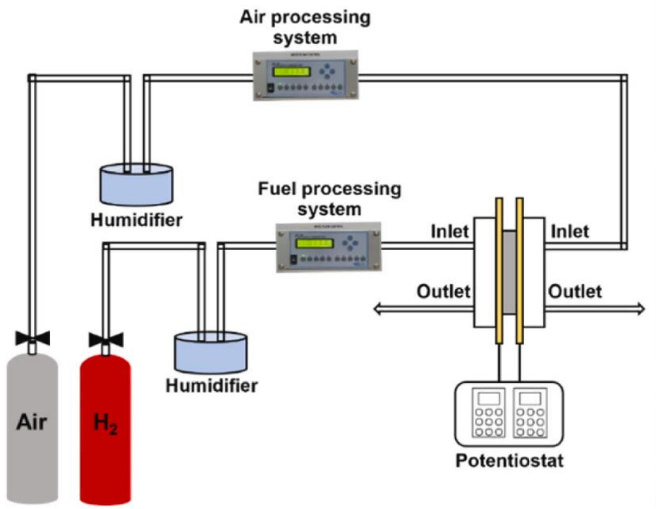


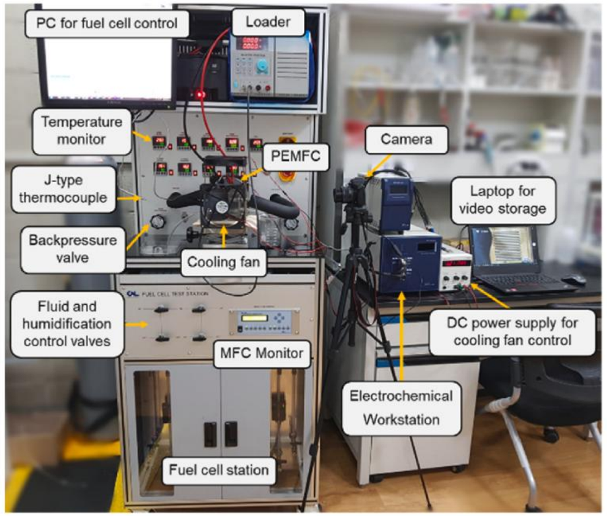
Result of the EIS estimation

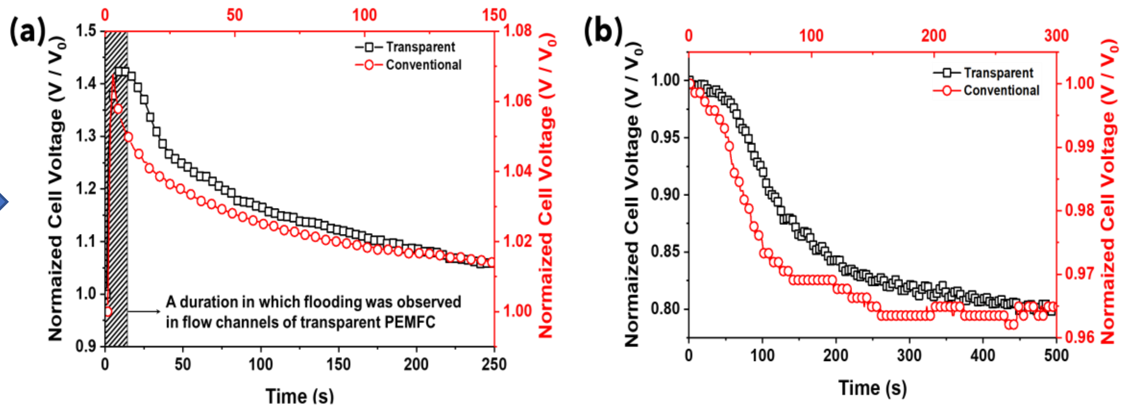
Pre-diagnosis of PEMFC Flooding & Drying

