Optimal Wind Turbine Design for H2 Production

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DOE Hydrogen Program
2024 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: 06/30/2024 (planning a no-cost extension)
- 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*: $425,456
  - Total Cost Share Funds Spent*: $32,944

    * As of 03/25/2024

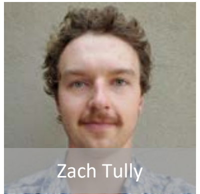
Barriers

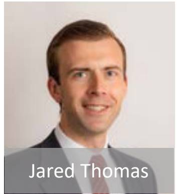
- Design for hydrogen generation from renewable energy, particularly wind energy

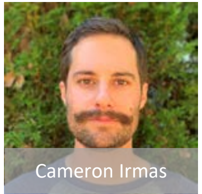
Partners

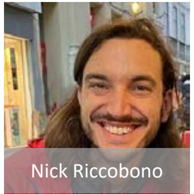
- National Renewable Energy Laboratory: Project lead
- General Electric (GE) Renewable Energy: advising on turbine design and performance/cost modeling; facilitating end-use customer survey
- Nel Hydrogen US: advising on electrolyzer performance/cost modeling.

NREL Contributors







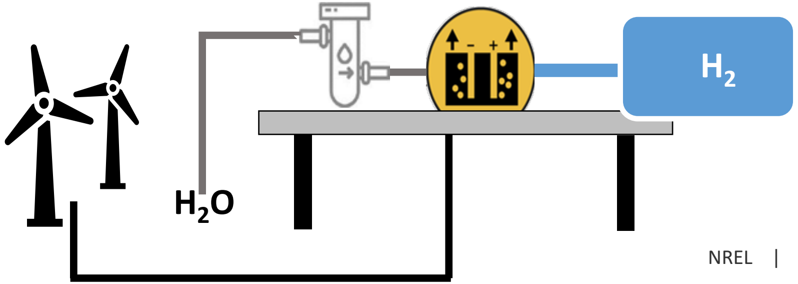


Potential Impact

- 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.

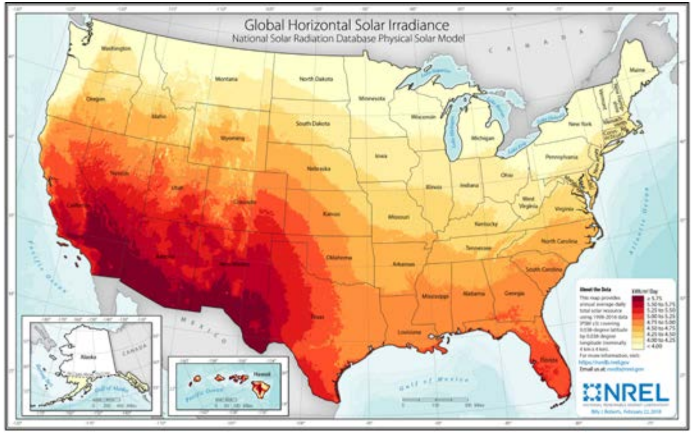
Approach – H2/Wind Coupling

- 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.



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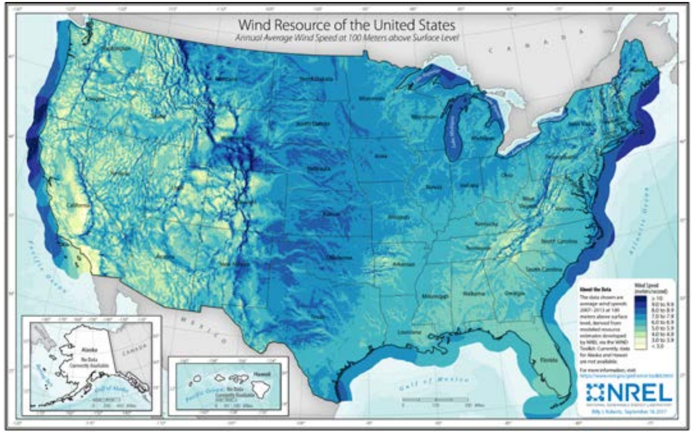
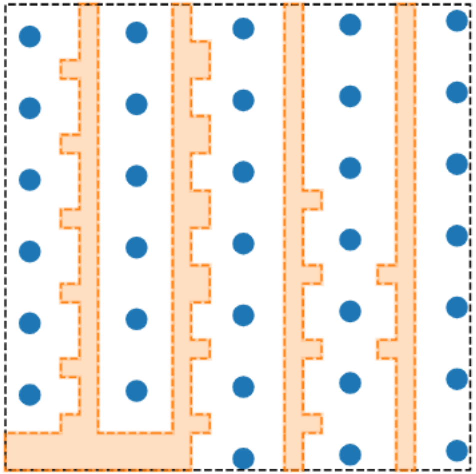


