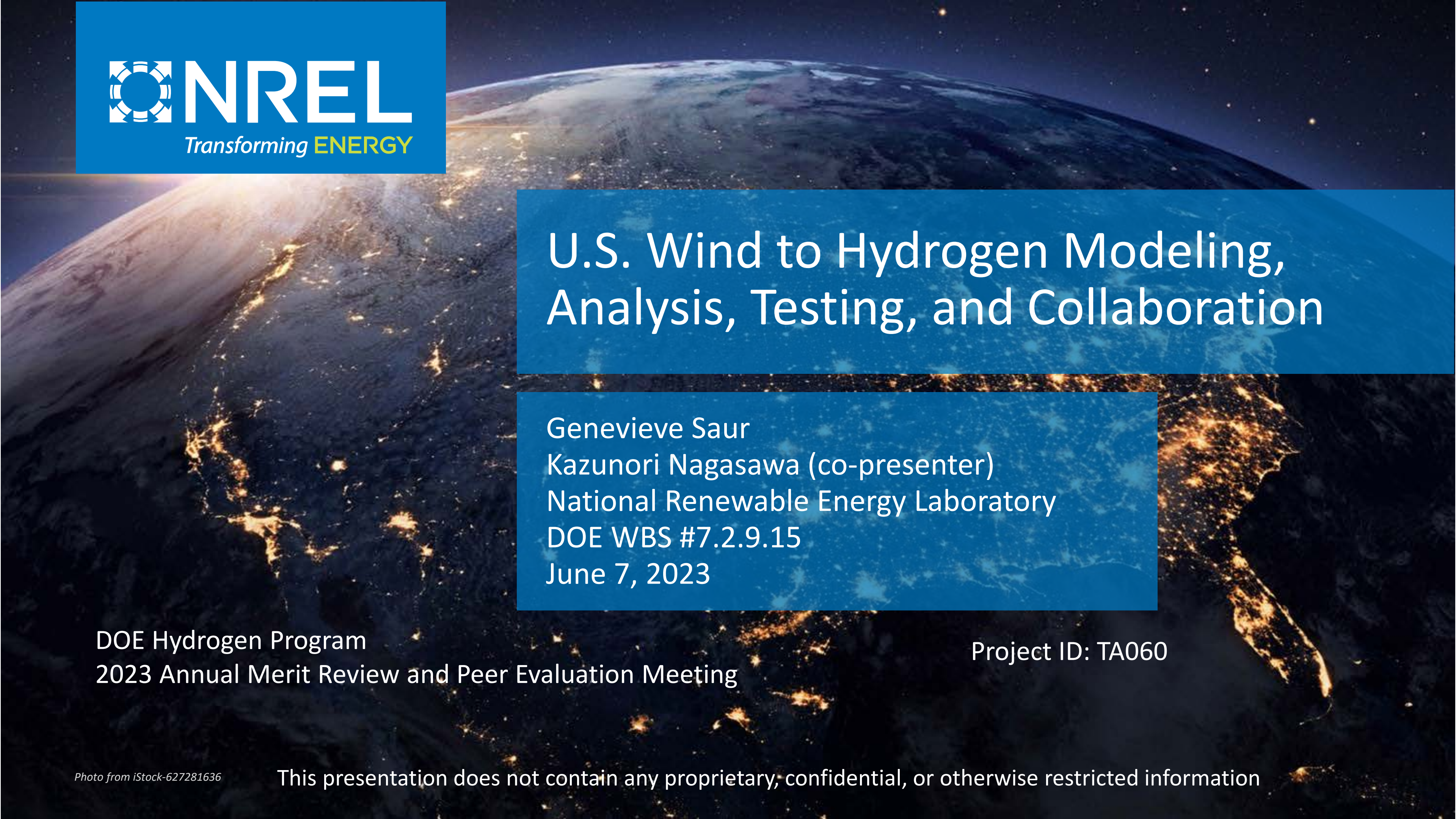

U.S. Wind to Hydrogen Modeling, Analysis, Testing, and Collaboration

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National Renewable Energy Laboratory
DOE WBS #7.2.9.15
June 7, 2023

DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting

Project ID: TA060

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Project Goal

- This project explores electrolytic hydrogen production hydrogen from offshore wind turbines, a promising pathway for decarbonization for multiple energy sectors.
- Topics:
  - Assessment for current and near-term technologies
  - Pursue international collaboration to share learnings and advance the technology
  - Support industry partners in research and demonstration activities
- FY23 Goals
  - Joint techno-economic assessment to identify a common framework for evaluation of projects, key barriers, and research needs
  - Hardware testing to accelerate development of an integrated, in-turbine offshore wind-hydrogen system
- The impact is to accelerate development and de-risk a promising hydrogen production pathway.