Background

- Challenge: PEMFC performance degraded by water management issues (flooding/drying)
- Problem: Real-time fault detection is difficult, hindering stable operation
- Objective: Develop a pre-diagnosis system for flooding and drying to enable preventative action
- Approach: Use deep learning (LSTM, CNN) to analyze time-series data for fault prediction







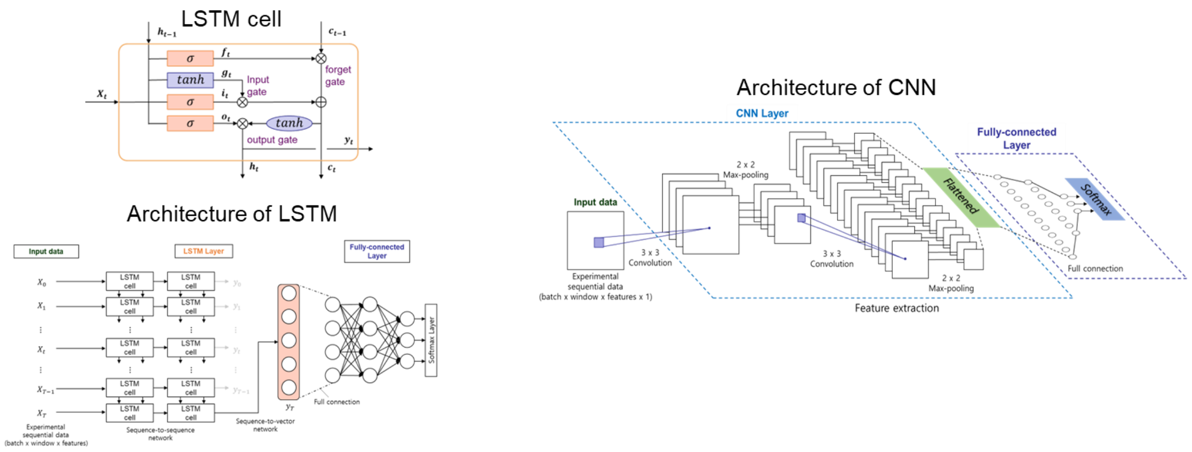
Experimental setup for PEMFC operations

Kim et al., Energy. (2023)

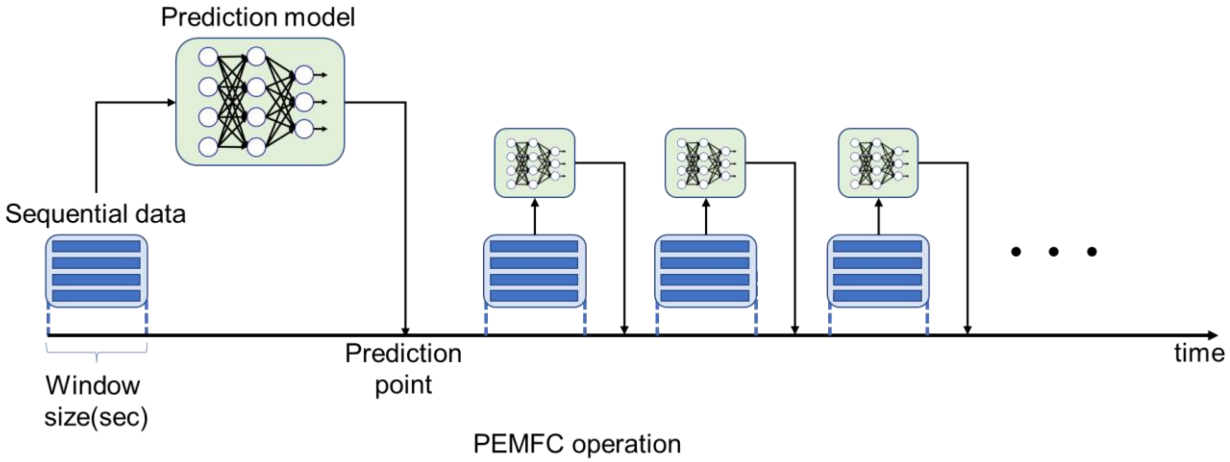
Pre-diagnosis of PEMFC Flooding & Drying