nrel.gov/gis/wind-resource-maps.html

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 3/25/2024)	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)	100%
12/31/2023	M.6 - Analysis showing societal impacts of proposed optimizations	20%
3/31/2024	M.7 - Complete original research paper draft on optimal turbine design for H2 production	90%
6/30/2024	M.8 - Complete original research paper draft on ARIES experiments	5%

Approach: Safety Planning and Culture

- A safety plan was not required to be submitted to the Hydrogen Safety Panel (HSP) for this project.
- Safety culture is being applied to this project by:
  - Waiting for the electrolyzer system to be fully commissioned before beginning experimental campaign
  - Working closely with our industry partner Nel to ensure safe operation of the hydrogen system
  - Incorporating best safety practices and lessons learned from other experiments using the ARIES platform.

Accomplishments and Progress:
Response to Previous Year Reviewers' Comments

- This project has not been previously reviewed at an AMR.

Accomplishments and Progress

- M.7 – Perform wind turbine optimizations for H2 production and detail results in original research paper draft.
  - We have achieved an initial LCOH reduction of 12.8% for our baseline wind turbine when considering just wind and H2 production. The optimization process and results are detailed in the following slides.
  - Currently working on research paper draft.
- M.8 – Gather experimental performance data of electrolyzer operation when powered virtually by optimal wind turbine design from M.7; detail results in original research paper draft.
  - Experimental system is fully commissioned, and we are finalizing a test plan.

Accomplishments and Progress – M7: Individual turbine optimization for H2 production

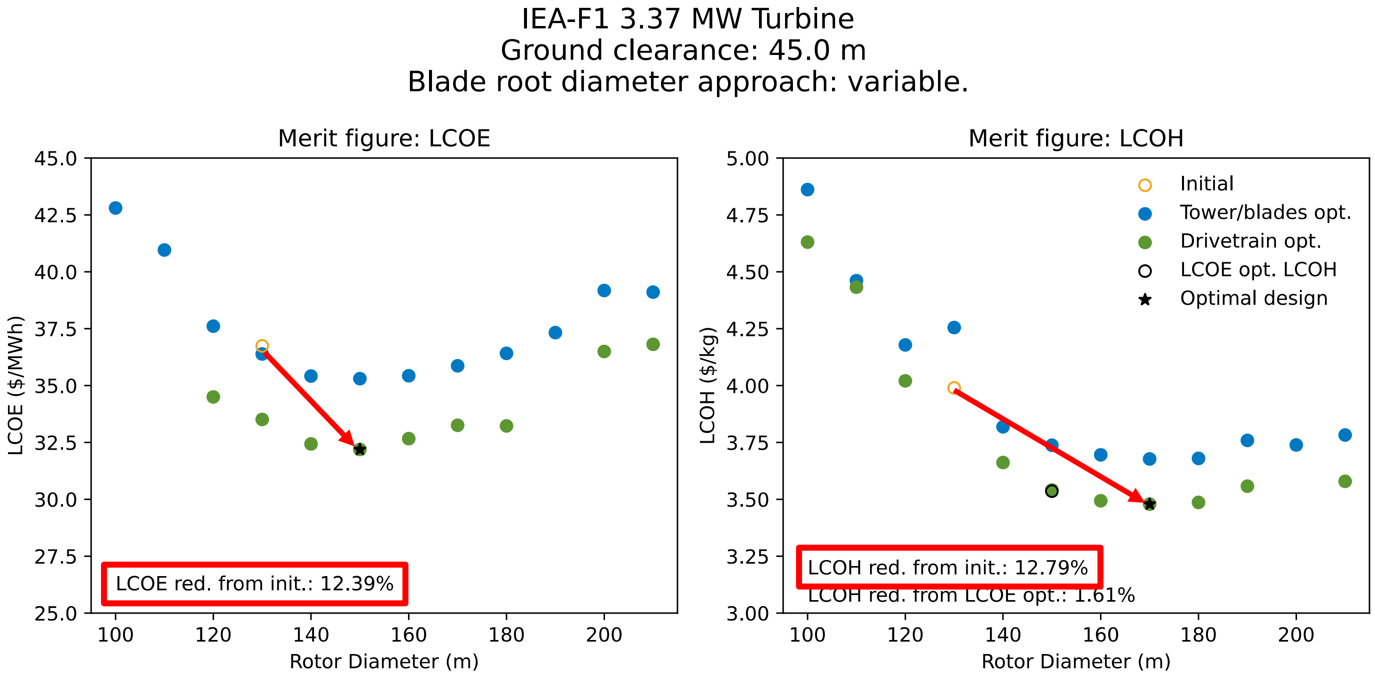
Using a modified WISDEM to include our electrolyzer model, individual turbine optimizations were performed with the objective of minimizing LCOH.

