

Offshore Wind to Hydrogen – Modeling, Analysis, Testing and International Collaboration Work

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Project ID: TA060

DOE Hydrogen Program
2024 Annual Merit Review and Peer Evaluation Meeting

Project Goals

This project explores electrolytic hydrogen production from an offshore wind turbine by:

- **Modeling:** Simulate an offshore wind turbine and generate power output profiles
- **Analysis:** Analyze offshore conditions and determine operational modes of the stack
- **Testing:** Perform hardware testing to evaluate dynamic characteristics
- **International Collaboration Work:** Share learnings and publish

Potential Outcomes:

- Accelerate development of an integrated, in-turbine offshore wind hydrogen system
- Support two DOE Energy Earthshots – Hydrogen and Floating Offshore Wind

Overview

Timeline and Budget

- Project Start Date: 01/01/2022
- FY23 DOE Funding: \$410k
- FY24 Planned DOE Funding (if applicable): \$0 (carryover)
- Total DOE Funds Received to Date^{**}: \$710k

^{**} Since the project started

Barriers

- Demonstration and performance evaluation of an electrolyzer system coupled with an offshore wind turbine
- Dynamic characterization of stack response and degradation effects

Partners [See also TA051]

- Giner (electrolysis characterization)
- GE Vernova Advanced Research (wind turbine integration)
- HYGRO – Netherlands (systems integration)
- Plug Power (stack supplier)
- TNO – Netherlands (international collaboration)