Key Result

- Model Development: Built a pre-diagnosis system using LSTM and CNN models
- Ensemble Method: Improved accuracy and prevented overfitting with a bagging ensemble method
- Accuracy: Achieved 89.1% accuracy for 30-second-ahead fault prediction
- Real-Time Applicability: Fast execution (<300ms) allows real-time monitoring and pre-diagnosis up to 60s in advance.
- Preemptive control strategy based on DDPG algorithm.



Flooding and Drying Prognostic Algorithm



Real-time monitoring system

Kim et al., Energy. (2023)

Fuel Cell Hybrid Electric System Management

- Fuel Cell Vehicle Energy Management
- System-Level Modeling of Fuel Cell Electric Powertrains in Heavy-Duty Hydrogen Vehicles
- Energy Management and Design of Fuel Cell System for Aircraft
- CO_2 Emissions of Fuel-cell Battery Hybrid System for Large Ships
- Comprehensive Techno-economic Assessment of SOFC Hybrid System in Marine Applications

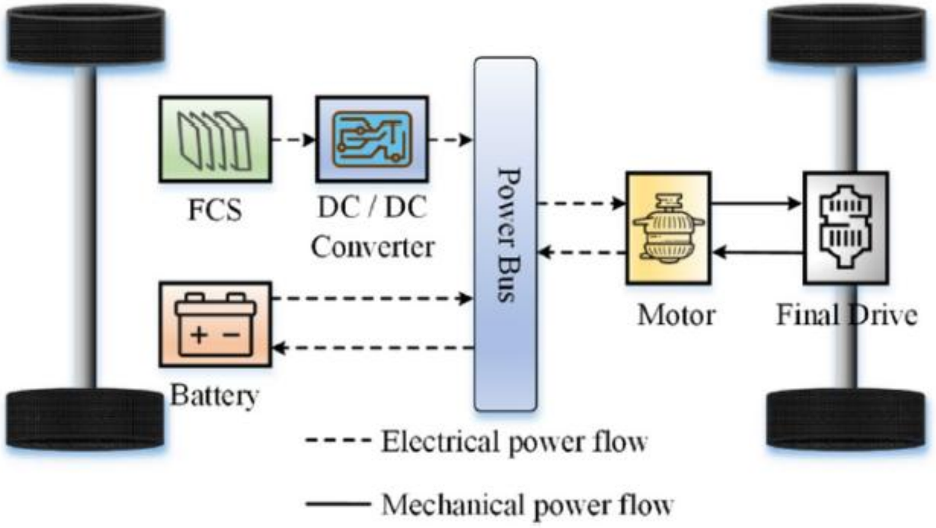
RECL Renewable Energy Conversion Lab.

Fuel Cell Vehicle Energy Management

1. Improved Soft Actor-Critic Energy Management

Why Energy Management is Critical

- Dual Power Sources: FCHVs use fuel cells (primary) and batteries (auxiliary) requiring optimal coordination
- Fuel Cell Degradation: Poor management causes rapid degradation from start-stops, load changes, and extreme loads
- Economic Impact: Inefficient energy distribution increases hydrogen consumption and reduces component lifespan



