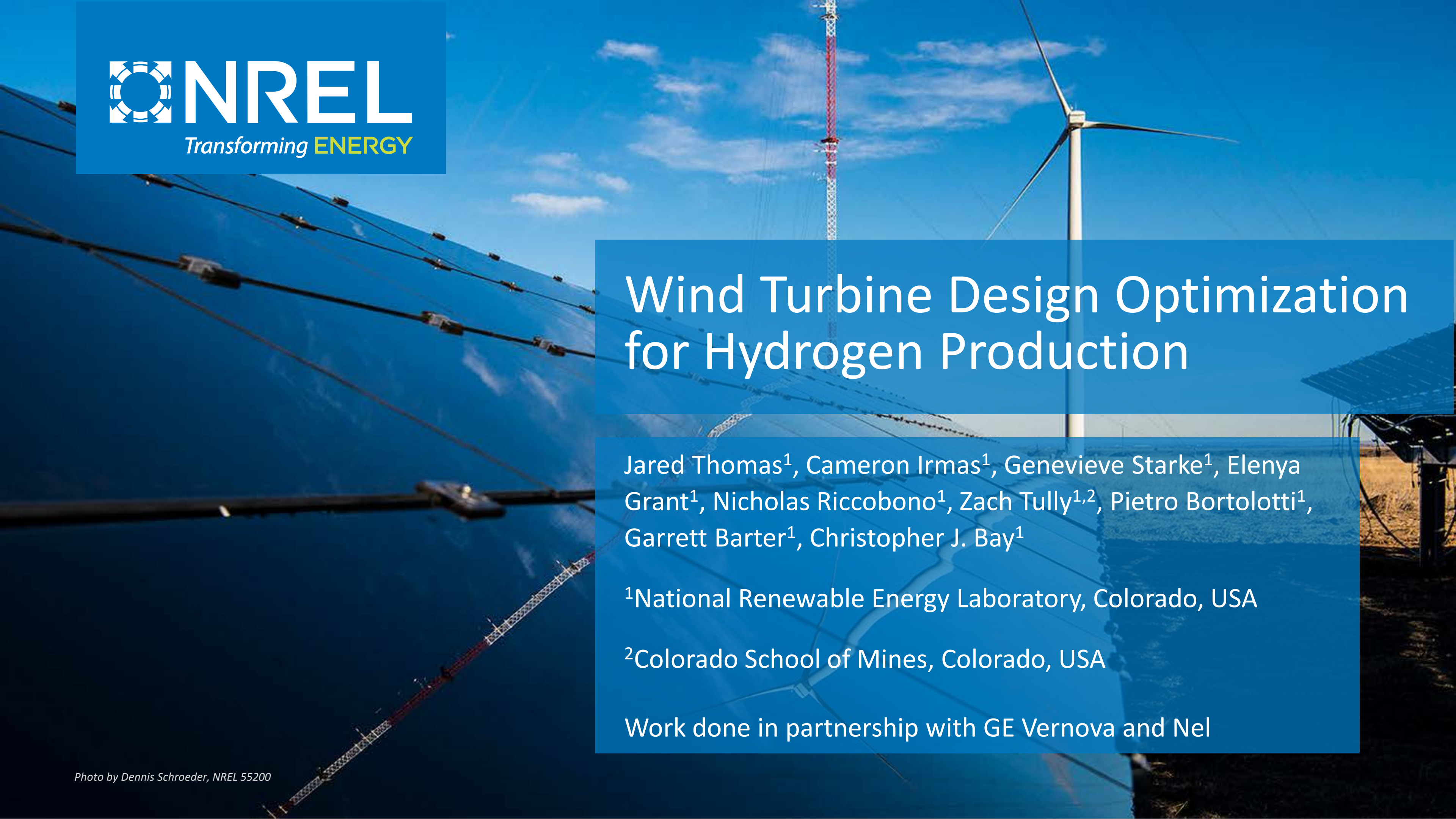


Photo by Dennis Schroeder, NREL 55200

Wind Turbine Design Optimization for Hydrogen Production

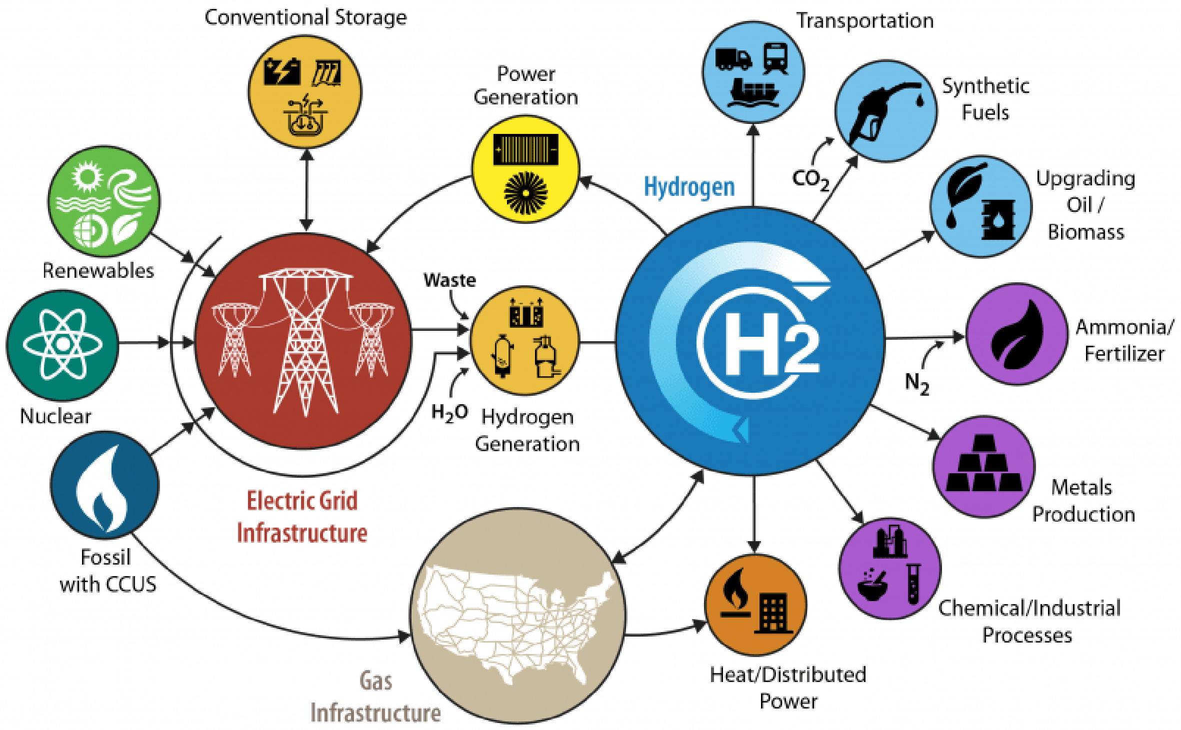
Jared Thomas[1], Cameron Irmas[1], Genevieve Starke[1], Elenya Grant[1], Nicholas Riccobono[1], Zach Tully[1,2], Pietro Bortolotti[1], Garrett Barter[1], Christopher J. Bay[1]