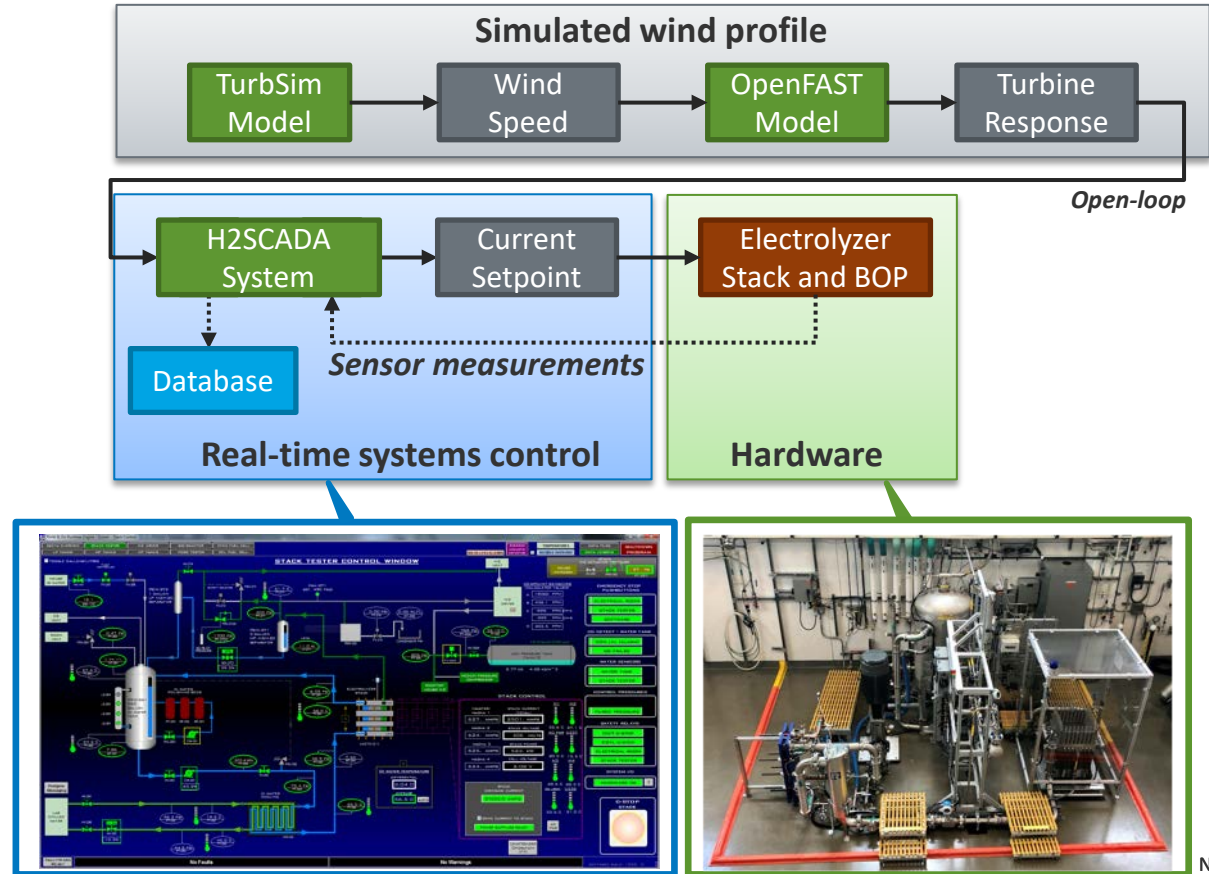
Relevance and Potential Impacts

- **Relevance:**
 - Offshore wind is still early market, especially in the United States
 - Offshore conditions and requirements are very different compared to onshore
 - System design and operations must be considered for harsh and remote locations
 - Industry interest is considerable
- **Potential Impacts:**
 - Leverage high-throughput, economically-scalable hydrogen delivery via undersea pipelines
 - Address grid and coastal constraints as renewable electricity is built out
 - Support two DOE Energy Earthshots – Hydrogen and Floating Offshore Wind
- **Objectives in FY24:**
 - Simulate an offshore wind turbine and analyze operational modes of an electrolyzer stack
 - Perform hardware testing of an electrolyzer stack under simulated wind conditions
 - Gain insights from high-fidelity data collected from hardware experiments

Approach: Experimental Design

- TurbSim & OpenFAST to create power profiles
 - Simulate various wind speeds and power outputs
 - Analyze profiles for stack operation
- H2SCADA to send setpoints while ensuring safety
 - Install a project stack
 - Perform break-in testing (500 hrs) and dynamic testing (200 hrs)
 - Collect high-fidelity measurements (~80 ms) for characterization

Build an analysis framework and integrate it with the H2SCADA system for hardware evaluation.

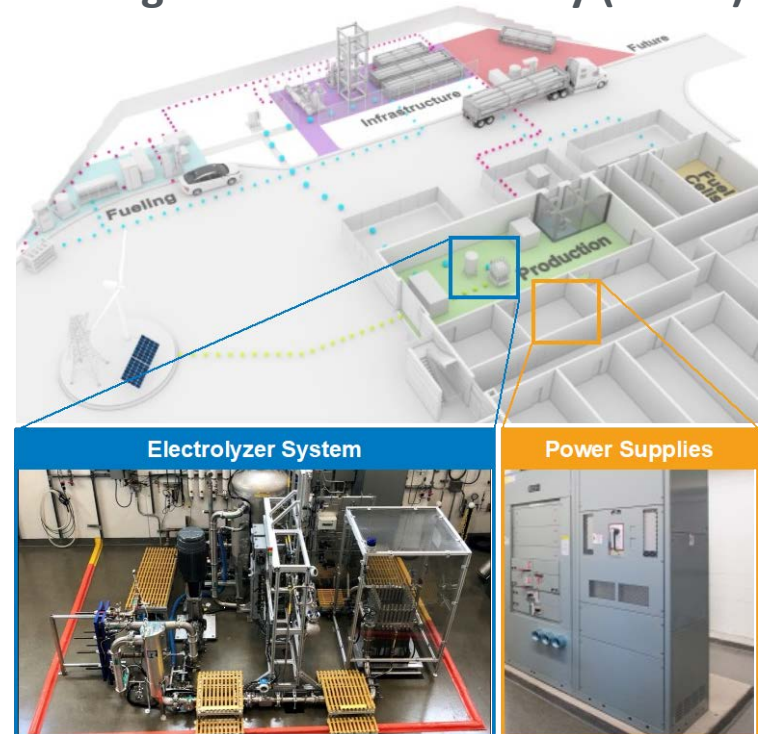


Approach: NREL's Electrolyzer Testbed to De-risk Integration Challenges

Identify fast-control effects due to wind turbine controls on the PEM electrolyzer stack

- Capability to test a 1-MW electrolyzer stack
 - 4,000 Adc and 250 Vdc power supplies
- Highly configurable balance-of-plant and H2SCADA system
 - Mitigate systems integration challenges
 - Diagnose operational problems if any
 - Ensure safety while an unattended mode of operation