The power train architecture of the FCHV

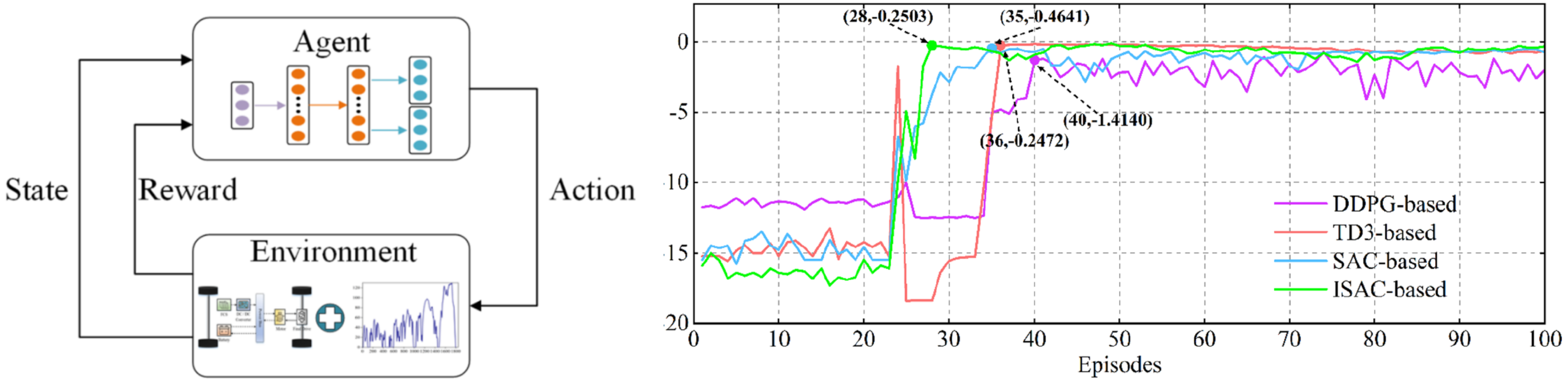
Zhang et al., IJPEM-GT. (2024)

Fuel Cell Vehicle Energy Management

1. Improved Soft Actor-Critic Energy Management

Our Innovative Approach

- ISAC Algorithm: Improved Soft Actor-Critic with maximum entropy for better exploration
- Smart Experience Sampling: Prioritized Experience Replay (PER) + Emphasizing Recent Experience (ERE)
- Holistic Optimization: Nonlinear fuel cell degradation model considering real-world aging factors
- Constrained Action Space: FCS power limited to 3.5-40 kW to avoid damaging conditions



Framework of DRL algorithms and reward curves

Fuel Cell Vehicle Energy Management

2. Superior Performance vs. State-of-the-Art DRL Methods

Key Result: ISAC-based EMS achieves best convergence, fuel economy, and 95%+ durability improvement

Convergence Speed	Fuel Economy	Fuel Cell Durability	Real-World Adaptability
• 47.89% faster average convergence • Most stable training performance • Outperforms DDPG, TD3, SAC	• 7.87% better than DDPG • 2.79% better than TD3 • Only 2.37% gap to optimal DP	• 97.67% degradation reduction • 42.12x lifetime improvement • Zero harmful operating conditions	• Validated on multiple driving cycles • Maintains SOC within 0.4-0.8 • 5.81% better on new cycles

Zhang et al., IJPEM-GT. (2024)

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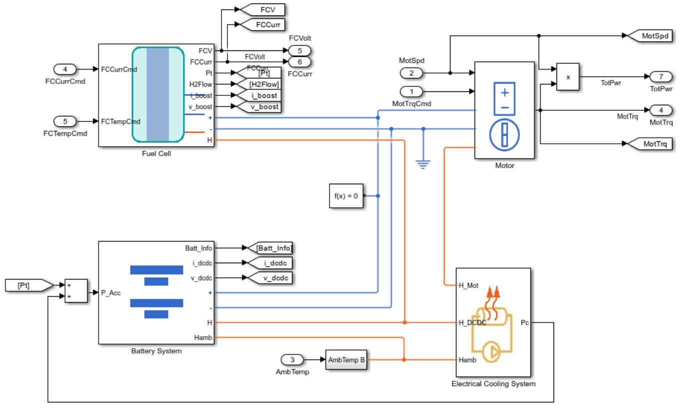
System-Level Modeling of Fuel Cell Electric Powertrains in Heavy-Duty Hydrogen Vehicles