[1]National Renewable Energy Laboratory, Colorado, USA

[2]Colorado School of Mines, Colorado, USA

Work done in partnership with GE Vernova and Nel

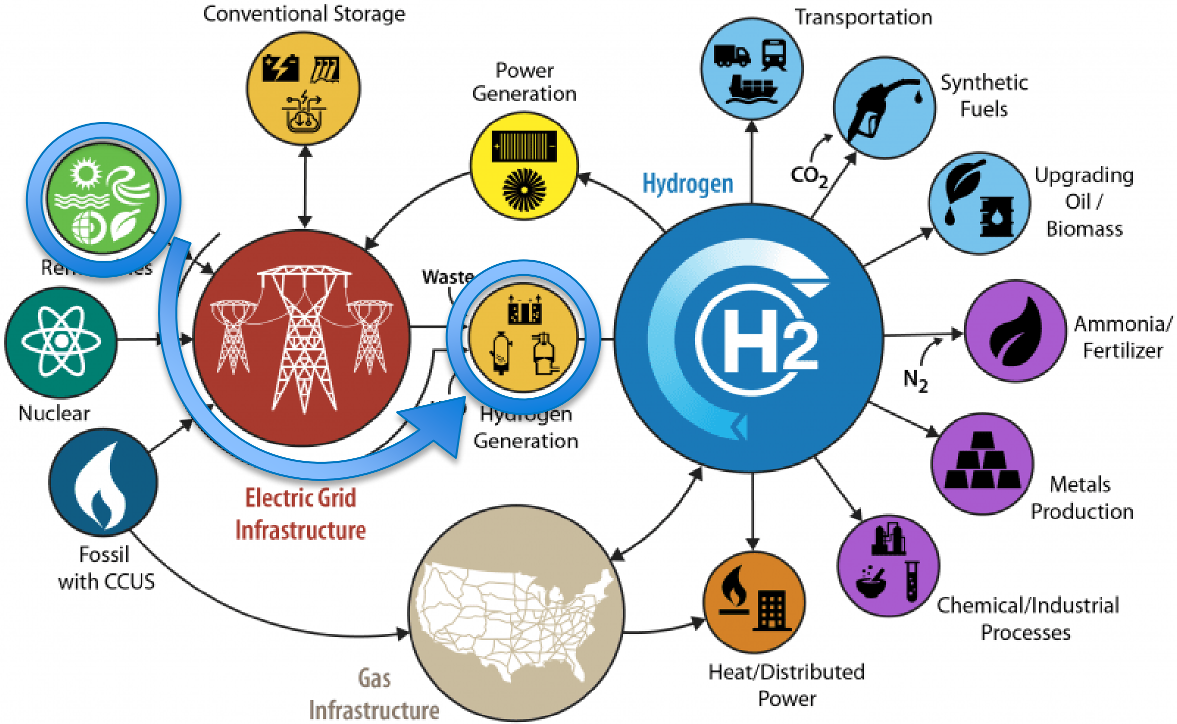
Background: H_2 at Scale



H2@Scale is a U.S. Department of Energy (DOE) initiative that includes hydrogen production, transport, storage, and utilization in an effort to decarbonize multiple sectors. CCUS stands for carbon capture, utilization, and storage.

Image from https://www.energy.gov/eere/fuelcells/h2scale

Background: H_2 at Scale



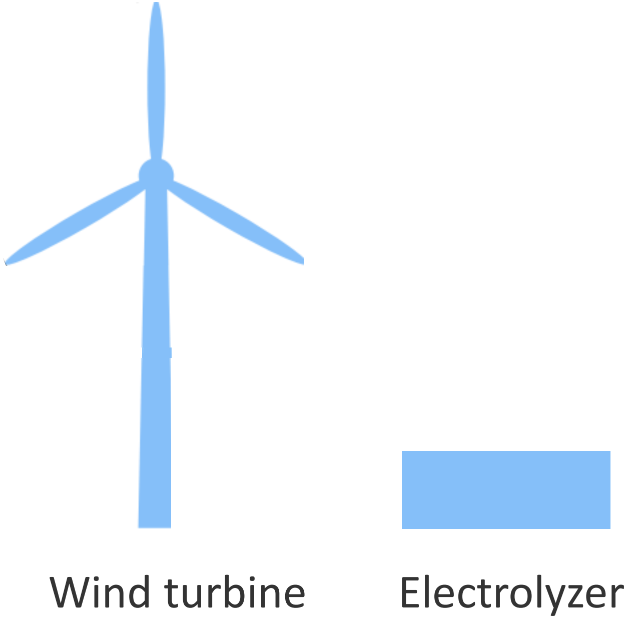
In this project, we are primarily focused on designing a wind turbine specifically for hydrogen production. This effort fits in with H2@Scale through the renewables to hydrogen pathway.

Image from https://www.energy.gov/eere/fuelcells/h2scale

Project Goal

Understand how wind turbine design could change to produce hydrogen instead of electricity.

Assuming Co-Located, Off-Grid System Without Storage



Approach

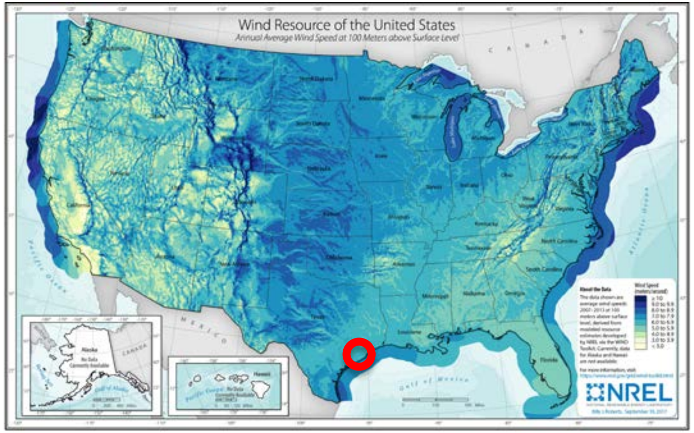
Redesign a baseline turbine for levelized cost of electricity (LCOE) and levelized cost of hydrogen (LCOH).