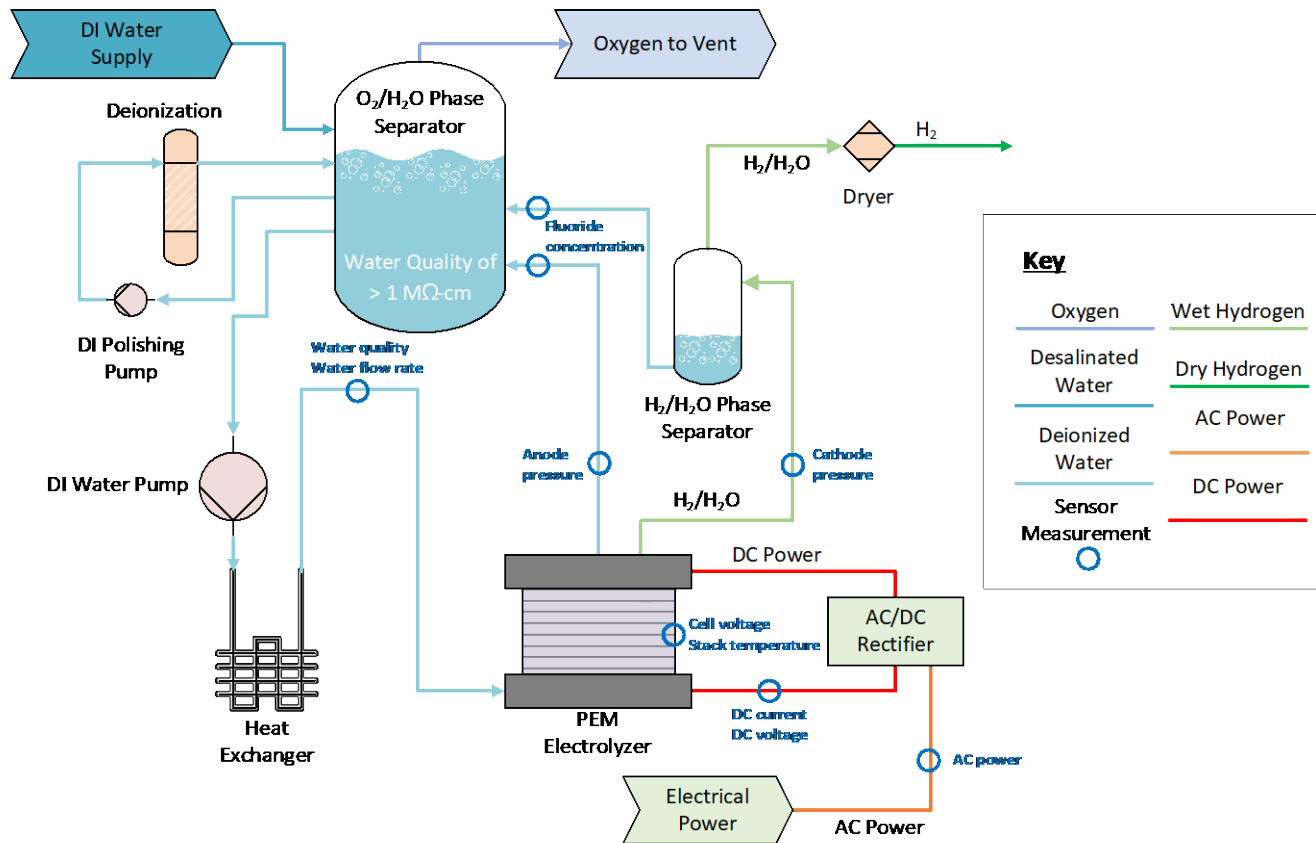
NREL's Hydrogen Infrastructure Testing and Research Facility (HITRF)



Approach: Sensor Measurements for Characterization

- Power supply
 - AC power
- Electrolyzer stack
 - Current
 - Voltage
 - Cell-level voltage
 - Temperature
 - Anode and cathode pressures
 - H₂ mass flow rate converted from stack current
- Water loop
 - DI water quality
 - Water flow rate
 - Anode and cathode fluoride concentrations (sampling, then IC)