Background

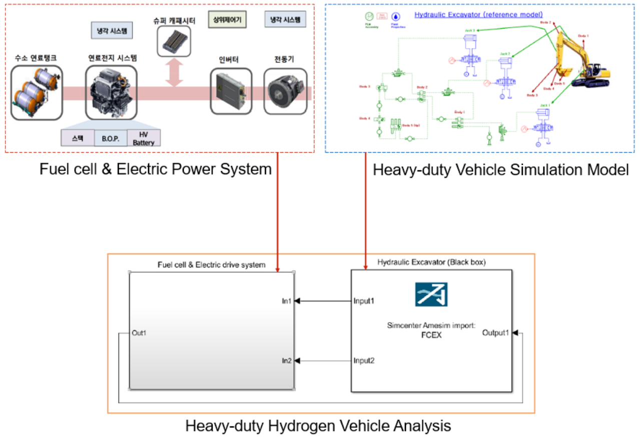
- Hydrogen-powered heavy machinery requires advanced model of fuel cell, hydrogen storage, and thermal management subsystems under various dynamic loads.

Key Results

- Hydrogen-powered heavy machinery requires advanced model of fuel cell, hydrogen storage, and thermal management subsystems under various dynamic loads.



Detailed Simulation of Fuel Cell Subsystem

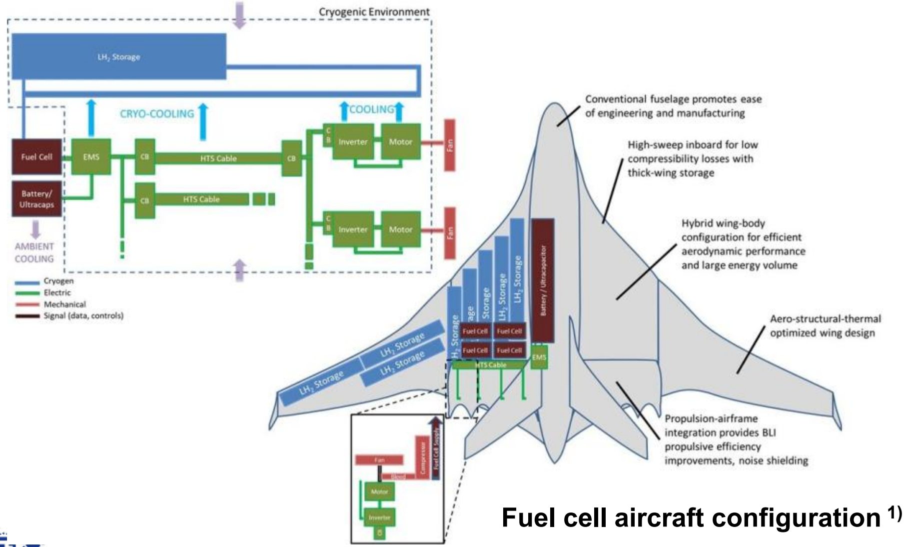


Simulation Model of a Hydrogen-powered Excavator Model

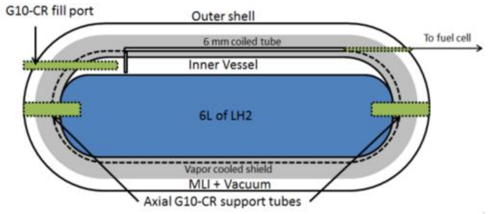
Energy Management and Design of Fuel Cell System for Aircraft Applications

Background

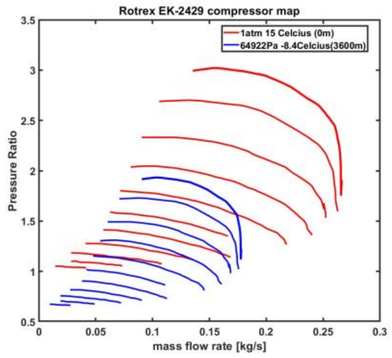
- Higher energy density is required compared to ground-based hydrogen fuel cell mobility.
- Optimization of stack operating parameters is essential, including reaction temperature, humidity, stoichiometric ratio, and pressure.
- Due to lower ambient pressure and temperature compared to ground conditions, optimal design of auxiliary systems such as cooling & heating system and compressor is required for stable fuel cell operation.