Overview

Timeline and Budget

- Project Start Date: 01/01/2022
- FY22 DOE Funding: $300k
- FY23 Planned DOE Funding: $300k
- Total DOE Funds Received to Date**: $600k

** Since the project started

Barriers

- J. Renewable Electricity Generation Integration
- F. Capital Cost
- H. Footprint, Size and Weight
- L. Operations and Maintenance
- M. Control and Safety

Partners

- Experimental Task:
  - Giner, GE Research, HYGRO, Plug Power
- TEA Assessment:
  - TNO (Netherlands)

Potential Impact

- **What:** Collection of projects addressing analytic and experimental requirements for developing proof-of-concept offshore wind-hydrogen projects
- **Why:** Offshore wind-H2 is a promising pathway for tightly integrated renewable H2
  - Addressing grid and coastal constraints as renewable electricity is built out
  - High-throughput, economically-scalable energy delivery via undersea pipelines
  - Overlaps with two DOE Energy Earthshots – Hydrogen and Floating Offshore Wind
- **Why:** Offshore wind is still early market, especially in the US; offshore wind-H2 is in infancy with no operational demonstrations to-date (though several projects in development)
  - Offshore conditions and requirements are very different compared to onshore
  - System design and operations must be considered for harsh, remote locations
  - Industry interest is considerable
- **How:** FY23 activity was focused on
  - Renewable electricity generation integration through experimental setup with industry
  - Capital cost, gap/uncertainty, common framework assessment through international working group

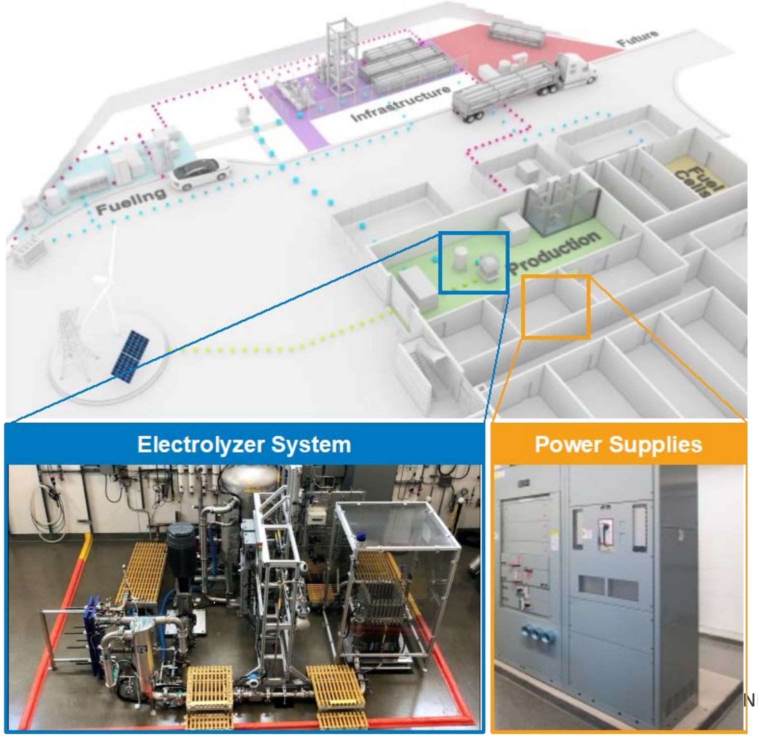
Integrated testing for distributed offshore wind-electrolysis system (experimental project)

