Low Total Cost of Hydrogen by Exploiting Off-Shore Wind and PEM Electrolysis Synergies

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DOE project award # DE-SC0020786

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DOE Hydrogen Program
2023 Annual Merit Review and
Peer Evaluation Meeting

AMR Project
ID # TA051

Project Goals

- Develop a model to calculate the levelized cost of hydrogen produced using off-shore wind integrated with electrolyzers (OSWE) based on wind speed, intermittency, water depth and distance to shore.
- Determine impact of seawater impurities on electrolyzer performance and develop viable solutions for obtaining sufficiently pure water for OSWE
- Build a 250 kW PEM water electrolyzer for wind turbine integration.
- Determine system process and instrumentation needs for OSWE and design power electronics and control systems for integration.
- Integrate PEM electrolyzer stack with wind turbine simulation to investigate OSWE operations.

Project Overview

Timeline

- Project start date: 8/23/2021
- Project End date: 2/22/2024*
  - 6-month NCE due to logistical delays in electrolyzer testing

Budget

- Total Project Value: $ 1,100,000
  - DOE Share: $1,100,000
  - DOE Funds Spent: $ by 4/14/2023

Barriers

- Economic viability of direct wind-electrolysis integration
- Hardware integration challenges

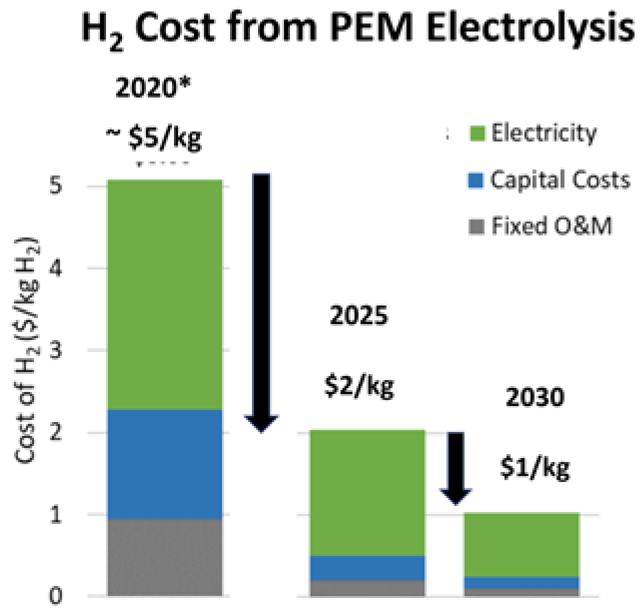
Project Team

- ☐ Giner Inc.: Prime
  - Overall project management; water quality impact; PEMWE stack design
- ☐ NREL: Subcontract
  - Wind turbine emulation; wind power and electrolyzer integration
- ☐ GE Research: Subcontract
  - Physical and electrical integration trades
- ☐ Hygro: Consultant
  - System economic analysis
- ☐ Plug Power: Vendor
  - PEMWE stack build

Relevance/Potential Impact

- The project objective is to model and validate an integrated system to produce low-cost clean hydrogen directly using offshore wind power and PEM water electrolysis

- Pertaining to DOE H_2 Energy Shot goals
  - Achieve the Hydrogen Shot goal of $1 for 1 kg hydrogen in 1 decade
  - Lower greenhouse gas emissions and critical pollutants
  - Build clean energy infrastructure
  - Provide pathways to private sector uptake

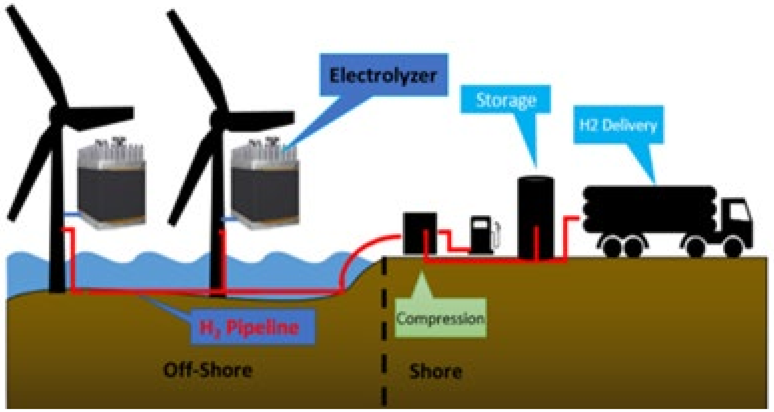


https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-plenary-doe-overview.pdf

*2020 Baseline: PEM (Polymer Electrolyte Membrane) low volume capital cost ~$1,500/kW, electricity at $50/MWh. Pathways to targets include capital cost < $300/kW by 2025, < $150/kW by 2030 (at scale). Assumes $50/MWh in 2020, $30/MWh in 2025, $20/MWh in 2030

Technological Approach

- Model OSWE under a variety of conditions to determine how factors including wind speed, intermittency, water depth and distance to shore affect hydrogen production cost.
- Study impact of seawater on PEM electrolyzer performance and determine limiting concentrations of impurities in water feed
- Integrate 250 kW electrolyzer stack with wind turbine.
  - Simulate wind turbine output and study effect on electrolyzer performance.
  - Determine how feedback from electrolyzer will affect wind turbine and develop mitigation strategies.
- Design power electronics and instrumentation needs for OSWE based on dynamic modeling and integrated electrolyzer testing.

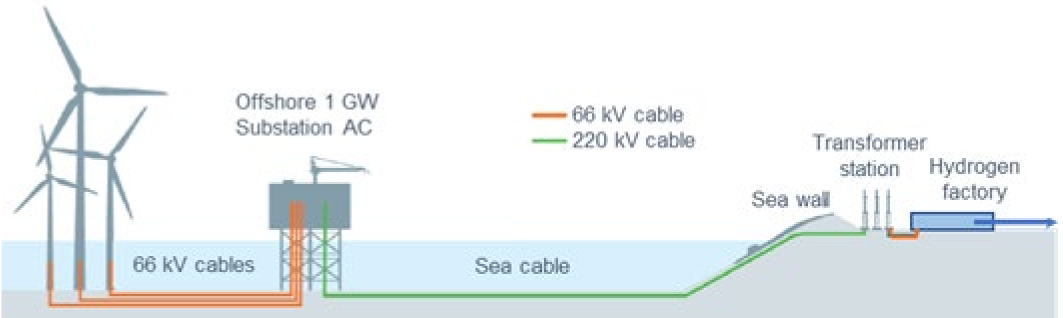


Major Milestones	Progress Made
Correlate catalyst (Pt or Ir) loading to the tolerance of PEM electrolyzer performance on seawater ion concentrations	80% complete: Measured performance electrolyzer under various catalyst loading to variable sea water ion concentrations
Receive all the components of 250 kW stack	100% complete: Stack design is selected and was assembled at Plug Power, installed at NREL
Design the layout of 5MW wind turbine-PEM electrolyzer integration	50% complete: modeling and preliminary electrolyzer tests are underway, will form basis of design for integrated system.

