Optimal Wind Turbine Design for H2 Production

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DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting

Project ID: TA061

Project Goal

- **Identify optimal wind turbine designs made specifically for hydrogen production with the goal of advancing affordable green hydrogen production**
- This project aims to couple wind turbine, wind plant, solar plant, and electrolyzer models to predict hydrogen production from variable, renewable power sources. This will be accomplished through:
  - Developing electrolyzer models informed by industry data
  - Optimizing wind turbine rotor diameter, hub height, and power rating for hydrogen production under different conditions and objectives
  - Validating the optimal turbine designs using the Advanced Research on Integrated Energy Systems (ARIES) research platform by scaling the electrical generation of the optimized designs and feeding this signal to a physical electrolyzer.

Overview

Timeline and Budget

- Project Start Date: 04/25/2022
- Project End Date: 04/24/2024
- Total Project Budget: $735,000
  - Total DOE Share: $500,000
  - Total Cost Share: $235,000 ($71,500 funds-in, $163,500 in-kind)
  - Total DOE Funds Spent*: $269,970
  - Total Cost Share Funds Spent*: $30,442

    * As of 04/14/2023

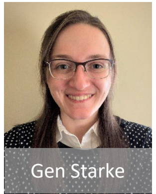
Barriers

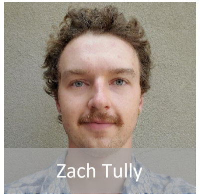
- Design for hydrogen generation from renewable energy, particularly wind energy

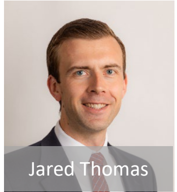
Partners

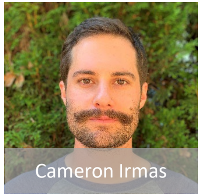
- National Renewable Energy Laboratory: Project lead
- General Electric (GE) Renewable Energy: advising on turbine design and performance/cost modeling; facilitating end-use customer survey
- Nel Hydrogen US: advising on electrolyzer performance/cost modeling.

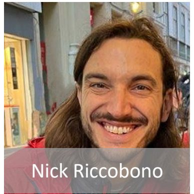
NREL Contributors









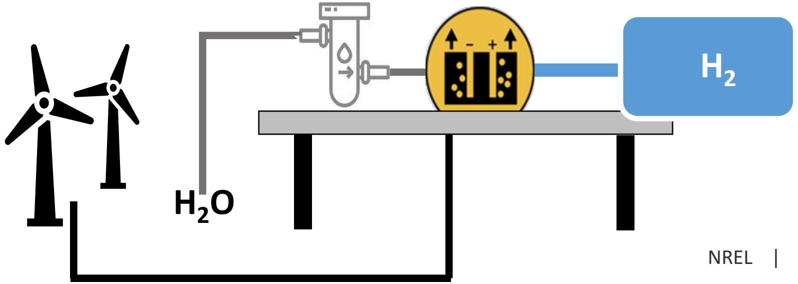


Potential Impact

- This work seeks to address the H2@Scale program's goal to "advance affordable hydrogen production" by optimizing the wind turbine design specifically for hydrogen (H2) production objectives within the H2@Scale pillar of technoeconomic modeling and analysis.
- Expected outcomes include:
  - The capability to design wind turbines for hydrogen production to unlock a reduced cost for renewable hydrogen and **accelerate the progress of the green hydrogen economy**
  - **Answers to relevant questions of interest from industry**, including optimal turbine sizing for H2 production, how different design objectives affect optimal technology couplings, and explore the benefits of different electrolyzer types (alkaline vs. polymer electrolyte membrane (PEM))
  - Reduced design cycle turnaround time to inform the optimal development of hybrid plants within the green hydrogen economy earlier in the project lifecycle, **accelerating uptake by industry**
  - **Increased certainty in the H2 production capabilities of hybrid plants**, leading to economic benefit as well as industrial energy savings by tuning plant performance for specific sites.