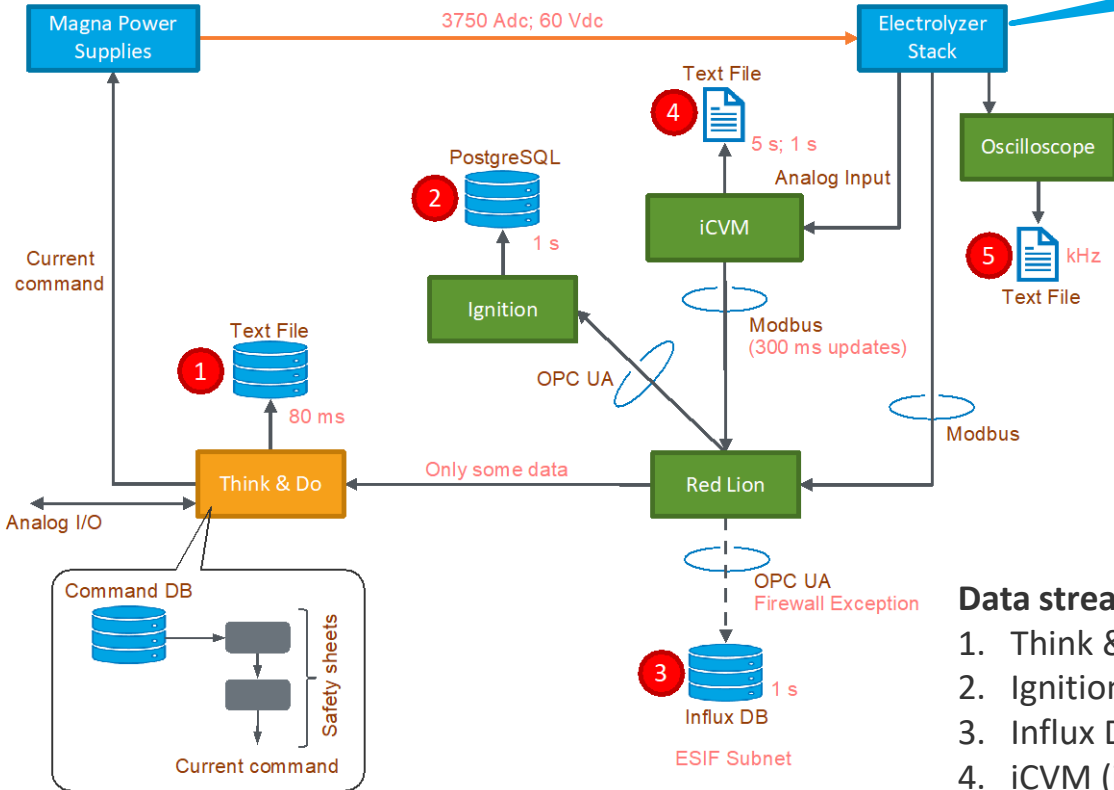
Characterize electrolyzer performance using synchronized sensor data.



Approach: Safety Planning and Culture

- Work for this project has been done in agreement with NREL's safety culture and Hazard Analysis Review procedures
- Design of the Electrolyzer Stack Test Bed underwent an extensive safety review process prior to assembly and commissioning
 - Completed an extensive Process Hazard Analysis (PHA) with relevant NREL subject matter experts (SMEs)
 - NREL "Authorities Having Jurisdiction" (AHJs) for fire and pressure safety participated in the PHAs
- The best design, construction, and safety practices learned from a decade of experience building and operating hydrogen systems at NREL were implemented in this project.
 - Training and requirements for build, operation, and maintenance of the hydrogen systems emphasize:
 - Reviewing the safety hazards of every task, every time
 - Everyone has "Stop Work" authority and the expectation to use it proactively
 - Immediate reporting of safety issues for review by SMEs and dedicated safety professionals
 - Prioritizing personnel safety above all else
- The established safety processes required per NREL's prime contract with the DOE exempted this project from Hydrogen Safety Panel review

Accomplishments: Installed Plug Power's 30-Cell Stack and Implemented High-Fidelity Data Acquisition System

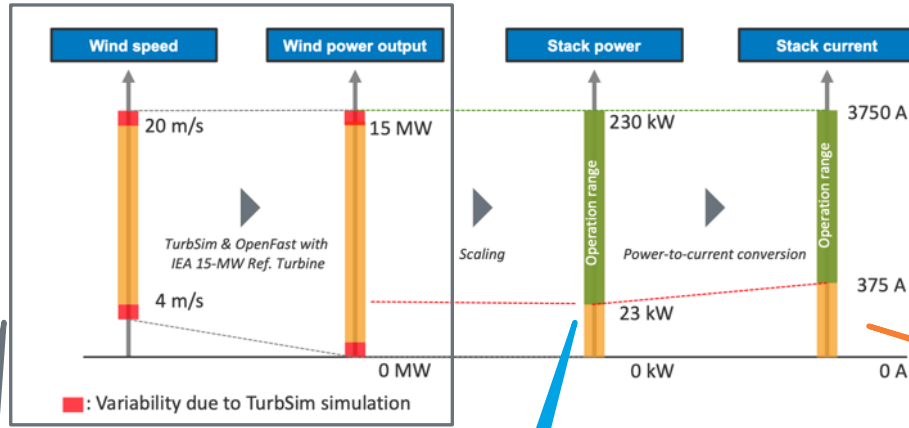


- 30-cell stack to reach ~225 kW input power
- **Different anode materials for each cell** (rainbow stack; not a commercial stack)
- DC power supply to meet 3750 A and ~60 V