Accomplishment: Modeling H_2 Cost under Two Scenarios

Centralized H_2 Production

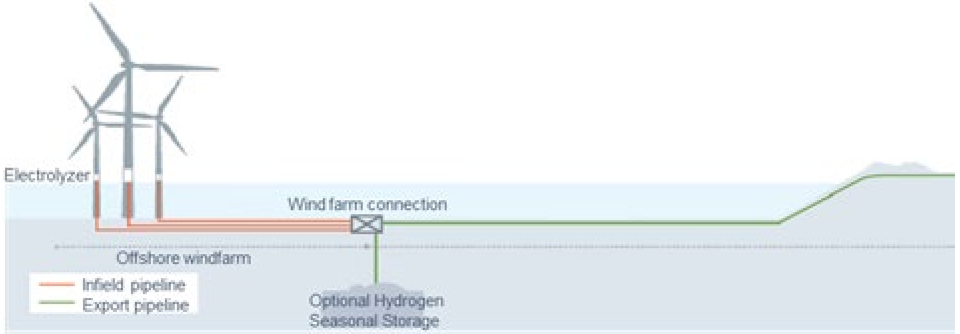
Off-shore Wind – Shore Electrolyzer (OSWSE)



- Electricity produced by off-shore wind turbine
- Inter-array cables to substation
- Electricity export to shore by cable
- AC-DC-AC-DC transformation
- On-shore substation
- On-shore electrolysis facility

H_2 Windfarm

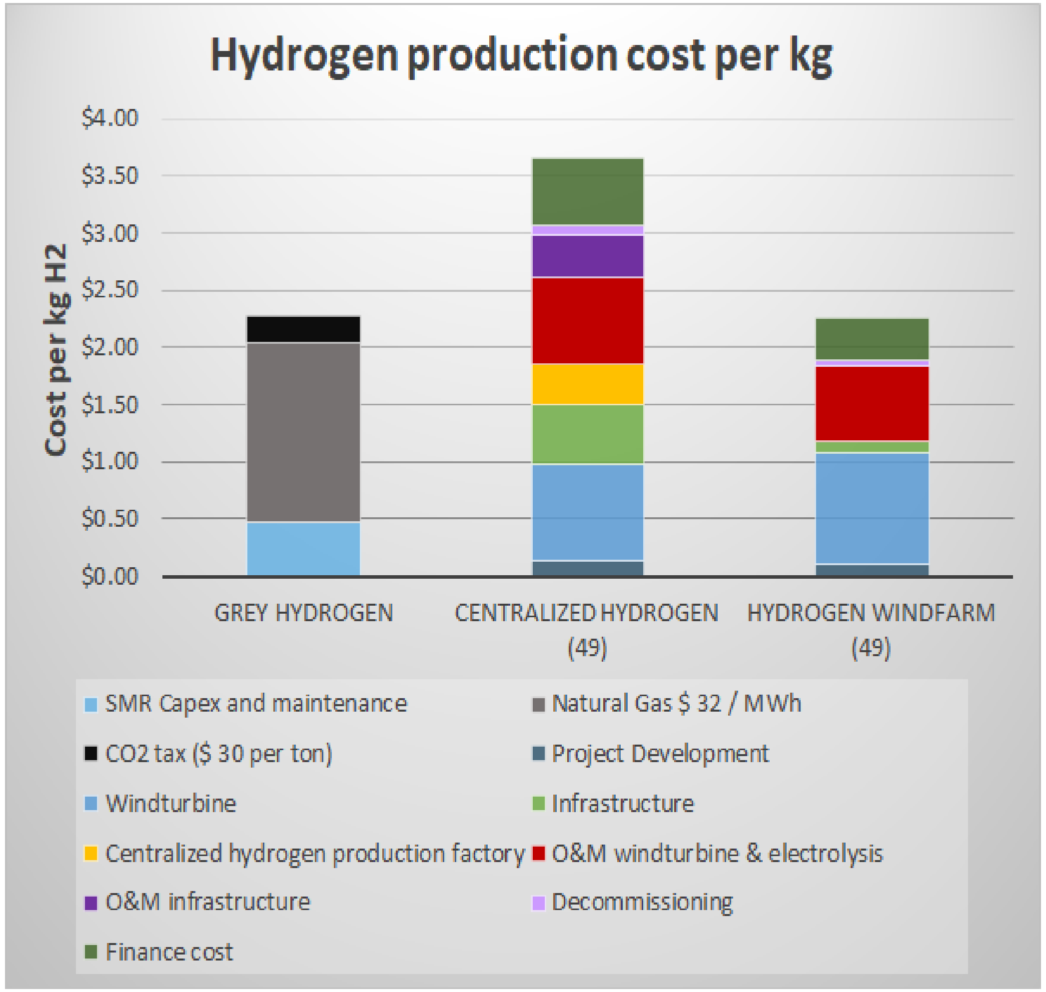
Off-shore Wind and Electrolyzer (OSWE)



- Wind turbines directly integrated with PEM electrolysis and compression
- Off-shore electrolysis facility
- Subsea pipeline connection to export H_2
- Power conversion lines eliminated
- Power transmission costs reduced