The 3 steps are shown to the right, along with the relevant design variables.

Sub-system(s) (Objective(s))	Design Variables
Tower (LCOE)	Tower: Section thickness, Section diameter
Tower + Blades (LCOH, LCOE)	Tower: Section thickness Blade: Chord, Twist, Spar cap Sweeps: rotor diameter, electrolyzer rating
Drivetrain (Nacelle Mass)	Drivetrain: Shaft length between main bearing 1 and main bearing 2, Shaft length from hub flange to main bearing, High-speed shaft length, Hub diameter, Low-speed shaft diameter, Low-speed shaft wall thickness, High-speed shaft diameter, High-speed shaft wall thickness, Bedplate web thickness, Bedplate flange thickness, Bedplate flange width.

Accomplishments and Progress – M7: Optimized wind turbine design using IEA 3.37MW turbine

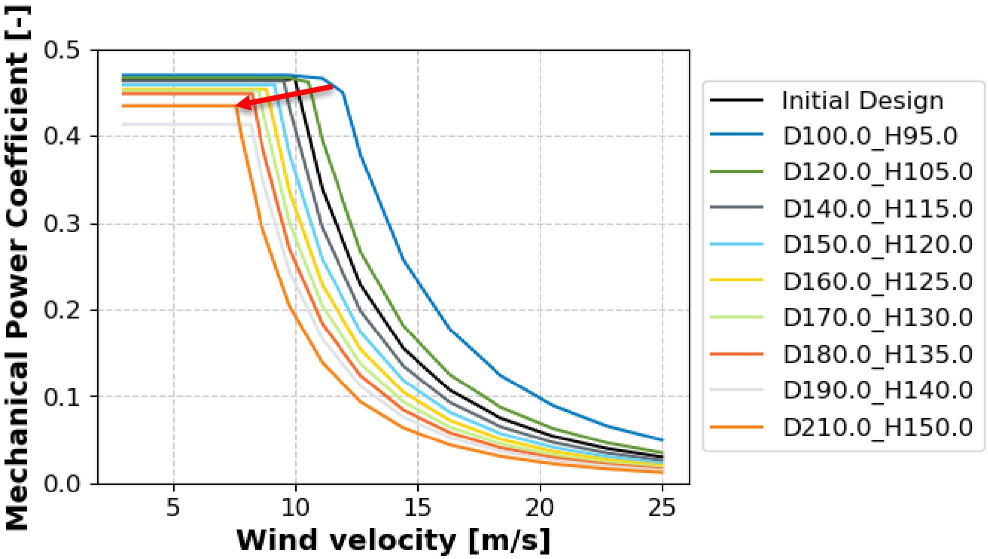
The LCOH optimized designs use a rotor diameter 20 m larger than the LCOE optimized design, which is 40 m larger than the initial design.