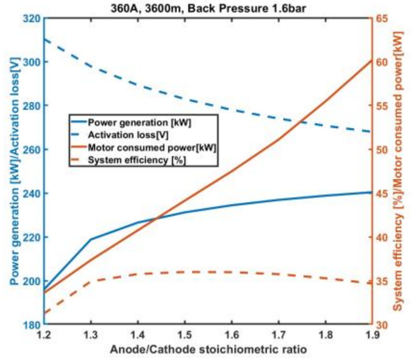
Fuel cell aircraft configuration [1)]



Schematic diagram of LH_2 tank [2)]



Variation of compressor map with altitude



Effect of stoichiometric ratio on fuel cell power and system efficiency

1) University of Illinois at Urbana-Champaign Department of Aerospace Engineering
2) Garceau, N.M. et al. Mater. Sci. Eng. 2015.

In Preparation

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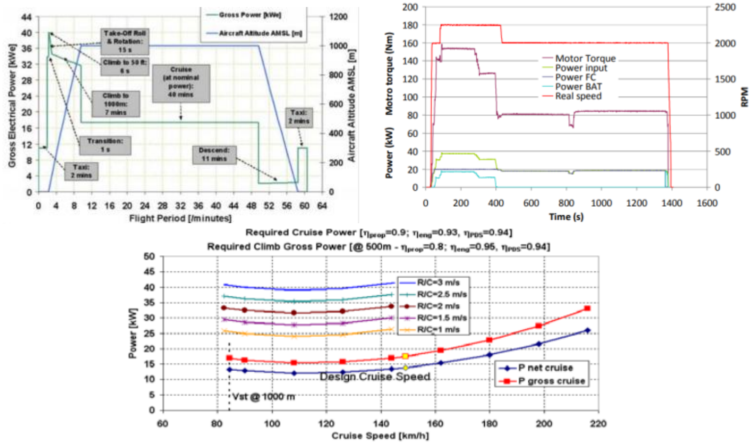
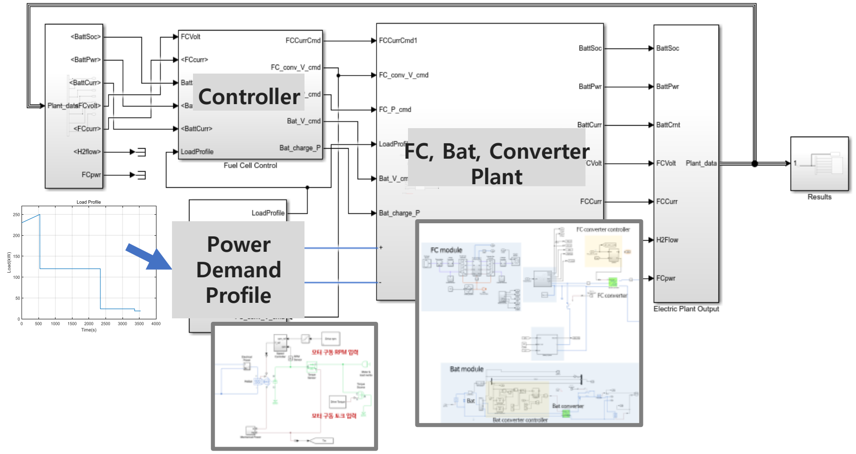
Energy Management and Design of Fuel Cell System for Aircraft Applications

Key Results

- 250 kW fuel cell battery hybrid propulsion system model
- System modeling includes fuel cell stack, balance of plant (BOP), battery, converter, and motor drive system
- Battery capacity determined equivalent to a 100 kW fuel cell, based on required power profile and battery C-rate
- Application of optimized control and operation strategy for each mission profile
- In preparation for a paper.