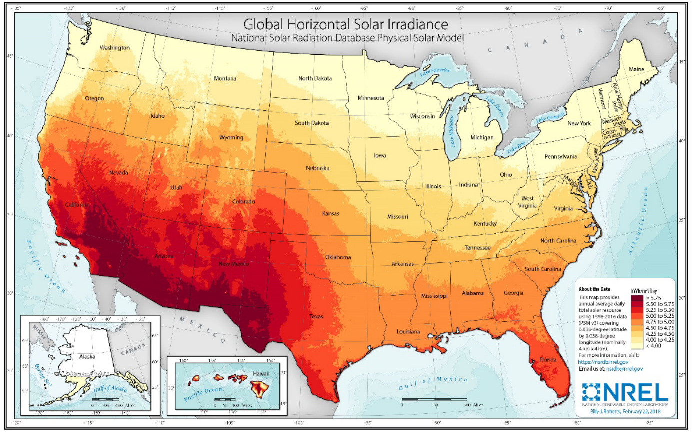
Approach – H2/Wind Coupling

- Develop and couple electrolyzer models with wind turbine/plant performance models
  - Nel Hydrogen US will assist in modeling the coupling to accurately predict hydrogen production
  - GE will advise on turbine performance and cost tunings
- Turbine performance predicted by the engineering models will be validated with higher-fidelity simulations
- Leverage NREL's existing work on the Hybrid Optimization and Performance Platform (HOPP) .

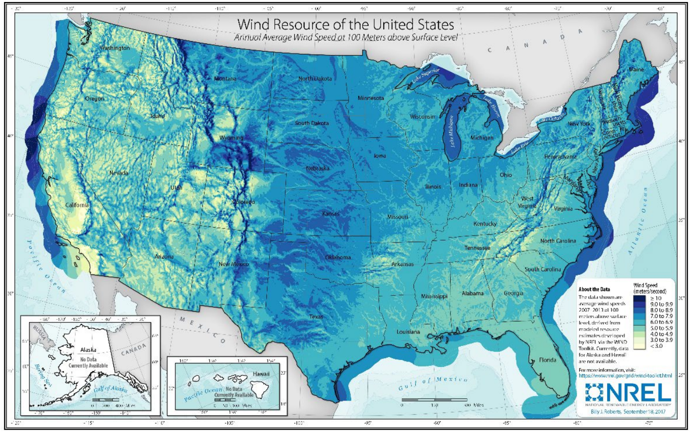


Approach – Customer Survey and Societal Impacts

- Work with GE to conduct end customer survey to identify geographic regions of interest for developing green hydrogen plants
  - Using associated wind/solar data to perform site-specific optimizations
  - Positive impact on the local economy and population will also influence which sites are selected for optimization, aiming to benefit populations that are vulnerable or have a lower socioeconomic status.



nrel.gov/gis/solar-resource-maps.html

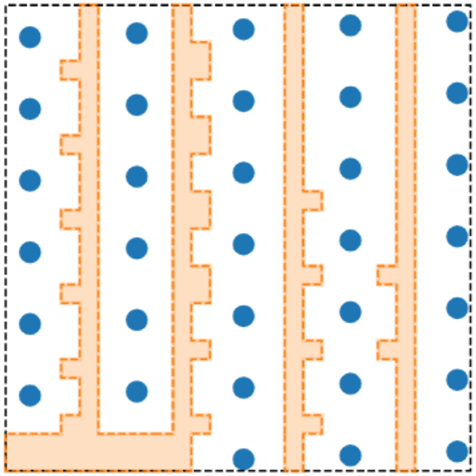


nrel.gov/gis/wind-resource-maps.html

Approach – Site-Specific Optimization for H2 Production

Optimize wind turbine design for H2 production at sites of interest by:

- Focusing first on single turbine-electrolyzer combinations, expanding to full plant optimizations
- Considering multiple objective functions including minimizing levelized cost of H2, maximizing H2 production, and simplified financial metrics (e.g., revenue or profit)
- Applying design variables, such as rotor diameter, hub height, rated power, electrolyzer ramp rates, and plant capacity
- Plant-level optimizations will be considered for both alkaline and PEM electrolyzers.



Example wind turbine (blue) & solar panel (orange) optimization for a specific site.

Approach – Validate Wind Turbine Designs With ARIES

- NREL's Advanced Research on Integrated Energy Systems facility will be used to validate the turbine designs
  - Wind turbines will be virtually modeled, producing an electric signal that will be fed to a physical electrolyzer to verify improved H2 production
  - Industry partner Nel will advise on electrolyzer modeling and operation (PEM electrolyzer at ARIES)
  - A go/no-go decision will be made for the testing based on one of the optimized designs demonstrating at least a 5% reduction in levelized cost of hydrogen (LCOH).