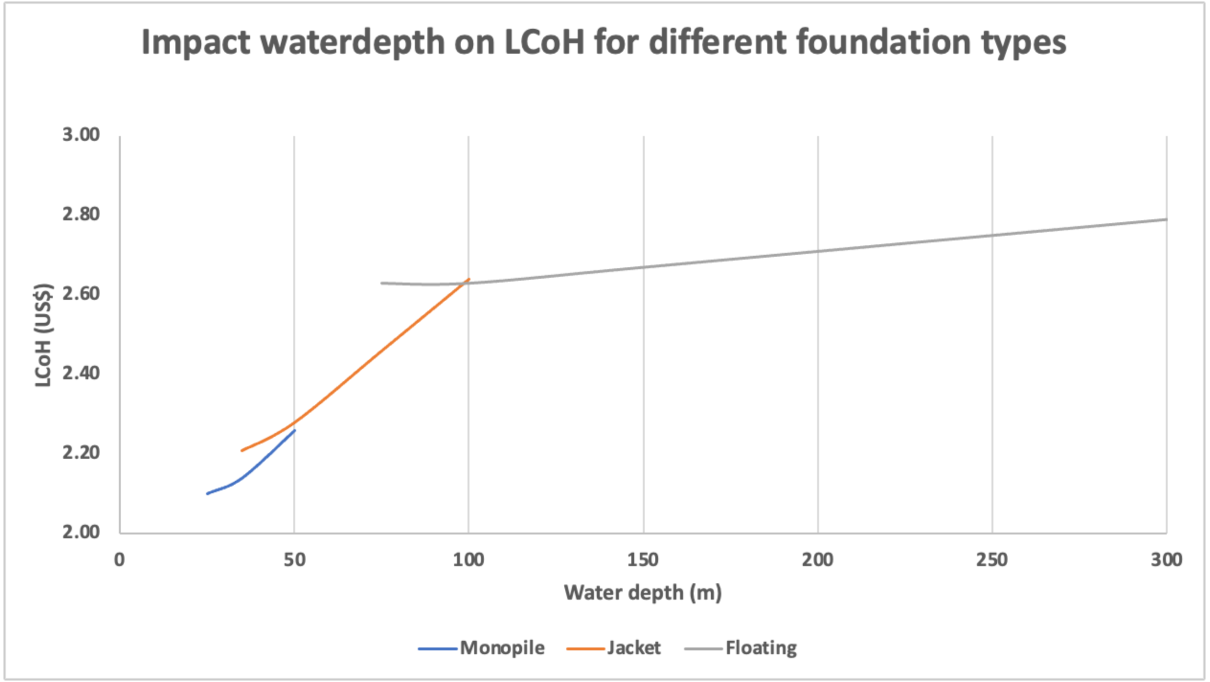
Power and H_2 Production Cost

	Energy Production	Centralized Hydrogen Production (OSWSE)	Hydrogen Windfarm (OSWE)	
# of turbines	49		49	
Production of Energy (MWh)	76,816,713		59,984,232	78%
Cost of energy ($/MWh)	52.84		56.53	107%
H2 Production (ton)		1,337,945	1,522,979	114%
Cost hydrogen ($ per kg)		3.66	2.27	62%



- The levelized cost of energy for hydrogen is slightly higher than that for power production.
- OSWE produces lower-cost H_2 compared to OSWSE, approaching $2.2/kg.
- Significant cost reduction on power transfer infrastructure, O&M infrastructure and centralized H2 production factory

Analysis related to water depth



Increasing water depth will increase LCoH

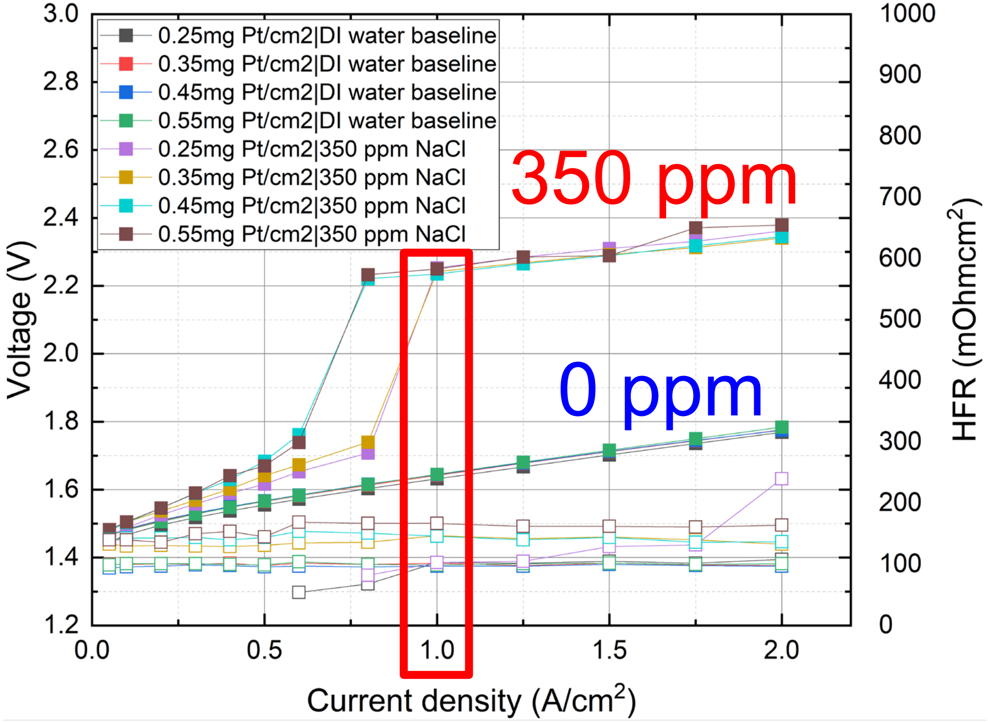
- Monopiles (15 - 50 m)
  - Lowest cost version
    - Least steel used and efficient production
    - Serial production established

- Jacket (40 – 100 m)
  - More steel used per foundation
  - Difficult installation offshore

- Floating (> 100 m)
  - More steel compared to bottom fixed
  - Lower installation cost
  - Only demonstrators
  - Less sensitive for water depth variations