Utilizing test facilities at NREL

Approach: Integrated testbed for distributed wind-electrolysis system

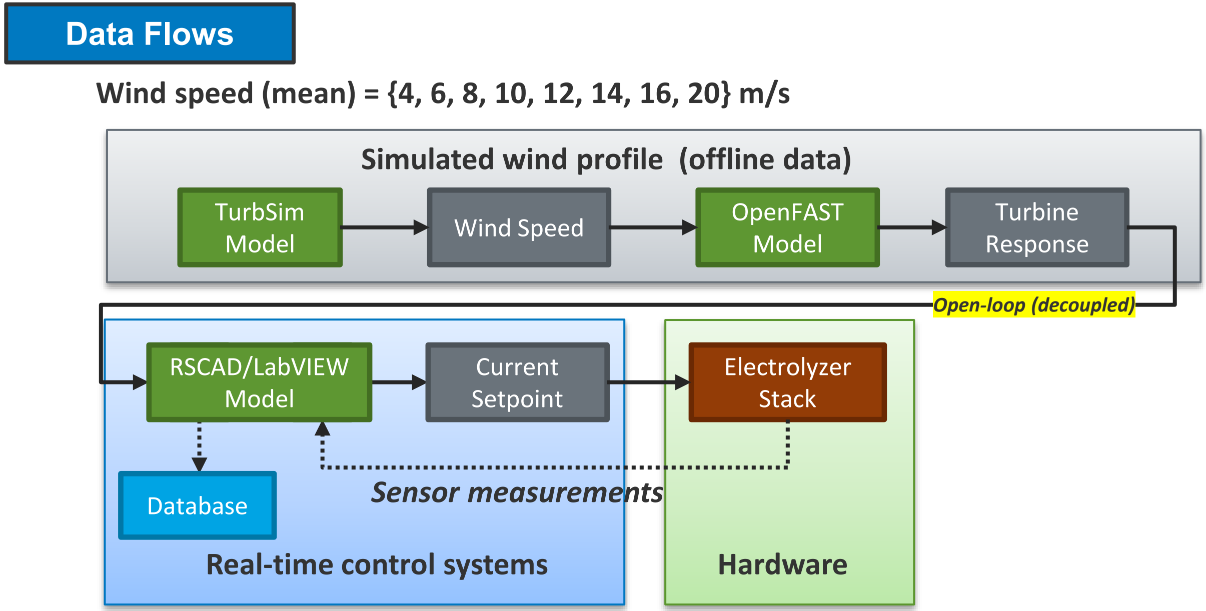
- **Goal:** Accelerate development of a distributed wind-electrolysis system through use of NREL testing facilities.
  - Industry partners: Giner (electrolysis), GE Research (wind), HYGRO (integration, and Plug Power (stack supplier) [See also TA051]
  - Initial de-risk testing to understand fast-control effects that the PEM electrolyzer will have on wind turbine controls
- **Target data:** NREL's 750-kW stack test bed to obtain high-fidelity data (~40 ms) to assess closely integrated system