Power distribution between fuel cell and battery under the mission profile of the ENFICA-FC aircraft [1)]



Configuration of fuel cell battery hybrid propulsion system model

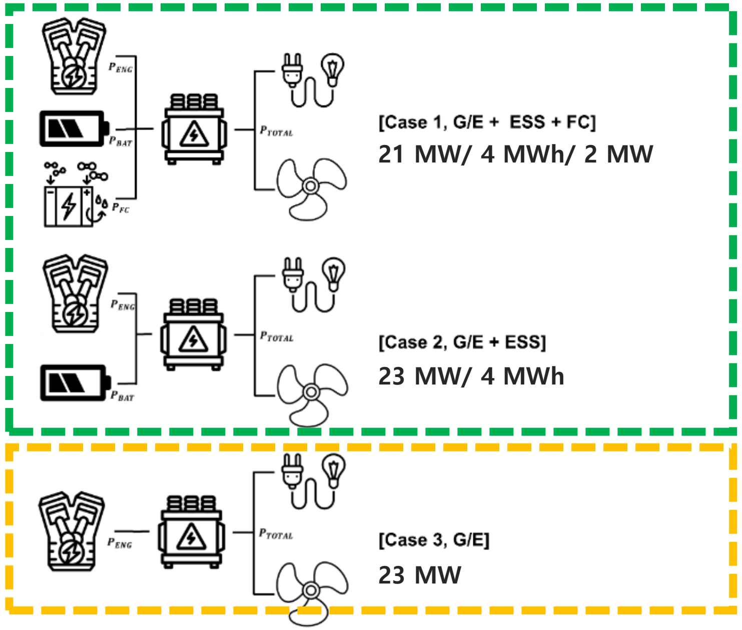
1) Romeo, G, et al. 2013

In Preparation

CO_2 Emissions of Fuel-cell Battery Hybrid System for Large Ships

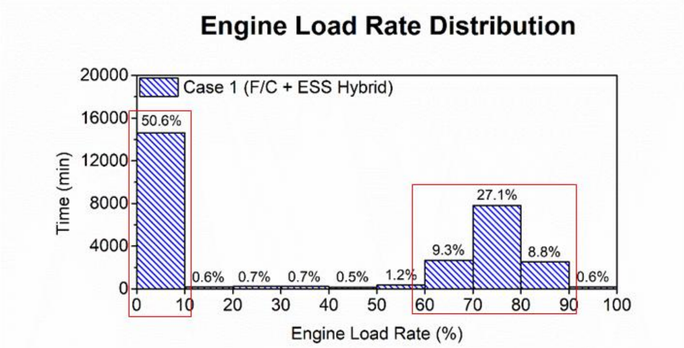
Overview

- Predict the fuel consumption and CO_2 emissions of the SOFC+ESS+G/E hybrid system