We swept the rotor diameter of a modified International Energy Agency (IEA) 3.4-MW wind turbine from 100 m to 200 m and optimized the blades and drivetrain at each rotor diameter for each objective individually (LCOE and LCOH).

Overview of the Baseline Turbine and Site

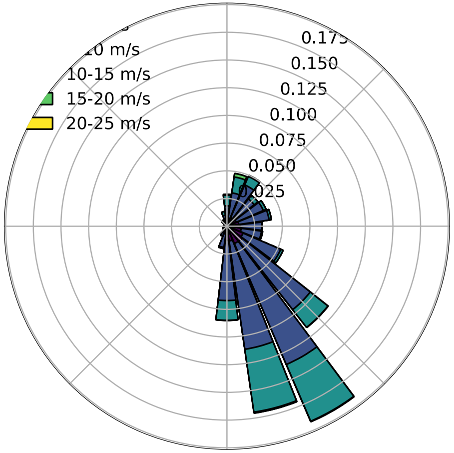
- Project focused on onshore hybrid systems
- A baseline turbine was selected:
  - IEA 3.4 MW: open-source onshore reference turbine, developed through IEA Wind Task 37 (https://github.com/IEAWindTask37/IEA-3.4-130-RWT)
- Site selected by customer survey to be along Texas coast, near the Gulf of Mexico

Metric	IEA 3.4 MW
Rotor diameter (m)	130
Hub height (m)	110
Nameplate power (MW)	3.37
Specific power (W/m^2)	254
Cut-in wind speed (m/s)	4
Cut-out wind speed (m/s)	25