Hydrogen system at ARIES. *Photo by NREL*

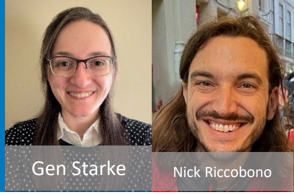
Approach – Milestones

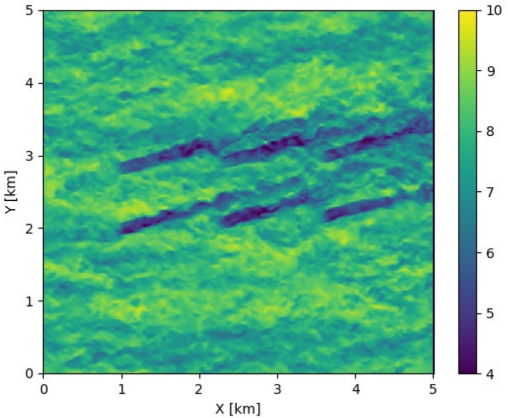
Date	Milestone/Deliverable (status as of 4/14/2023)	Complete
6/30/2022	M.1 - Electrolyzer model developed and detailed in slide deck	100%
9/30/2022	M.2 - Coupling of electrolyzer and single turbine simulated for 12 hours	100%
12/31/2022	M.3a - Coupling of electrolyzer with 20-megawatt wind/hydrogen plant simulated for 2 hours	100%
12/31/2022	M.3b - Recruit student to team with focus on recruiting from underrepresented communities	100%
3/31/2023	M.4 - Complete first turbine design optimization	100%
6/30/2023	M.5 - Go/no-go decision to move ahead with experiments (optimized design showing >5% reduction in LCOH)	45%
9/30/2023	M.6 - Complete original research paper draft on optimal turbine design for H2 production	10%
12/31/2023	M.7 - Analysis showing societal impacts of proposed optimizations	0%
3/31/2024	M.8 - Complete original research paper draft on ARIES experiments	0%