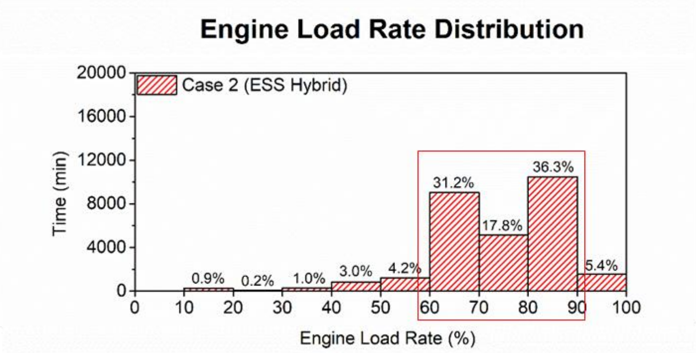


Key Result

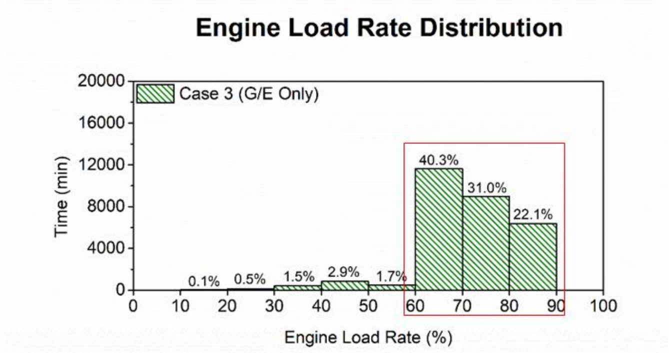
- CO_2 Emission Reduction: 6.1% lower than conventional power sources.
- Generator Engine: Operates intermittently at a high load rate.
- ESS: Reduces the generator engine's operation.
- SOFC System: Higher efficiency compared to generator engines.



[G/E load rate distribution in SOFC ESS G/E case]



[G/E load rate distribution in G/E ESS case]



[G/E load rate distribution in G/E only case]

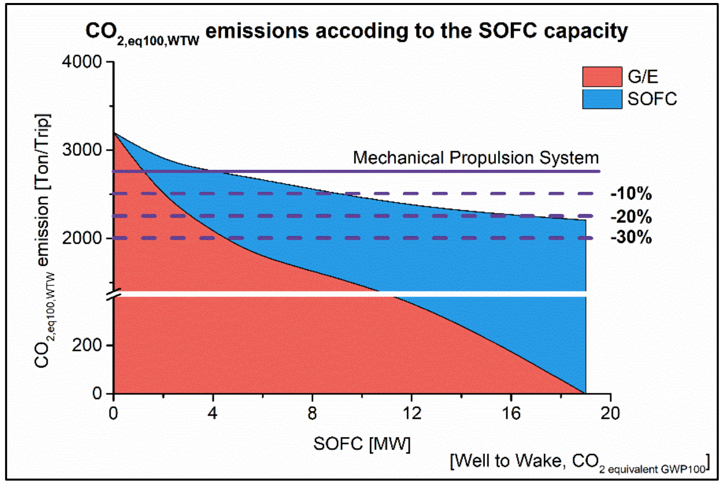
Lee et al., IJOGE. (2025)

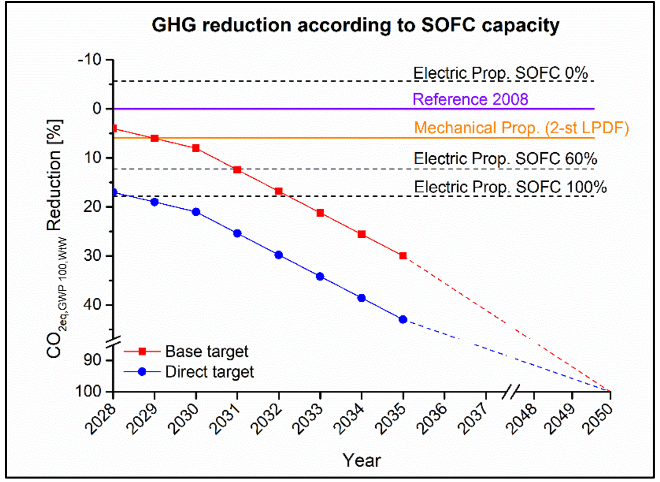
Comprehensive Techno-economic Assessment of SOFC Hybrid System in Marine Applications

Key Result

- Total cost of ownership (TCO) = CAPEX + OPEX
  - Initial Investment Cost (CAPEX): The prices of the SOFC, ESS, and G/E.
  - Operating Expenses (OPEX): Fuel price, Carbon tax, and stack/ESS replacement.

- SOFC Competitiveness: Increases with 'Well-to-Wake' carbon emission measurement.
- Economic feasibility: SOFC stack degradation rate is a critical factor.
- MEPC 83 Mid-term Targets: 100% SOFC system predicted to miss targets starting in 2029 (Direct) and 2033 (Base).





Under review

Thank you for your attention

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