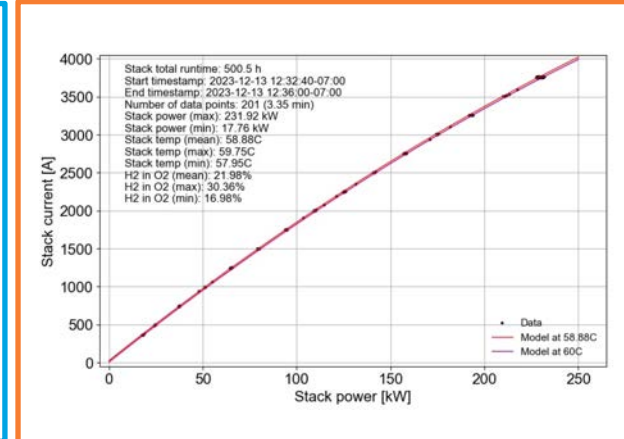
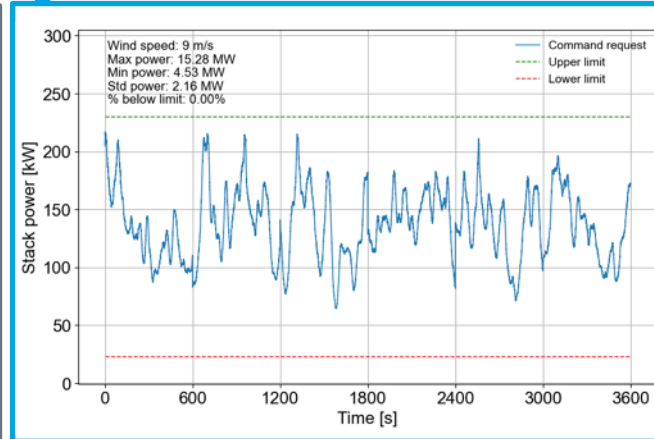
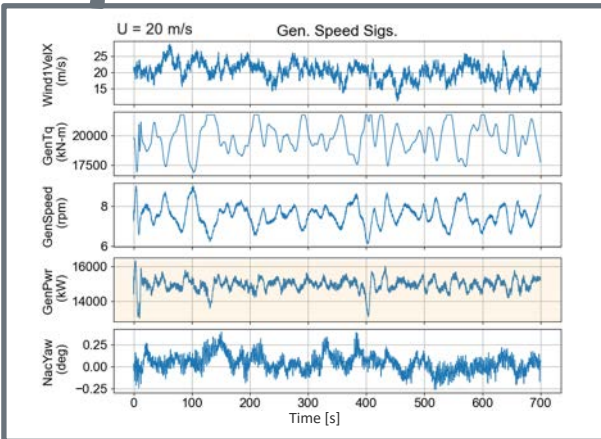
Data streams:

1. Think & Do: **80-ms data (core high-fidelity dataset)**
2. Ignition: 1-s data (synchronized timestamp)
3. Influx DB: 1-s data (synchronized timestamp)
4. iCVM (individual cell voltage measurement): 1-/5-s data
5. Oscilloscope: kHz data (supplemental data)

Accomplishments: Simulated a Wind Turbine Model to Prepare Dynamic Testing Data With an Empirical Power-To-Current Model