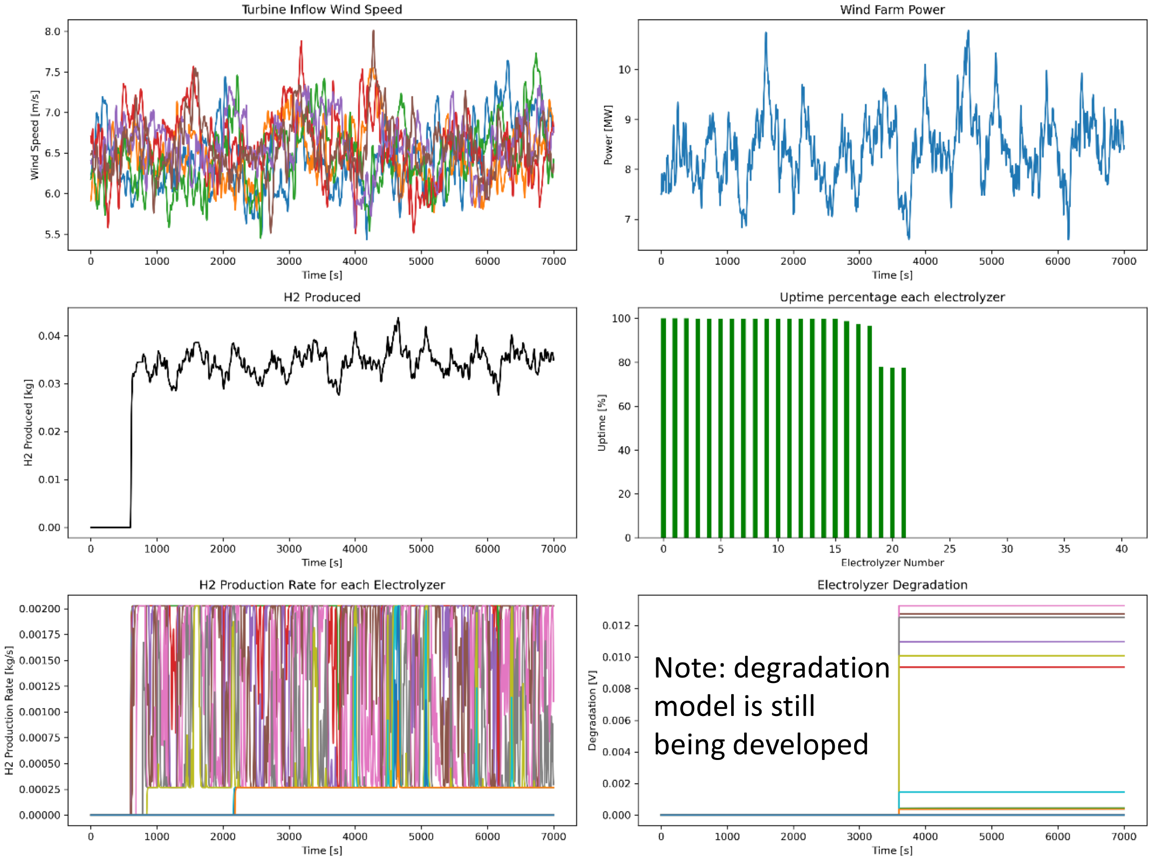
Accomplishments and Progress

- M.1 - Developed initial electrolyzer model, made available as open-source on GitHub (https://github.com/NREL/electrolyzer)
- M.2 - Coupled electrolyzer model to single turbines simulations (turbines simulated using WEIS, https://github.com/WISDEM/WEIS)
- M.3a – Coupled multiple electrolyzers to a 6 turbine wind plant in high-fidelity simulation
- M.3b – Have several student researchers, 1 through GEM Scholar program, 3 through graduate student internships
- M.4 – Initial optimized turbine design using the IEA 3.4MW turbine as a baseline; optimized for H2 produced as the objective function
- M.5 – Developing LCOH model to be used in optimization; extending wind turbine/electrolyzer control strategy.

Accomplishments and Progress – M.3a

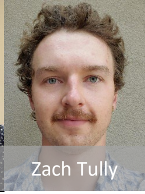






- Successful model structure combining wind farm simulation and hydrogen production

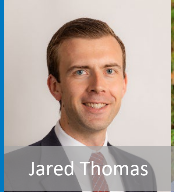
Accomplishments and Progress – M.3a

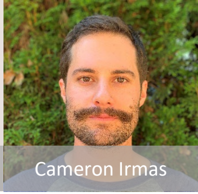


Controller	7 m/s	9 m/s	12 m/s	16 m/s	9 m/s Aligned	12 m/s Aligned
Baseline	110.4 kg	220.3 kg	503.0 kg	519.6 kg	152.9 kg	454.2 kg
Power Sharing *Eager Degradation*	136.9 kg	256.4 kg	510.8 kg	523.9 kg	183.9 kg	471.7 kg
Sequential *Even Wear Degradation*	94.6 kg	131.9 kg	487.7 kg	519.6 kg	65.4 kg	417.9 kg
Sequential *Rotation*	101.1 kg	205.7 kg	486.8 kg	506.1 kg	145.7 kg	461.3 kg
Sequential *Single Wear Degradation*	32.9 kg	39.1 kg	482.8 kg	514.2 kg	17.9 kg	410.8 kg