Accomplishments and Progress – M7:
Aerodynamic performance of optimal wind turbine design

As rotor diameter increases, rated power is reached at lower wind speeds, which results in a more consistent power output.

IEA Optimized Turbine

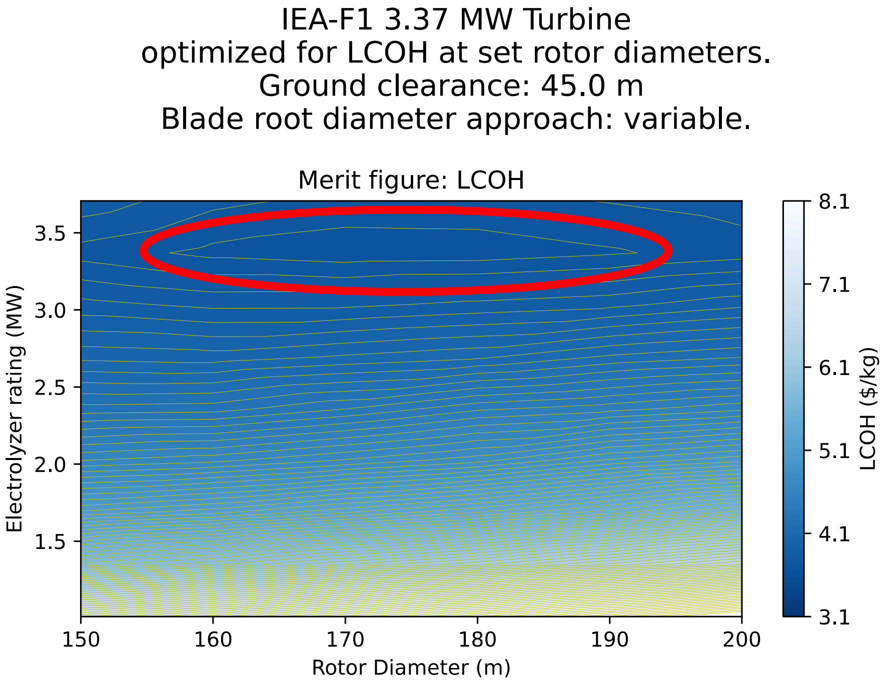


Accomplishments and Progress – M7:
Optimized wind turbine design across electrolyzer capacities

Electrolyzer rating has a stronger influence on LCOH than rotor diameter.

There is a range of rotor diameters that achieve near-optimal LCOH values, **these simulations show that the electrolyzer rating should be close to the turbine rating**.

Note that the optimal relative turbine to electrolyzer rating may shift significantly when storage or grid connection are included.



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.

DEIA/Community Benefits Plans and Activities

- This project does not have a CBP or DEIA plan, but we have taken steps to support the Justice40 Initiative by:
  - Recruiting a Graduate Education Minority (GEM) Fellow to the project, contributing to them being hired at NREL
  - Including societal impact analysis in our project plan.

Remaining Challenges and Barriers

- Completing experimental campaign
  - The system has been fully commissioned, so we can now begin collecting data; we are pursuing a no-cost time extension to give adequate time to complete the data collection
  - Conducting specific power-varying experiments may challenge the equipment
  - Analyzing the data to share results in a publication.

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

Proposed Future Work

- FY 2024:
  - Write original paper draft on individual wind turbine optimizations
  - Complete ARIES experimental validation campaign
  - Write original paper draft detailing ARIES experiment and results.
- Current project completion date: 6/30/2023
  - The modeling effort of this project is already being used in several other projects within the HOPP software framework
  - We are also pursuing funding opportunities for doing design studies for offshore wind-to-H2 facilities that will consider H2 specific wind turbines.

Summary

Wind turbine and plant design can lower the cost of H2 production. The impacts from our initial analysis show LCOH reductions of **7-12%**.

Developed innovative **open-source electrolyzer models coupled with wind energy design tools** that have already been implemented in other projects.

Wind turbine designs will be **tested using the ARIES research platform at NREL**, validating the developed electrolyzer model.

Thank You

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Technical Backup and Additional Information

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.
- 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.