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



Approach: 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

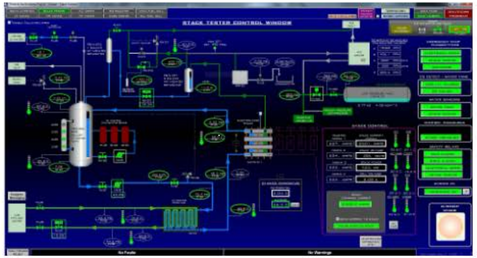


Data Flows

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

RTDS

H2SCADA



Real-time control systems

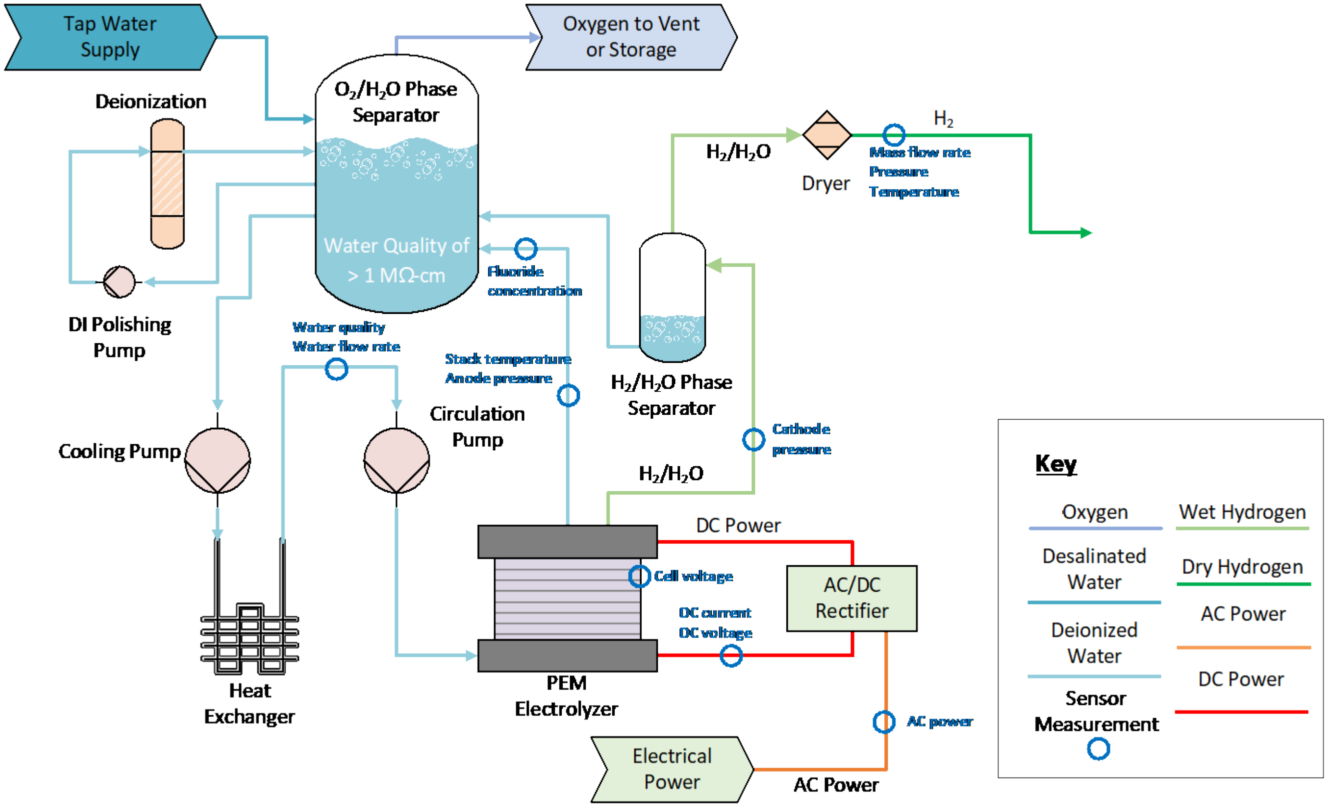
Stack Testbed

Hardware

Approach: System configuration with sensor measurements

- 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)

Data acquisition plan to assess stack responses and degradation

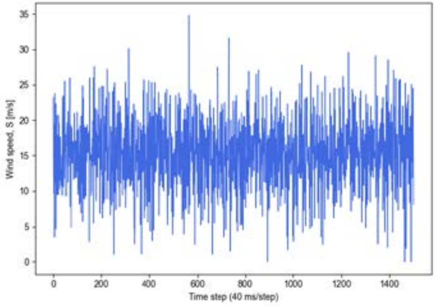


Accomplishments: Simulation framework for experiments

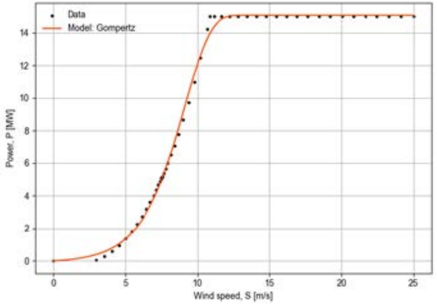
- Wind speed
  - TurbSim according to IEC 61400 DLC 1.2 (NTM), class IB, with mean wind speed of {4, 6, 8, 10, 12, 14, 16, 20} m/s
- Power curve
  - OpenFAST simulating IEA 15 MW WTG response
- Power converter model
  - Efficiency curve or fixed efficiency
- Polarization model
  - Power-to-current relationship
  - 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)