Accomplishment: Seawater Ion Impact Electrolyzer Performance

Cathode Loading Effects: 350 ppm NaCl

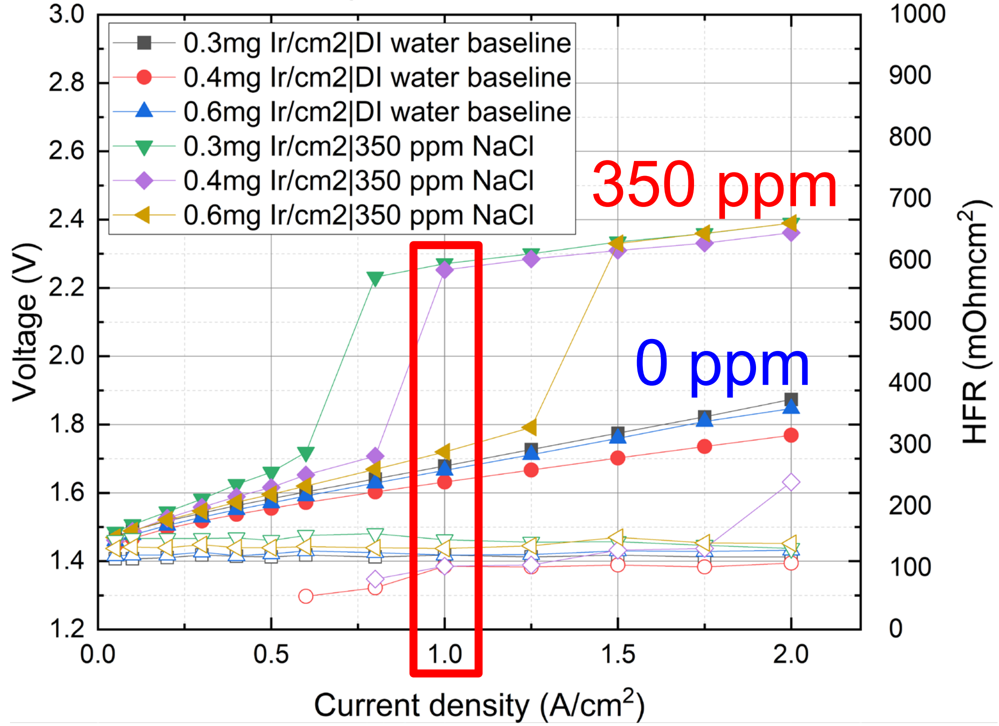


Cathode	NaCl (ppm)				NaCl (ppm)		
Pt	0	3.5	35	350	3.5	35	350
Catalyst Loading (mg)	Voltage at 1 A/cm^2				% diff. vs. DI Water Baseline		
0.25	1.632	1.638	1.659	2.253	0.37%	1.65%	38.05%
0.35	1.642	1.644	1.685	2.242	0.12%	2.62%	36.54%
0.45	1.644	1.651	1.694	2.235	0.43%	3.04%	35.95%
0.55	1.645	1.651	1.694	2.25	0.36%	2.98%	36.78%

- NaCl is the most abundant salt in seawater and its concentration in seawater is ~29 g/L. 350ppm (mg/L) NaCl is a typical drinking water level concentration, while ultra pure water has a dissolved ion concentration of < 0.1ppb.
- 3.5 ppm NaCl does not significantly affect cell performance and HFR over a 2-3 h test for all cathode loadings
- 35 ppm NaCl is slightly worse as expected, while 350 ppm shows catastrophic loss of performance at all Pt loadings
- 0.25 mg of Pt produces lowest voltages in lower ppm tests, **but 0.45 mg Pt performed best in 350 ppm NaCl**

Accomplishment: Seawater Ion Impact Electrolyzer Performance

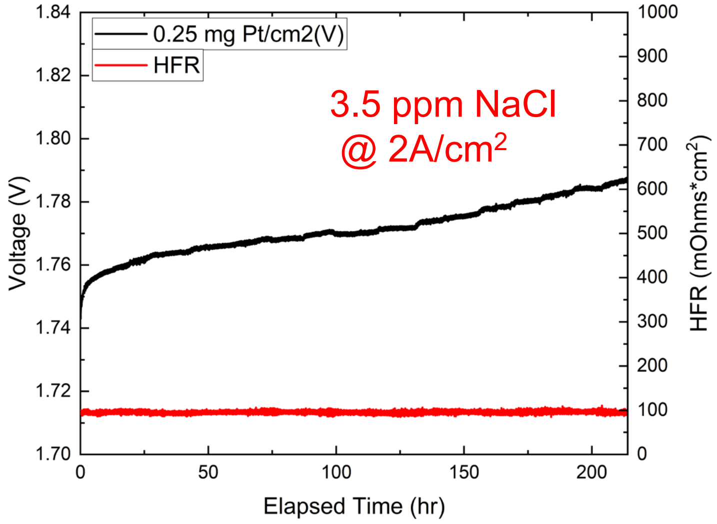
Anode Loading Effects: 350 ppm NaCl

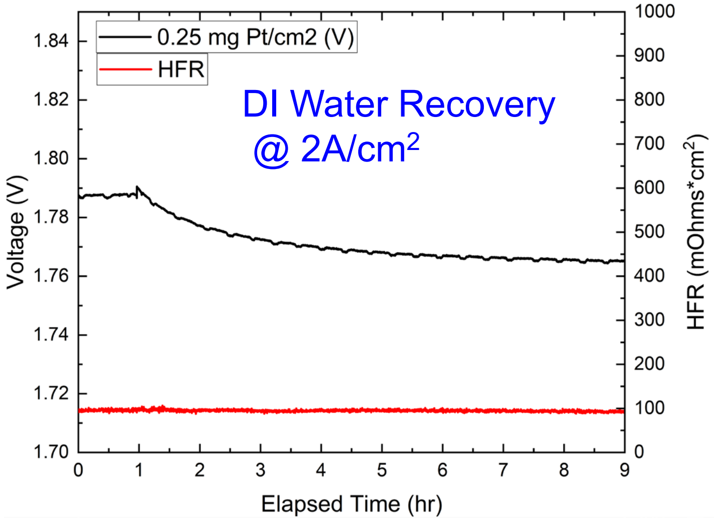


Anode	NaCl (ppm)				NaCl (ppm)		
Ir	0	3.5	35	350	3.5	35	350
Catalyst Loading (mg)	Voltage at 1 A/cm2				% diff. Vs. DI Water Baseline		
0.3	1.679	1.688	1.71	2.271	0.54%	1.85%	35.26%
0.4	1.632	1.638	1.708	2.253	0.37%	4.66%	38.05%
0.6	1.666	1.666	1.647	1.72	0.00%	-1.14%	3.24%
0.8	Ongoing Testing						
1	Ongoing Testing						

- 3.5 ppm NaCl does not significantly affect cell performance and HFR over a 2-3 h test for all cathode loadings
- 35 ppm NaCl is slightly worse as expected for all cathode loadings
- 350 ppm shows catastrophic loss of performance at <0.6 mg Ir
  - Trend may indicate that 0.8 & 1.0 mg Ir improve performance further