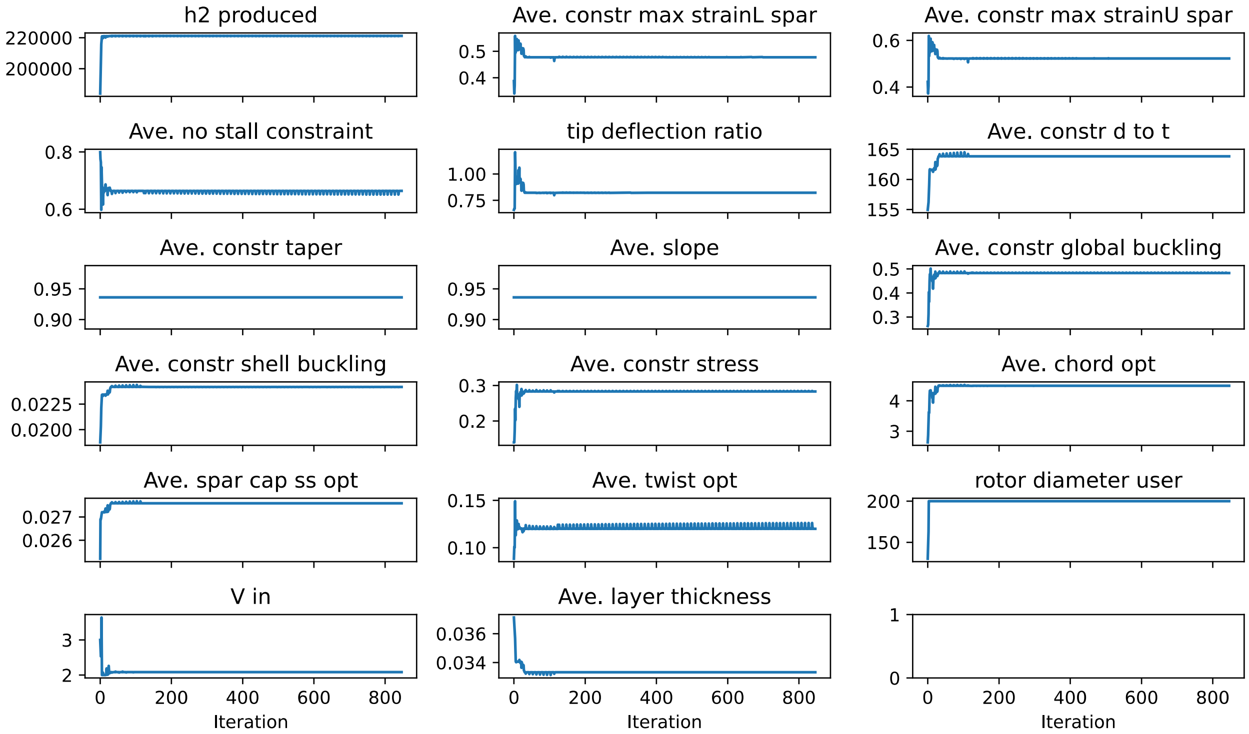
- Total hydrogen produced for each simulation run with the highest productions for each simulation across controller cases are highlighted in green.
- Like the individual turbine results, for the higher wind speed cases, the degradation management strategies matter less (less variation in H2 produced) as the electrolyzers are more fully utilized.
- The “Aligned” cases are for a wind direction where the wind turbines wake one another. For the other cases, each of the turbines are seeing a similar freestream wind speed.

Accomplishments and Progress – M.4

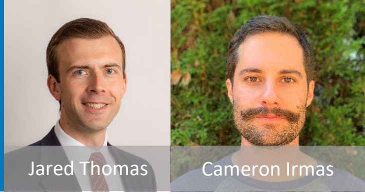




- Initial turbine optimization for objective function maximizing H2 produced
- Baseline turbine is the IEA 3.4 MW onshore reference turbine (https://github.com/IEAWindTask37/IEA-3.4-130-RWT)
- Result shows a larger rotor diameter and lower cut-in wind speed, which leads to more constant power and more H2 produced.



Accomplishments and Progress – M.4



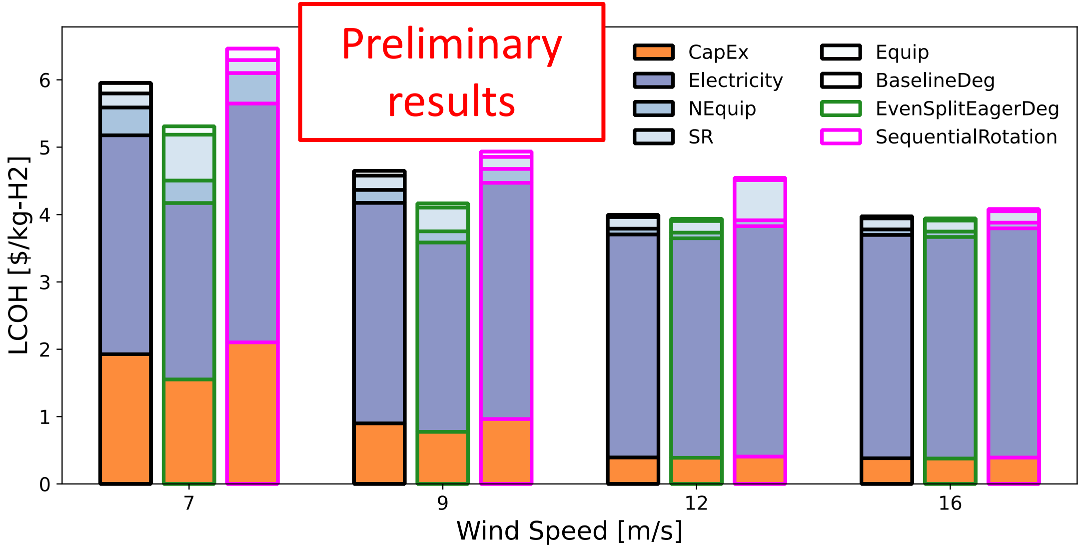
Preliminary Optimization Results for Maximizing H2 Production			
	H2 (kg)	Rotor Diameter (m)	Cut In Speed (m/s)
Start	183,909	130	3.0
End	221,218	200	2.1
Change	+ 20.3 %	+ 53.8 %	- 30.5 %