Built the simulation framework for hardware experiments

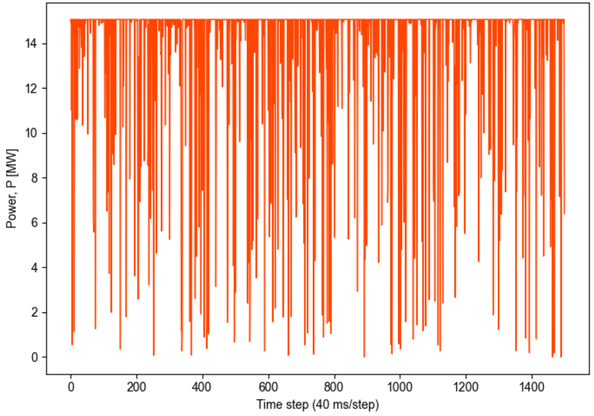
Wind Speed



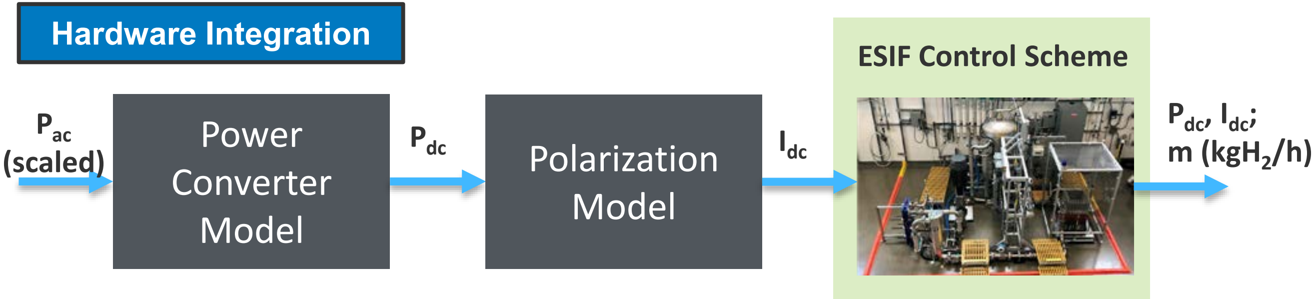
Power Curve



Power Profile



Hardware Integration

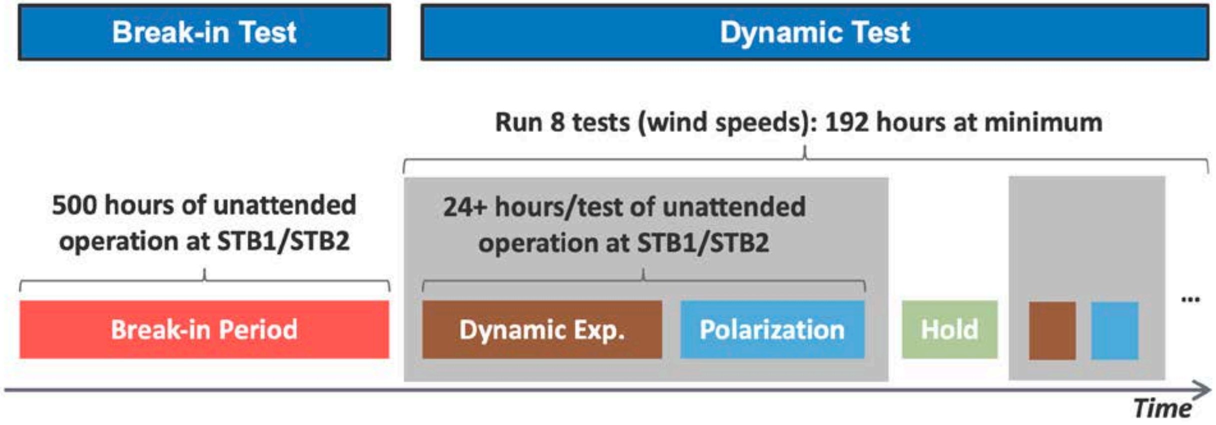


IEA 15 MW reference: https://www.nrel.gov/docs/fy20osti/75698.pdf
Wind class parameters: https://cleanpower.org/wp-content/uploads/2021/05/ACP-61400-1-202x_Draft.pdf
OpenFAST documentation: https://buildmedia.readthedocs.org/media/pdf/openfast/latest/openfast.pdf