Long-term NaCl Salt Impact and Performance Recovery





Cathode	NaCl (ppm)			NaCl (ppm)		
Pt	3.5			0		
Catalyst Loading (mg)	Start V	Final V	Degradation Rate (μV/h)	Recovery Time (h)	Final V	% Recovery
0.25	1.743	1.784	186	9	1.764	98.80%
0.35	1.798	1.998	2000	9	1.831	98.16%
0.45	1.785	2.025	1333	9	1.816	98.26%
0.55	1.829	2.072	1013	9	1.853	98.69%

- 3.5 ppm NaCl solution was fed to the cell for ~ 220 hours and voltage rose steadily throughout the experiment
  - HFR remained fairly stable
  - Poisoning effect primarily on the catalysts
- Increasing Pt loading did not improve tolerance; 0.25 mg Pt representative data shown above
- Over 98% voltage recovery when returning to DI water after only 9 h
- Electrolyzer operations should be designed to respond to ion intrusion – may require lowering current/voltage operation temporarily
  - Priority should be given to mitigating impact on wind turbine

Accomplishment: Build 220 kW PEMWE Stack

INPUT	
STACK POWER CONSUMPTION	220 kW
STACK VOLTAGE	59 VDC
STACK CURRENT	3750 A
WATER CONSUMPTION	9 kg per kg H_2
OUTPUT (HYDROGEN GAS)	
VOLUME	47 Nm^3/hour
MASS	100 kg/day
PURITY	Up to 99.999%
PRESSURE	40 barg
OPERATIONAL	
START UP TIME	30 s warm / 5 min cold
AVERAGE STACK EFFICIENCY	52.5 kW/kg H_2
LOAD FOLLOWING	Instantaneous

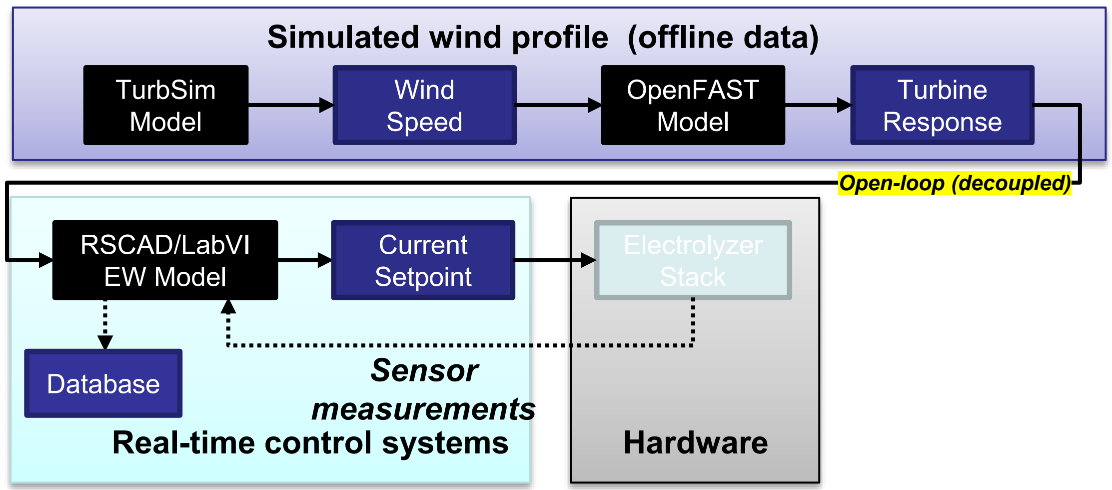
- Plug Power's 1 MW PEMWE platform (129 cells typical)
- 30 cell stack to reach 220 kW input power
- Operation: 3750 A and ~60 V
- To be ready in Q2 2023 and installed at NREL

Accomplishment: Simulation models and data preparation

- TurbSim & OpenFAST to create power profiles
  - Generate AC output profiles
  - Estimate DC output with a rectifier efficiency
- RSCAD model sends current setpoints to the electrolyzer system
  - Up to 50 us (target: 40 ms)
  - Synchronized sensor measurements and storage
- Open-loop simulation
  - OpenFAST and RSCAD are decoupled: 1) prepare offline data and 2) feed it into the RSCAD model

Data Flows

Wind speed (mean) = {4, 6, 8, 10, 12, 14, 16, 20} m/s



Simulated wind profile (offline data)

TurbSim Model

Wind Speed

OpenFAST Model

Turbine Response

Open-loop (decoupled)