- Preliminary optimization shows a 20.3% increase in H2 produced, resulting from more steady energy from the wind turbine; we expect future optimizations for LCOH to return different optimal turbine design values
- Ongoing studies to validate wind turbine design and looking at other baseline designs
- Future optimizations will include solar and storage as well as optimizing for LCOH.

Accomplishments and Progress – M.5

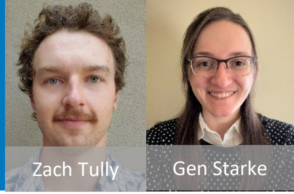
- Reference costs and methodology adapted from [1]
- Assumes 4% discount rate, 33% installation factor, and 25-year plant life
- Cost scaling for increased *component capacity* using learning rates
- Allows for on-shore, off-shore or in-turbine electrolyzer placement
- Compatible with current code architecture
- Simple approximation of annual performance based on time-series results
- Preliminary results are comparable to existing literature and other projects
  - Assume on-shore placement and 0.044 $/kWh cost of energy
  - Stack replacement costs are a function of degradation

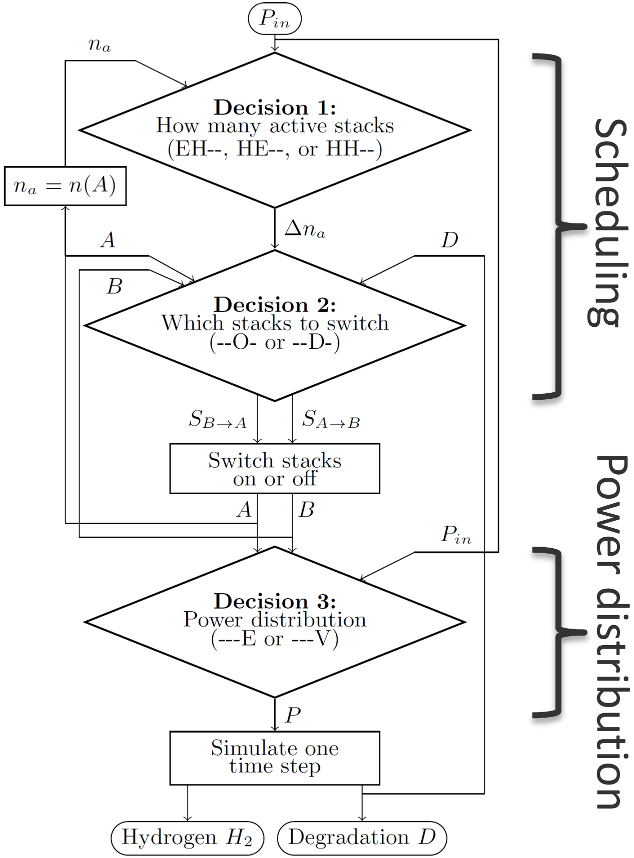
- Future work
  - Include cost scaling for increased *manufacturing capacity*
  - Incorporate cost projections for future years
  - Increase resolution for cost breakdown
  - Add advanced annual performance projections based on time-series data



[1] A. Singlitico, J. Østergaard, and S. Chatzivasileiadis, "Onshore, offshore or in-turbine electrolysis? techno-economic overview of alternative integration designs for green hydrogen production into offshore wind power hubs," *Renewable and Sustainable Energy Transition*, vol. 1, p. 100005, 2021.