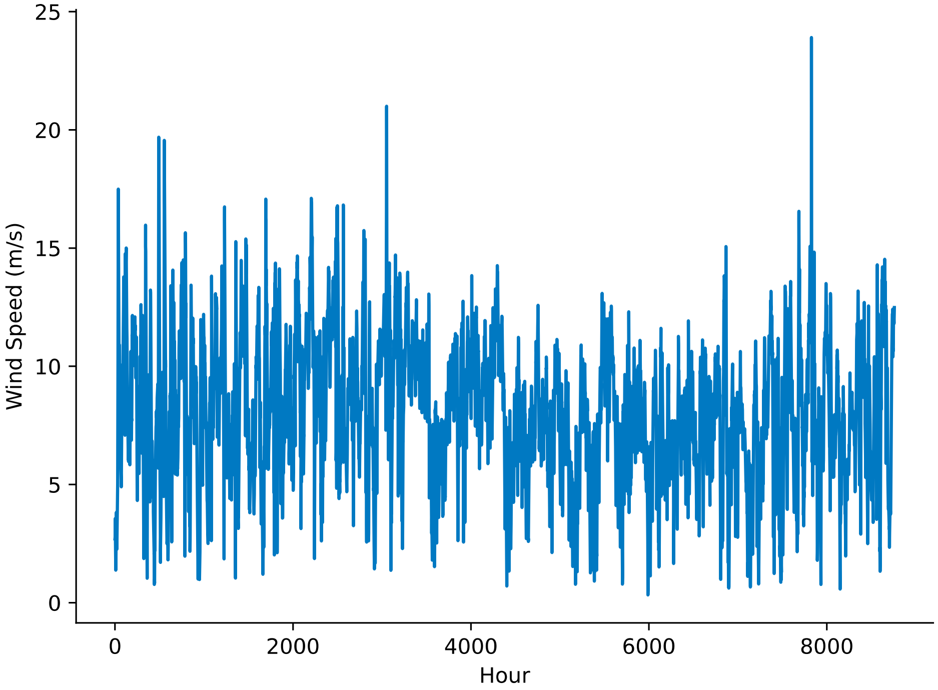


nrel.gov/gis/wind-resource-maps.html

Wind Resource

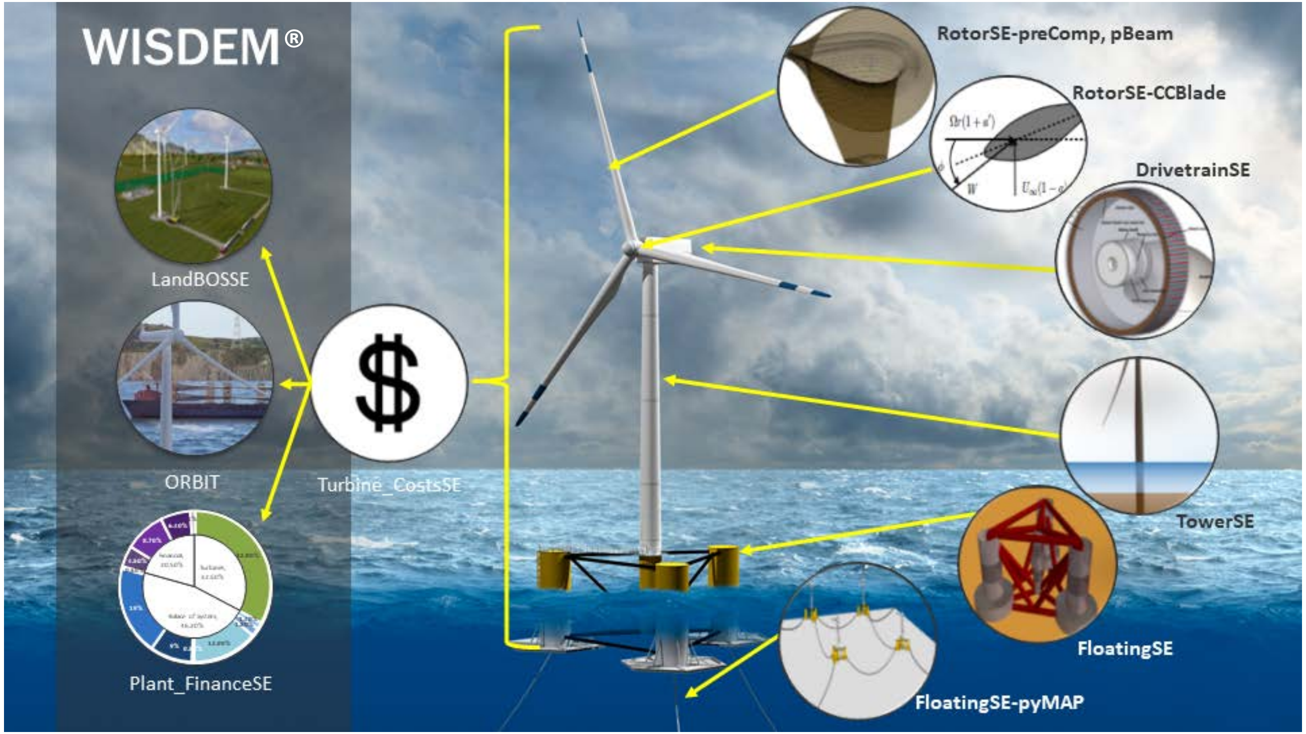


Wind rose



Hourly wind resource over a single year used to estimate hydrogen production for the wind turbines