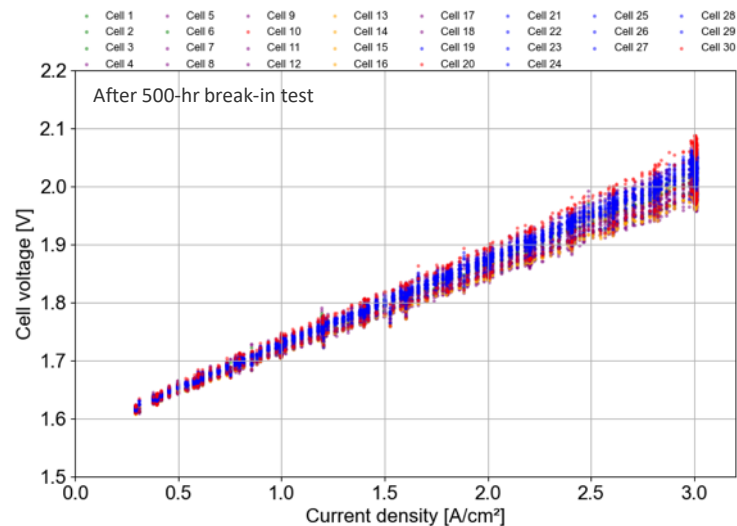
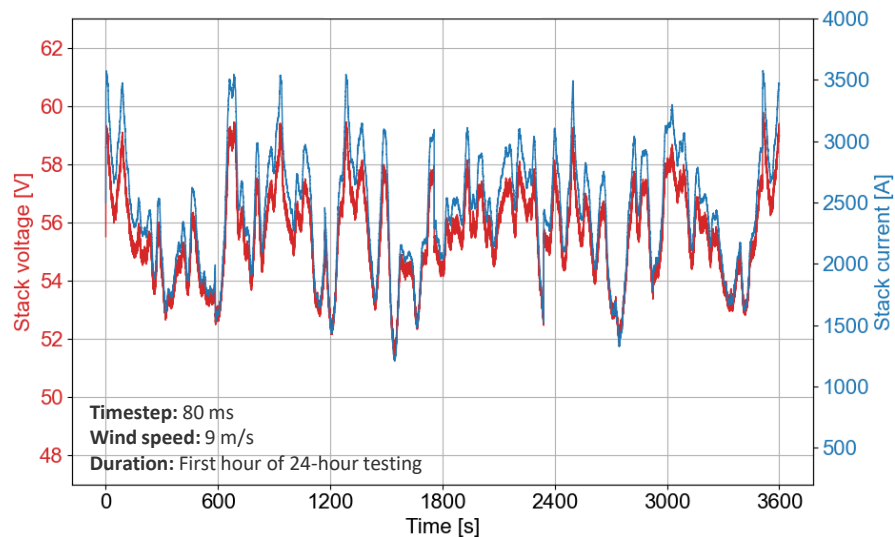


- Simulated 4 m/s to 20 m/s with a 1 m/s increment
- Generated a 10-min profile with 6 seeds, then consolidated to make a 24-hour profile
- **Selected 8 wind speeds to ensure the minimum operating point of the electrolyzer system (≥ 7 m/s)**
- Created an empirical power-to-current model from polarization data after the break-in test



Accomplishments: Completed a Total of ~700 Hours of Break-in and Dynamic Tests to Facilitate Electrolyzer-Turbine Integration

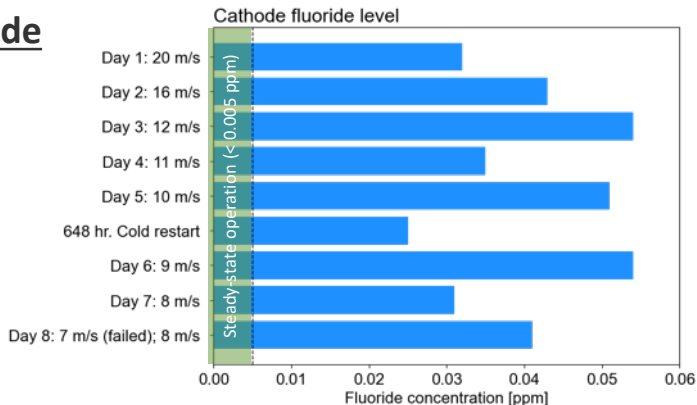
- Performed 500 hrs of steady-state operation, and then collected ~200 hrs of high-fidelity (80 ms) dynamic operation of an electrolyzer stack under simulated offshore wind profiles
- Dynamic testing indicates **reasonable stack response following fluctuated wind outputs**
- Cathode and anode water samples were collected after each dynamic profile for quantifying fluoride-level concentrations to reveal stack degradation from dynamic operations



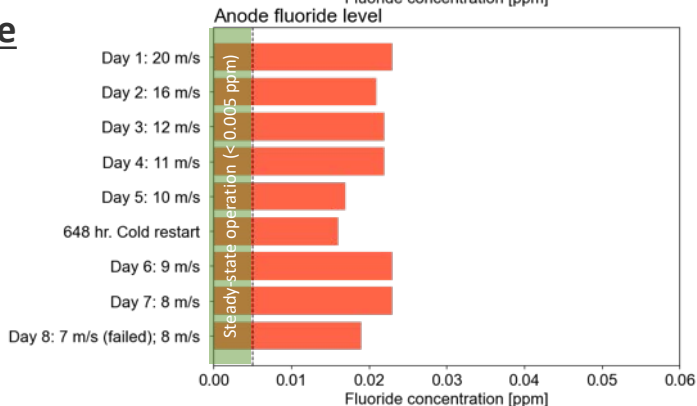
Accomplishments: Determined an Increase of Fluoride Level After Dynamic Testing and Demonstrated a Sub-Second Stack Response

Increase of fluoride concentration after dynamic testing; not a commercial stack and more investigation is needed