RSCAD/LabVI EW Model

Current Setpoint

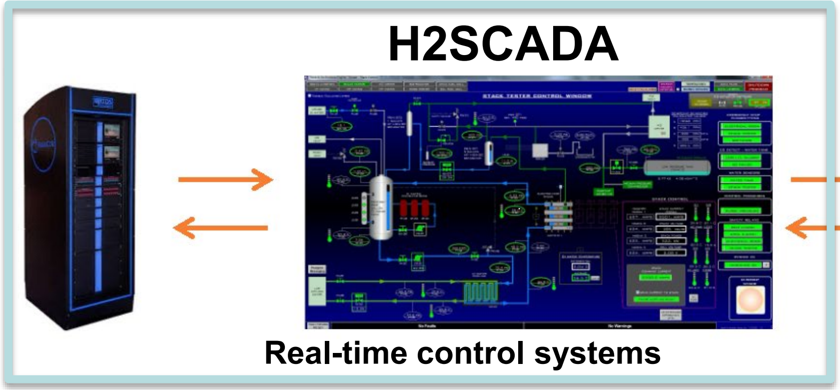
Electrolyzer Stack

Database

Sensor measurements

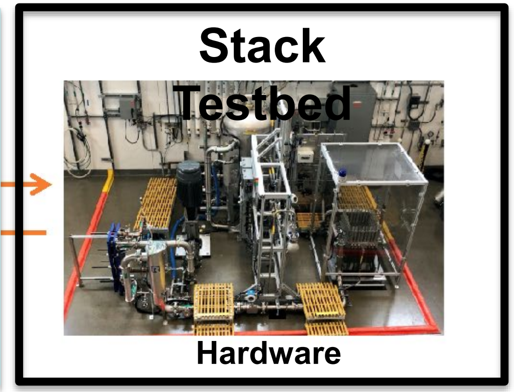
Real-time control systems

Hardware



H2SCADA

Real-time control systems



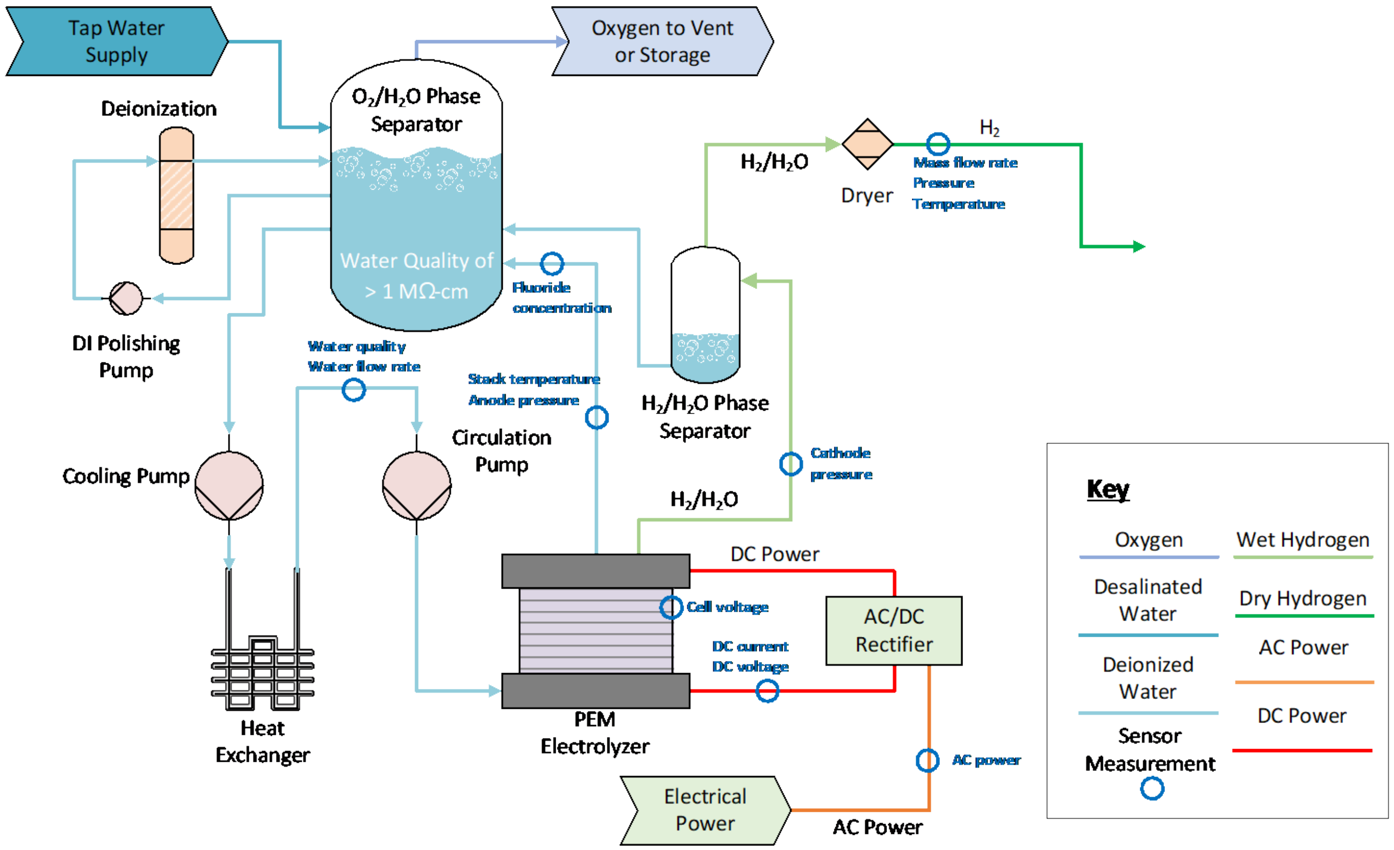
Stack Testbed

Hardware

Accomplishment: System Configuration with sensor measurements

Data acquisition plan to assess stack responses and degradation

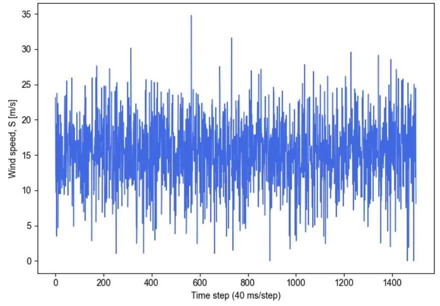
- Power converter
    - AC power
- Stack data
    - Current
    - Voltage
    - Cell-level voltage monitoring
    - Anode and cathode pressures
    - Temperature
- H2 production
    - Current to mass flow rate conversion
- Water loop
    - Inflow water quality
    - Outflow fluoride concentrations: anode and cathode sides (effluent water sampling)



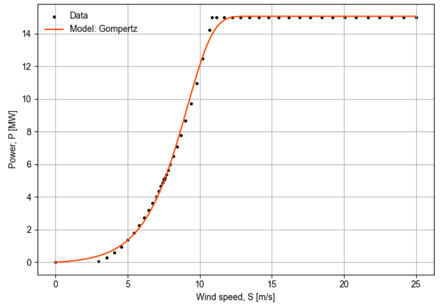
Accomplishment: Simulation framework for experiments

- Wind speed
  - TurbSim according to IEC 61400 DLC 1.2 (NTM), class IB, with mean wind speed of {4, 6, 8, 10, 12, 14, 16, 20} m/s
- Power curve
  - OpenFAST simulating IEA 15 MW WTG response
- Power converter model
  - Efficiency curve or fixed efficiency
- Polarization model
  - Power-to-current relationship
  - Stack temperature effects
  - Degradation (state of the stack condition)
- Integration with the main control scheme
  - H2SCADA at ESIF
  - Time delays of each control block (communication delay)
  - Transient stack characteristics (electrochemical response/delay)