Accomplishments and Progress – M.5



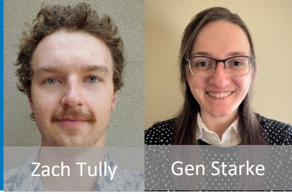


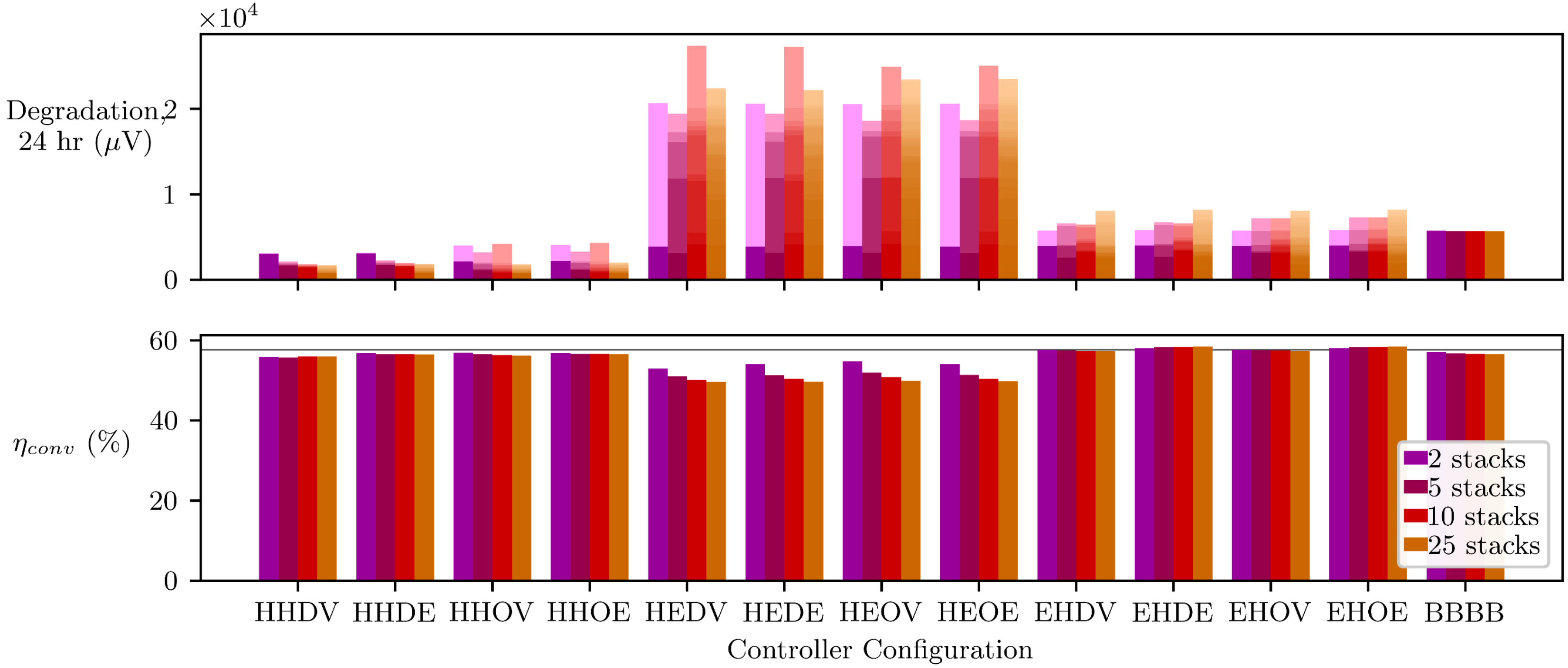
- Manuscript submitted to 2023 Conference on Control Technology and Applications (CCTA) on novel multi-stack scheduling and power distribution H2 plant controller
- 12 controller configurations + baseline.

<u>Highlights</u>

- Hysteretic switching on and off
- Degradation-based switching order
- Variable power distribution.