Wind Turbine Modeling: WISDEM®



Overview of the WISDEM framework

WISDEM: Wind Plant Integrated Systems Design and Engineering Model

SE: System Engineering

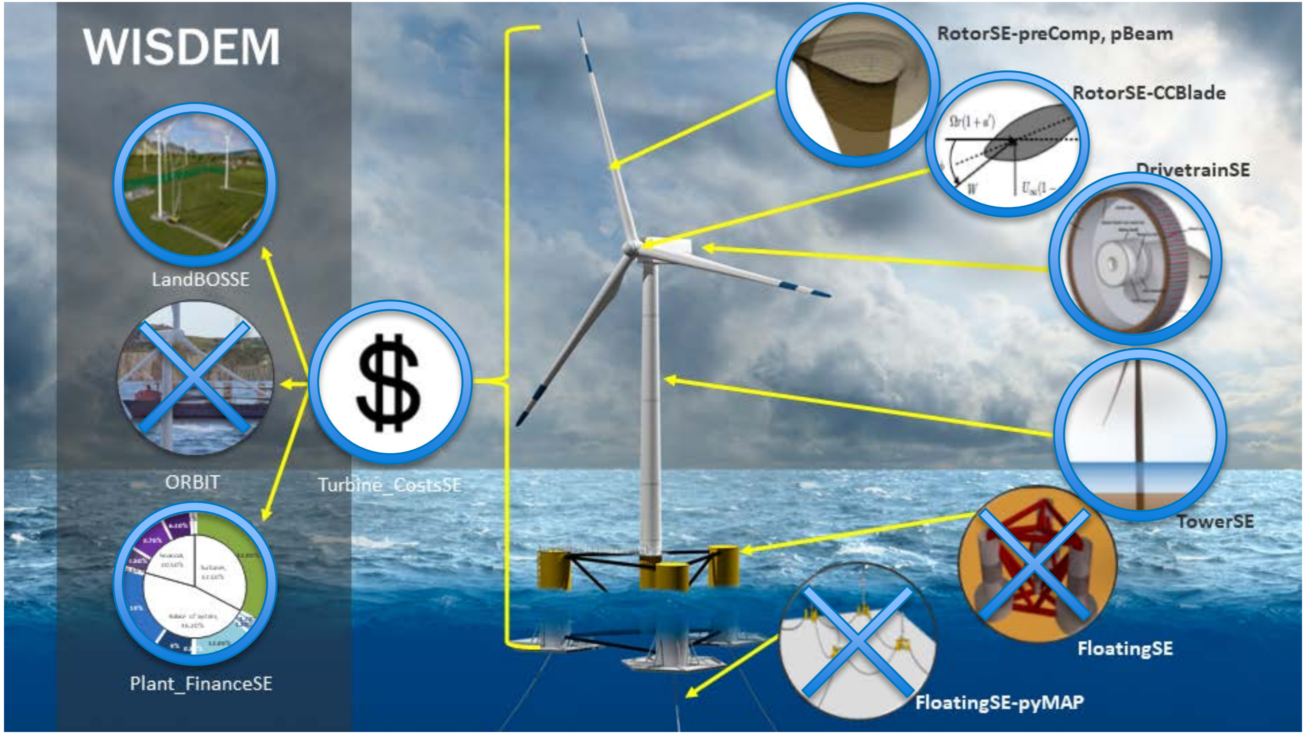
ORBIT: Offshore Renewables Balance of system and Installation Tool

BOS: Balance of System

MAP: Mooring Analysis Program

NREL WISDEM Team. 2023. “Wind-Plant Integrated System Design and Engineering Model (WISDEM) [code].” https://github.com/WISDEM/WISDEM. Version f893264.

Wind Turbine Modeling – Only Onshore Modules



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SE: System Engineering
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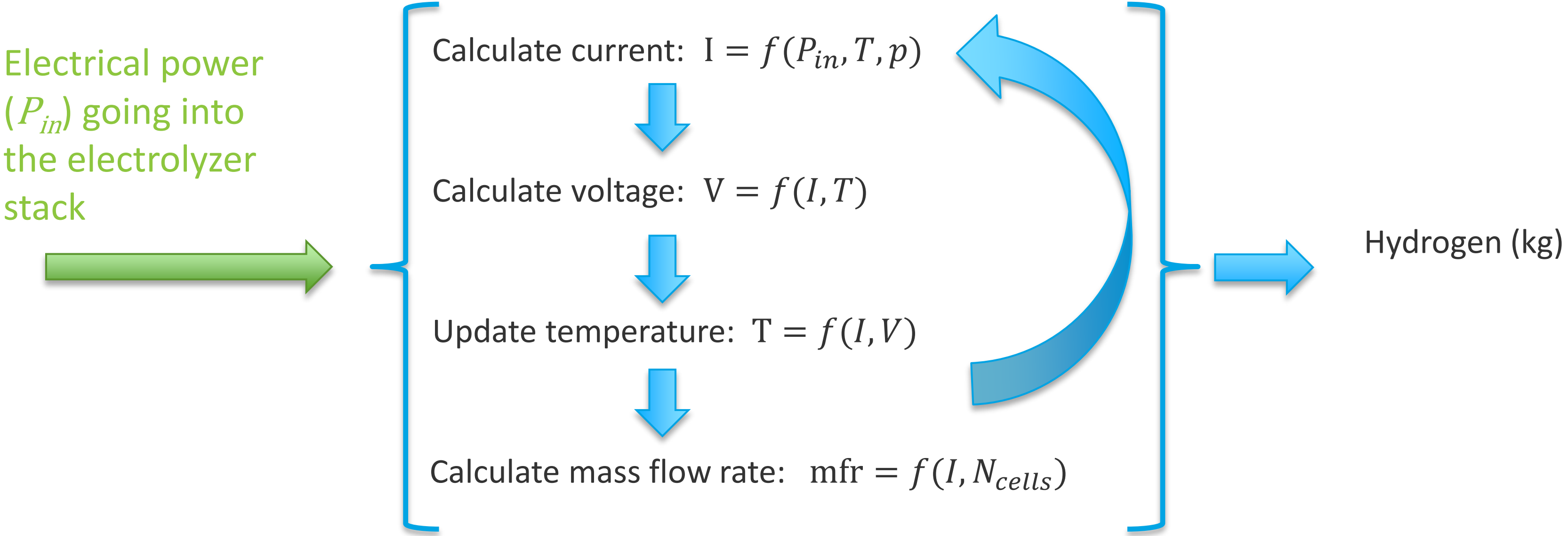
NREL WISDEM Team. 2023. “Wind-Plant Integrated System Design and Engineering Model (WISDEM) [code].” https://github.com/WISDEM/WISDEM. Version f893264.