Cathode

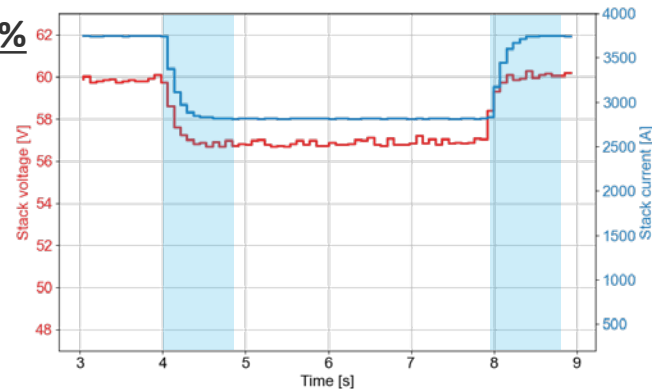


Anode

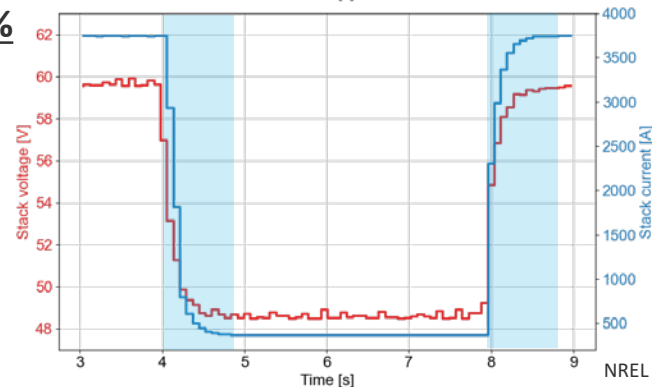


Sub-second step up/down response of an electrolyzer stack

75%–100%



25%–100%



Response to 2023 Reviewers' Comments

- “There could be a more explicit statement of the parameter that will be assessed (and modeled) as part of the experimental project, for instance, how response time is being measured (what the measurement is, exactly) and polarization curves.”
 - Agreed, we designed an experiment to collect a high-fidelity core dataset including stack current, stack voltage, and cell-level voltage monitoring to identify an effect (quantify an increase of cell voltage). Plus, we collected effluent water samples to potentially reveal degradation of the stack along with polarization curves.
- “Further analysis should be added to gauge whether the volume (and required stack power density) of the electrolysis system fits on an offshore platform.”
 - Agreed, the volume and mass of the system affect LCOH for an offshore wind platform. The FY24 tasks were aimed to address operational feasibility based on dynamic wind profiles.

Collaboration and Coordination

- Experimental project is in support of an industry team of Giner (electrolysis characterization), GE Vernova Advanced Research (wind turbine integration), HYGRO (systems integration), and Plug Power (stack supplier)



- International collaboration on offshore wind hydrogen in coordination with TNO in the Netherlands and Step4Wind project in UK

Remaining Challenges and Barriers

This project is about to close as the experiments were completed

- Interpretation of experimental data
- International coordination on operations and maintenance modelling of an integrated system

Proposed Future Work

- Complete data analysis to de-risk integrated system design
- Publish results to share learnings
- Consider next steps to accelerate technology development

Summary

This project aims to evaluate dynamic electrolyzer performance based on offshore wind profiles

- Simulated an offshore wind turbine model and determined profiles having wind speed of more than 7 m/s to maintain the lowest operating setpoint of the stack; **energy storage system will help maintain the system up and running**
- Installed a 30-cell rainbow stack, implemented 80-ms data acquisition system, and **completed a total of ~700 hours of unattended operation**
- Confirmed **reasonable stack response following fluctuated offshore wind profiles**; demonstrated a sub-second stack response
- Determined **an increase of fluoride level after each dynamic testing** (further investigation is needed)
- Extensive data analysis will be performed to gain insights from experimental work
 - Complete data analysis to de-risk integrated system design
 - Publish results to share learnings

Thank You

www.nrel.gov

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Technical Backup and Additional Information

Technology Transfer Activities

- The experimental project is pursuing several funding opportunities, and the goal is product development of an in-turbine electrolysis system
- The OSW-H2 working group is not pursuing technology transfer activities