Wind Speed

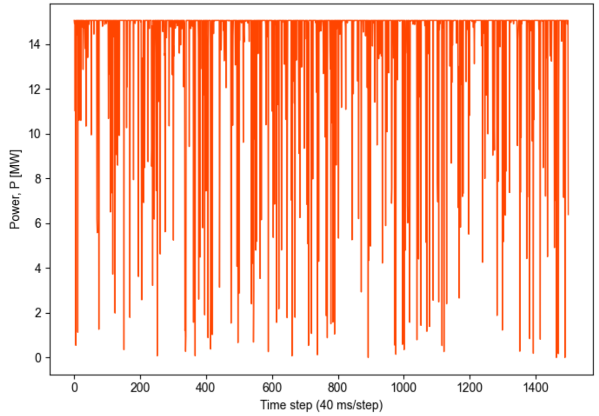


Power Curve

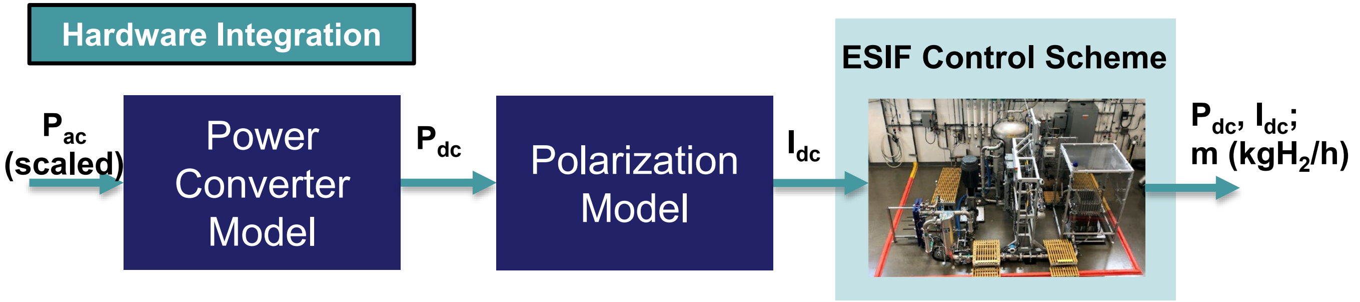


Built the simulation framework for hardware experiments

Power Profile



Hardware Integration



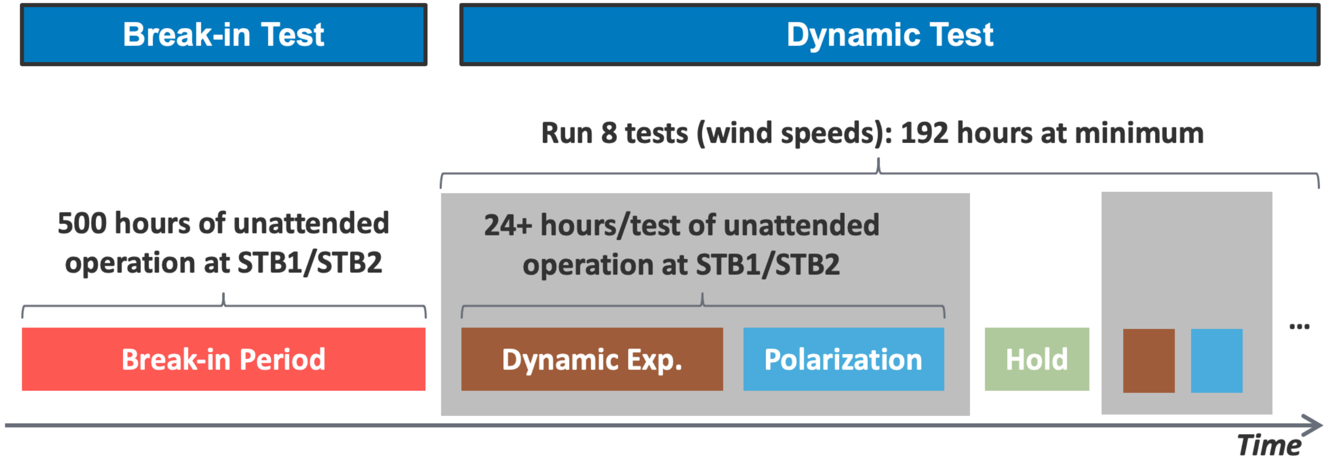
P_{ac} (scaled) → Power Converter Model → P_{dc} → Polarization Model → I_{dc} → ESIF Control Scheme → P_{dc}, I_{dc}; m (kgH_2/h)

IEA 15 MW reference: https://www.nrel.gov/docs/fy20osti/75698.pdf
Wind class parameters: https://cleanpower.org/wp-content/uploads/2021/05/ACP-61400-1-202x_Draft.pdf
OpenFAST documentation: https://buildmedia.readthedocs.org/media/pdf/openfast/latest/openfast.pdf

Accomplishments: Test Procedures

- Break-in test
  - 500 hours of break-in operation
- Dynamic test
  1. 24 hours/test
  2. Take a polarization curve at fixed stack temperature
  3. Hold at fixed current; avoid shutdowns/startups (keep BOP operation)
  4. Perform 8 dynamic tests

Experimental testing to begin in May 2023



Break-in Test

Dynamic Test

Run 8 tests (wind speeds): 192 hours at minimum

500 hours of unattended operation at STB1/STB2

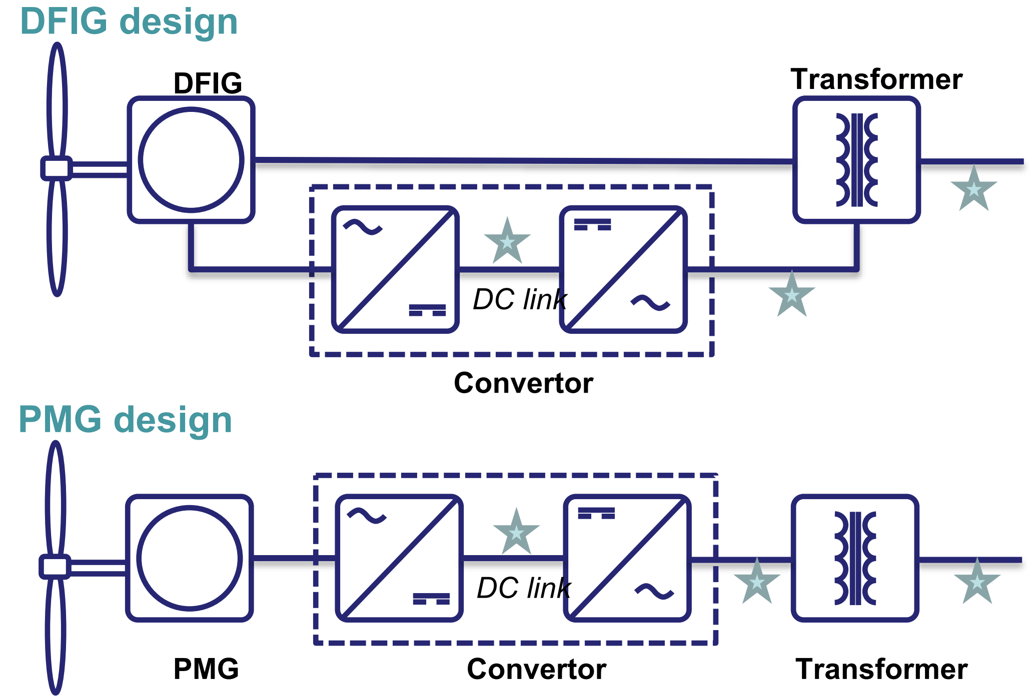
24+ hours/test of unattended operation at STB1/STB2

How to combine Wind Energy with Electrolysis?