Electrolyzer Model: Overview



Electrical power (P_{in}) going into the electrolyzer stack

Calculate current: $\mathrm{I} = f(P_{in}, T, p)$

Calculate voltage: $\mathrm{V} = f(I, T)$

Update temperature: $\mathrm{T} = f(I, V)$

Calculate mass flow rate: $\mathrm{mfr} = f(I, N_{cells})$

Hydrogen (kg)

Electrolyzer Sizing

Input desired stack power and current density

$$P_{desired}$$
$$j_{desired}$$

1

Solve for the number of cells by iteratively increasing or decreasing the number of cells

$$P_{desired} \approx P(N_{cells})$$

2

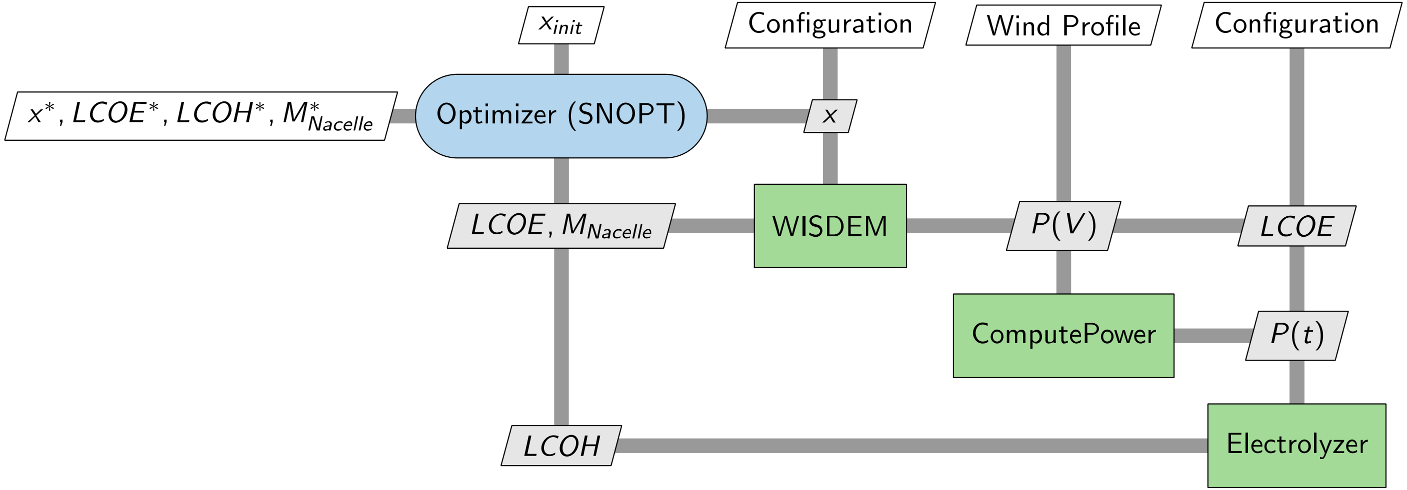
Solve for the max current and cell area using root finding (*fsolve)*

$$P_{desired} - P(I_{max}) \Rightarrow 0$$

$$j_{desired} - \frac{I_{max}}{A_{cell}} \Rightarrow 0$$

Root solve done with SciPy's *fsolve* function that wraps MINPACK's hybrd and hybrj algorithms