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



Offshore wind-hydrogen working group

International collaboration between researchers
at NREL (US) and TNO (Netherlands)

Approach: NREL-TNO International Working Group on Offshore Wind-H2

- **What:** An international working group on offshore wind-H2 between NREL and TNO is leveraging cross-Atlantic research to aid understanding.
- **Why:** TNO and NREL are often requested to analyse or review the techno-economics of these offshore hydrogen production concepts, summarized in techno-economic analyses (TEA's).
  - No concepts in operations, so many assumptions are made.
  - Drivers are landing cables challenges in built-up coastlines and development cost of electricity infrastructure further offshore
- **How:** TNO and NREL have compared several existing techno-economic analyses of the different concepts, to identify:
  - Compare concepts and identify knowledge gaps
  - Identify which factors in the TEAs have the highest uncertainty and impact
  - Outline strategies for lowering the uncertainty

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Approach: NREL-TNO International Working Group on Offshore Wind-H2

1. Define TEA input sheet

- NREL-TNO revise and agree on template and base scenario parameters for TEA input sheet

2. Complete TEA input sheet

- TNO and NREL complete (individually) TEA input sheet

4. Compare results

- Compare values and certainties, consciously agree on each item in the input sheet
- Special focus on items showing discrepancies between NL and USA, large uncertainty

5. Sensitivity analysis

- Determine what uncertainties have the highest impact
- Prioritize in the uncertain parameters

6. Define next steps

- Identify actions required to converge and reduce uncertainties

In FY23 capital costs were the focus topic.

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Approach: NREL-TNO OSW-H2 Case Studies

CASE 1
Distributed in-turbine electrolysis

Image from Strom of Strohm, Siemens concept

CASE 2
Centralized offshore platform

Image from Recharge

CASE 3
Onshore electrolysis

Image from Howden of Holland Hydrogen 1

- The case studies were chosen based on common studies already in progress at NREL and TNO.
- They represent basic concepts to focus initial efforts.

Approach: NREL-TNO Initial Assumptions

- The goal of this study was not to present precise values, but:
  - Evaluate general trends between concepts
  - Identify highest uncertainties and differences
  - Identify differences between European and US considerations
  - Identify components/subsystems of the offshore hydrogen value chain where additional effort/research/demonstrations can reduce uncertainties.

Offshore conditions	Sea depth Distance from shore	40 m 100 km
Wind farm	Produced electric power Turbine size Nr. of turbines	1 GW 15 MW 67
Electrolyzer (on platforms)	Technology Module size Delivered pressure	PEM 100-200 MW 30 bar
H2 transport	New pipeline (dedicated for wind farm only)	
Power transmission	New HVDC cable (dedicated for wind farm only)	
Onshore boundary	Export pressure	50 bar

- PEM electrolysis assumed as best available technology for offshore (due to footprint and dynamic response)

Initial assumptions provided common basis for expert interpretation of differences in the comparison.

Accomplishment: NREL-TNO OSW-H2 Case Uncertainties

CASE 1
Distributed in-turbine electrolysis

- Necessity of additional compression and storage beyond turbine level for inter-array and export pipeline
- Infield design of pipelines and collection not designed or optimized
- O&M requirements for distributed electrolysis unclear

CASE 2
Centralized offshore platform

- Platform size and cost is a big uncertainty and major contribution (footprint and weight of electrolysis system)
- Optimization of windfarm size to electrolyzer capacity not performed
- Installation and O&M costs uncertain (also Case 1)

CASE 3
Onshore electrolysis

- Grid connection not considered, but is factor in optimal sizing and operation
- Buffer storage dependant on demand scenario (offshore-case 1&2- may be able to use inherent pipeline storage or inexpensive undersea storage)

- Trade-off between CapEX and OPEX for offshore operation not optimized.
- More uncertainty for system design offshore.