Accomplishments and Progress – M.5





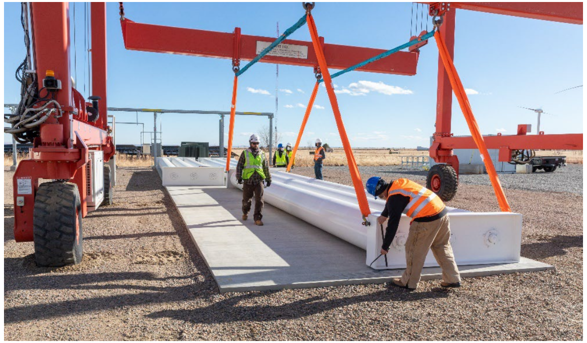
Ongoing analysis of controller configuration to maximize efficiency and minimize degradation

Collaboration and Coordination

- This project has two industry partners:
  - **General Electric Renewable Energy** (sub)
    - Provide feedback on turbine designs
    - Give valuable insight on tuning of turbine performance/cost models
    - Facilitate the end customer survey to ensure optimizations are relevant based on current markets.
  - **Nel Hydrogen US** (sub)
    - Provide feedback on electrolyzer modeling and cost tuning
    - Ensure successful demonstration of H2 production at ARIES.
- Coordinated with HFTO/WETO project "Integrated Modeling, TEA, and Reference Design for Renewable Hydrogen to Green Steel and Ammonia" which is using our electrolyzer model
- Integrating model with the Hybrid Optimization Performance Platform (HOPP) and the Virtual Emulation Environment (VEE) to be used at ARIES.

Remaining Challenges and Barriers

- Go/No-go milestone demonstrating >5% reduction in LCOH
- Gathering site data for optimization sites informed by the customer feedback survey and include grid-connected systems in the study
- Commissioning of the electrolyzer has been delayed due to system integration challenges and site electrical safety required modifications but is scheduled to happen before the beginning of the experimental part of the project.



Installing hydrogen storage at ARIES. Photo by Werner Slocum, NREL

Proposed Future Work

- Remainder of FY 2023:
  - Integrate storage and solar/PV models into optimization
  - Complete optimizations that include data identified from the customer survey and relevant grid-connected scenarios
  - Demonstrate >5% reduction in LCOH for optimized wind plant design
  - Begin experimental validation of electrolyzer model and results.
- FY 2024:
  - Complete ARIES experimental validation campaign
  - Write journal article detailing ARIES experiment and results.

Any proposed future work is subject to change based on funding levels.

Summary

- This project aims to lower the cost of green hydrogen through the design and optimization of wind turbines specifically for H2 production (as opposed to maximal energy production/levelized cost of energy reduction as is currently done)
- Developed open-source electrolyzer model and successfully coupled with wind turbine simulations
- Preliminary optimization results show potential for lower LCOH
- Turbine and electrolyzer modeling and cost estimation are being informed from GE and Nel Hydrogen US, respectively
- Wind turbine designs will be validated using the ARIES research platform at NREL.

Thank You

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Technical Backup and Additional Information

(Include this "divider" slide before your technical backup slides [maximum 20]. These technical backup slides will be available for oral presenters to use for Q&A and will be included in the published web PDFs for oral and poster presentations.

*Note there is **one required slide** in this section and several suggested slides.)*

Technology Transfer Activities

- Developed and published open-source electrolyzer model on GitHub
- Integrating electrolyzer model into Wind-Plant Integrated System Design & Engineering Model (WISDEM®) and HOPP
- Will pursue additional funding from DOE’s Hydrogen and Fuel Cell Technologies Office and DOE’s Wind Energy Technologies Office
- GE and Nel Hydrogen US are immediately interested in the results of this project to inform direction of investments.

Publications and Presentations

- Starke, Genevieve, Tully, Zachary, Irmas, Cameron, Riccobon, Nicholas, Thomas, Jared, Grant, Elenya, Bhaskar, Parangat, King, Jennifer, and Bay, Christopher. “An electrolyzer model for green hydrogen and optimal wind turbine design.” *2023 Wind Energy Science Conference*, May 23rd-26th, 2023. Accepted.
- Tully, Zachary, Starke, Genevieve, Johnson, Kathryn, and King, Jennifer. “An investigation of heuristic control strategies for multi-electrolyzer wind-hydrogen systems considering degradation.” *IEEE 2023 Conference on Control Technology Applications*, August 16th-18th, 2023. Submitted.