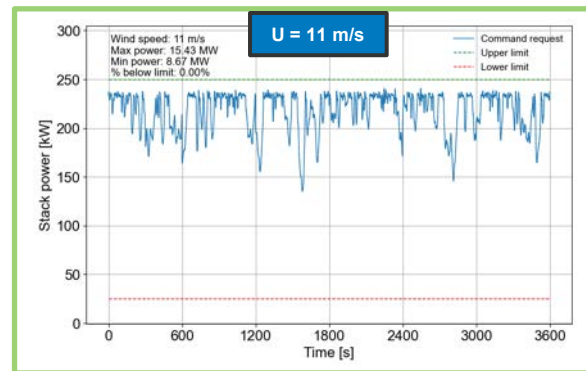
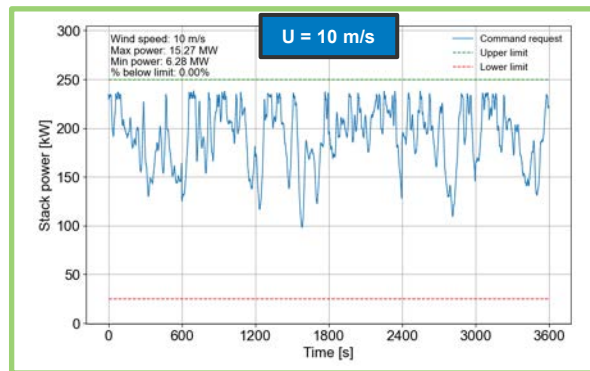
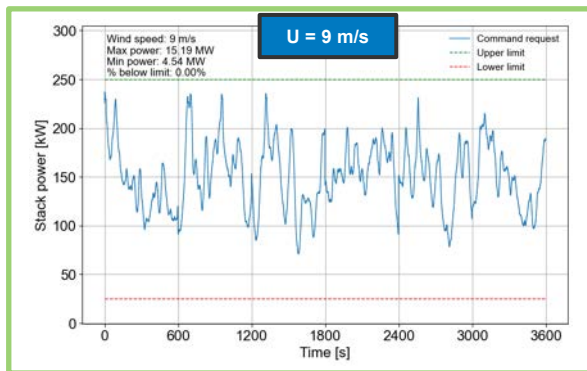
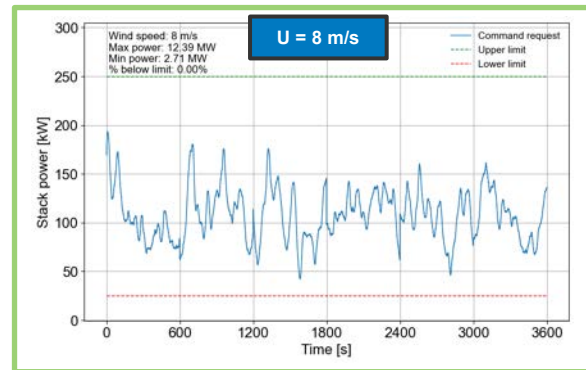
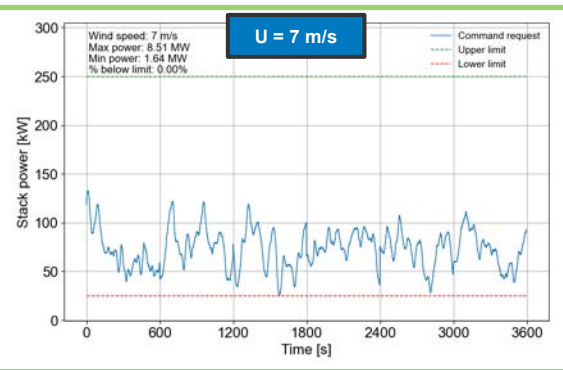
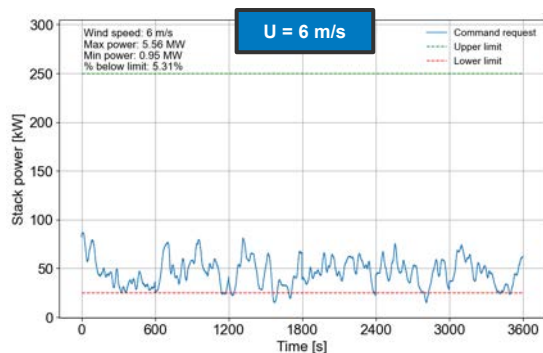
Special Recognitions and Awards

- None at this time

Publications and Presentations

- Hugo Groenemans, Genevieve Saur, Cortney Mittelsteadt, Judith Lattimer, Hui Xu, “Techno-economic analysis of offshore wind PEM water electrolysis for H₂ production”, *Current Opinion in Chemical Engineering*, Volume 37, 2022, 100828, ISSN 2211-3398, <https://doi.org/10.1016/j.coche.2022.100828>.

8 profiles were used for dynamic testing



Green boxes are the profiles selected for dynamic testing.