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Accomplishment: NREL-TNO OSW-H2 Key Insights

- Electrolyzer costs in US are more aggressive due to Hydrogen Earthshot
- Offshore wind costs in Netherlands lower due to more mature supply chain including turbine manufacturing and installation vessels
  - Jones Act will require purpose built ships registered in US
  - US supply chain is still under-developed, but ramping up
- Case study takeaways:
  - The in-turbine case has the most competitive CAPEX, but also biggest uncertainties around OPEX and design
  - Central offshore electrolysis may benefit from cost of export pipelines vs electrical infrastructure, but platform costs are very significant and OPEX uncertain
  - Onshore electrolysis benefits from flexibility of grid connection, but less hydrogen storage and pipeline cost flexibility

- Capital cost assessment completed, but not available publicly yet
- A lot of similarities in US-NL assessments, differences from supply chain and R&D cost reduction expectations

Accomplishment: NREL-TNO OSW-H2 Reducing costs and uncertainty

- Main potential cost reductions through innovation:
  - In-turbine electrolysis: process intensification via turbine-electrolyzer integration
  - Electrolyzer: R&D on stack level to increase durability/reliability and reduce footprint and cost
  - Modularization / standardization of modules
- Main uncertainties:
  - Additional CAPEX due to offshore (unmanned) operations, including e.g. additional equipment and reliability/redundancy
  - O&M costs for electrolysis, to model offshore ramifications and optimize between system design and operation considerations.
  - Uncertainties in dynamic operation to understand operational performance window (effect of running above nominal load, at min load, cold start, hot start etc); degradation and optimized dispatch
  - BoP requirements for the electrolysis system to understand the trade-off between reliability and flexibility
  - Turn down rate or minimum load is very important uncertainty affecting the design. Differs per technology.

- Pilots and demonstrations will be key for reducing uncertainty

Accomplishment: NREL-TNO OSW-H2 Recommendations for improving TEA

- Explicit CAPEX assumptions along with equipment sizing and utilization
- Clear description of modelling to the subsystem level to understand the electrical and H2 flow performance impact on BoP (such as compression, pipelines, storage, water desalinization).
- Detailed modelling of siting considerations (size and weight) of subsystems needed for platform analysis
- Modelling at multiple time scales to understand dynamic range impact on BoP
- Operation analysis is needed to understand the impact of maintenance regimes
- O&M data is needed from onshore electrolysis to model the impact of offshore maintenance strategies
- Failure Modes and Effects Analysis (FMEA) is needed to understand the impact of subsystem failures on the system design
- Pipeline modelling to understand the compression needs, size consideration, and feasibility of use as inherent buffer storage

- OPEX modelling is a key need to fully evaluate concepts

Accomplishments and Progress:
Response to Previous Year Reviewers’ Comments

- This project has not been reviewed previously

Collaboration and Coordination

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

GINERLABS GE Research HYGRO plug™

- The OSW-H2 working group is in collaboration with TNO (supported by RVO in the Netherlands)

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Remaining Challenges and Barriers

- Experimental project will commence testing end of May 2023
  - Results from testing will help guide next steps
- The OSW-H2 working group has an analysis on capital costs, but is working on ways to present results along with the uncertainty inherent in analysis of systems that don’t yet exist.

Proposed Future Work

- Experimental project:
  - Results of testing will be collected and analyzed
  - Results of dynamic response rate testing will inform future needs to de-risk design
- NREL-TNO OSW-H2 working group
  - Publish joint white paper on current results and begin work on OPEX contribution to overall economics and system design

*For **new projects**, this criteria counts for 25% of your score.

Summary

- Offshore wind-H2 systems are very different from on-shore systems:
  - Environmental factors being remote and in harsh conditions
  - Integration of closely coupled systems that must be economic and reliable
- Offshore wind-H2 has no operational projects (yet) so there are a lot of uncertainties and areas to work through
- NREL is has a collection of projects to tackle:
  - Hardware integration and product development with industry
  - Analysis so we can address the right questions through internal and international collaborations

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Rogier Blom, Arvind Tiwari (GE Research)
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US-NL OSW-H2 Working Group:
Lennert Buijs, Michele Tedesco (TNO)
Michael Hahn (DOE/HFTO)

Thank You

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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.