Physical Integration

	Impact on			
Solution	**Turbine dynamics**	**Electrolyzer**	**Service**	**Safety**
In nacelle	**High**	**High**	**High**	**High**
Outside nacelle, separate module	**High**	**Medium**	**Medium**	**Limited**
Inside tower	**Limited**	**Medium**	**High**	**High**
Outside tower	**Limited**	**Limited**	**Limited**	**Limited**
On floating platform – above water line	**Limited**	**Limited**	**Limited**	**Limited**
Inside floating platform – below water line	**Limited**	**High**	**High**	**Medium**
On sea bed	**No impact**	**Very high**	**Very high**	**Medium**

Electrical Integration



★ Possible integration interface with Electrolyzer Power Electronics

Response to Previous Year Reviewer’s Comments

This project was not previously reviewed.

Collaboration and Coordination

- **Giner, Inc. (prime):** Judith Lattimer, Shirley Zhong, Shuo Ding, and Max Pupucevski – Project Lead, management and coordination, small-scale electrolyzer building and testing, saltwater management and mitigation assessment
- **NREL (sub):** Genevieve Saur, Kumaraguru Prabakar, Kazunori Nagasawa, and Dan Leighton – Coordinate electrolyzer installation and testing at NREL for integration with simulated wind turbine experiments.
- **GE (sub)**: Rogier Blom and Arvind Tiwari – Perform trade off analysis for physical and electrical integration of wind turbine system with electrolysis system.
- **HYGRO (consultant):** Hugo Groenemans and Michiel Damen – Modeling OSWE costs, development of dynamic modeling for integration of electrolyzer with wind turbine.
- **Plug Power (vendor):** Cortney Mittelsteadt, Zach Green, and Jason Wiley – Build and ship 250 kW Electrolyzer stack to NREL for integration with simulated wind turbine system.

Remaining Challenges and Barriers

- On-site demonstration of this technology is the next logical step to validate the modeling
  - Designing the power electronics required for integration, the first step to physical integration of the two systems, is currently underway
  - Real-world testing of the integration will likely have to be done in steps, starting with on-shore small-scale turbines and electrolyzers
- Utilization of seawater directly for electrolysis would be ideal
  - Will require purification system be included in the electrolyzer BOP
  - Development of more tolerant catalysts/membrane components for saltwater intrusion would enable this technology to be more robust for offshore applications

Proposed Future Work

- Continue modeling H_2 production cost for OSWE system
  - Impact of distance to shore
  - Energy (hydrogen) storage amount in pipelines to shore and other storage solutions
- Determination of catalyst loading vs. tolerance for saltwater ions
- Development of mitigation strategies for saltwater intrusion
  - Investigate salt water-tolerant catalysts/coatings
  - This will fulfill Go/No-Go milestone for Task 2
- The 250 kW electrolyzer will be delivered to NREL for integration with selected testbed infrastructure
  - This will fulfill Go/No-Go milestone for Task 3
- Integration and testing of electrolyzer stack at NREL with simulated wind turbine data
- These results will be used to design fully integrated wind turbine electrolysis system for OSWE
  - This will fulfill major upcoming milestones for Tasks 4 & 5.

Summary

- Modeling H_2 production cost for direct integration of PEM water electrolysis with off-shore wind turbine has been performed that predicts \$2.2/kg H_2
- Correlation of catalyst loading to the 6 most common seawater ions has been investigated, thus providing insights for electrolyzer-wind turbine operations
- Stack is being assembled and delivered to NREL to start simulated wind turbine experiments in May 2023.
  - Detailed experimental plan is designed and being implemented at Test Bed 1.
- Experimental design for integrated power electronics has been detailed.

Milestone	Description	Projected Completion	Actual Completion	% Complete
1.2	Determine the LCoH at variable water depth	5/22/22	12/22/22	100
1.3	Determine the LCoH at variable distance to shore	11/22/22	TBD	50
1.4	Determine the maximum H2 storage in pipeline with variable pipeline length, diameter, and H2 pressure	02/22/23	TBD	50
2.3	Correlate catalyst (Pt or Ir) loading to the tolerance of PEM electrolyzer performance on seawater ion concentrations	5/22/22	TBD	90
2.5	Determine the feasibility of water recirculation for PEM electrolyzer and recirculation threshold	11/22/22	TBD	80
3.1	Receive all the components of 250 kW stack	8/22/22	4/1/23	100
3.2	Complete the 250 kW stack build	8/22/22	4/30/23	100
3.3	Achieve average baseline cell performance 1.75 V at 2 A/cm2 with voltage variation less than 5% from cell to cell	11/22/22	TBD	0
4.1	Design the layout of 5MW wind turbine-PEM electrolyzer system integration	2/2/22	12/22/22	100
4.3	Generate modified power electronics including inverter for the electrolyzer-wind turbine integration	8/22/22	12/22/22	100
5.1	Get the test bed ready at NREL	8/22/22	4/30/23	100
5.2	Complete the wind turbine/electrolyzer integration	11/22/22	5/05/23	100

Acknowledgements

- Financial support from DOE SBIR funding under award number: DE-SC0020786
- Hydrogen and Fuel Cell Technologies Office (HFTO) for additional support
- Project Manger: Dr. Michael Hahn

Technical Backup and Additional Information

Technology Transfer Activities

- We are working with GE, Hygro, and Plug Power on a technology-to-market plan

Publications and Presentations

- H. Groenemans, G. Saur, C. Mittelsteadt, J. Lattimer, and H. Xu, “Techno-economic Analysis of Off-Shore Wind PEM Water Electrolysis for H2 Production”, *Current Opinion in Chemical Engineering*, Volume 37, September 2022, 100828, https://doi.org/10.1016/j.coche.2022.100828