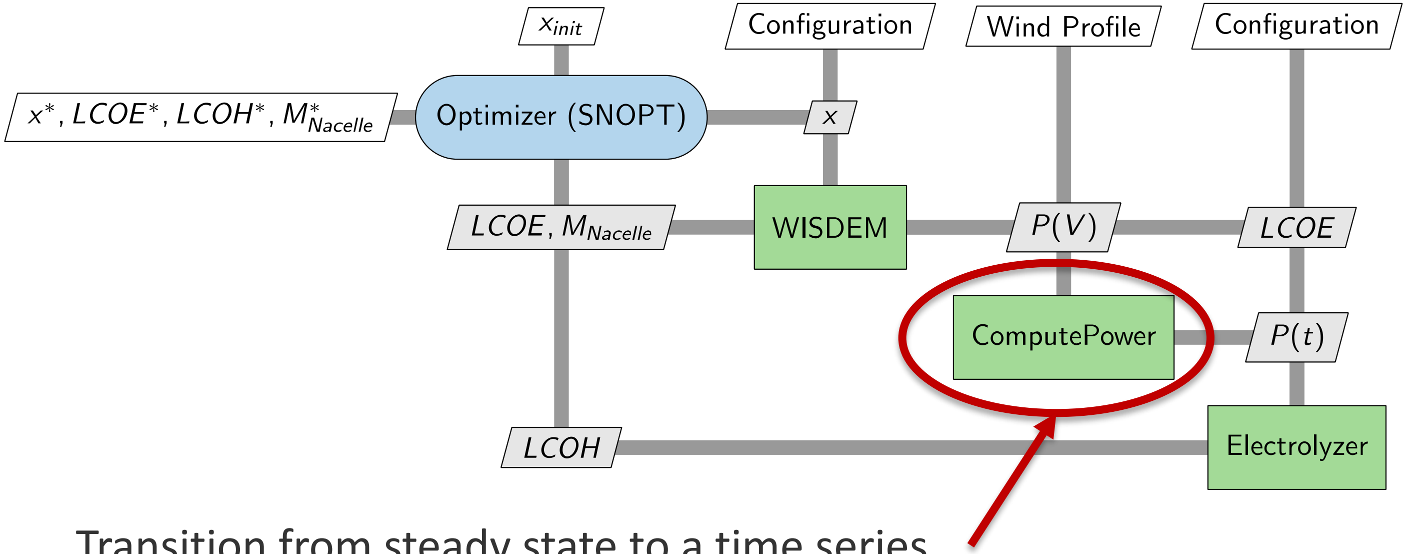
Optimization Configuration



LCOE: levelized cost of energy
LCOH: levelized cost of hydrogen
SNOPT: sparse nonlinear optimizer
x: design variables
x*: optimal design variables
V: wind velocity
P(V): power as a function of wind velocity
t: time
P(t): power as a function of time
M$_{\text{Nacelle}}$: nacelle mass

Simplified extended design structure matrix (XDSM) diagram of the simplified optimization framework

Optimization Configuration



Transition from steady state to a time series.

LCOE: levelized cost of energy
LCOH: levelized cost of hydrogen
SNOPT: sparse non-linear optimizer
x: design variables
x^*: optimal design variables
V: wind velocity
P(V): power as a function of wind velocity
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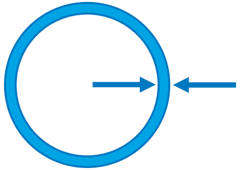
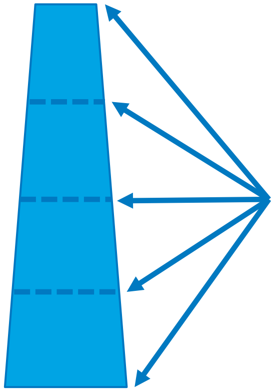
Simplified extended design structure matrix (XDSM) diagram of the simplified optimization framework

Preprocessing: Redesign IEA Baseline Tower for U.S. Transport

Design Variables



Thickness (11 locations)



Diameter (11 locations)

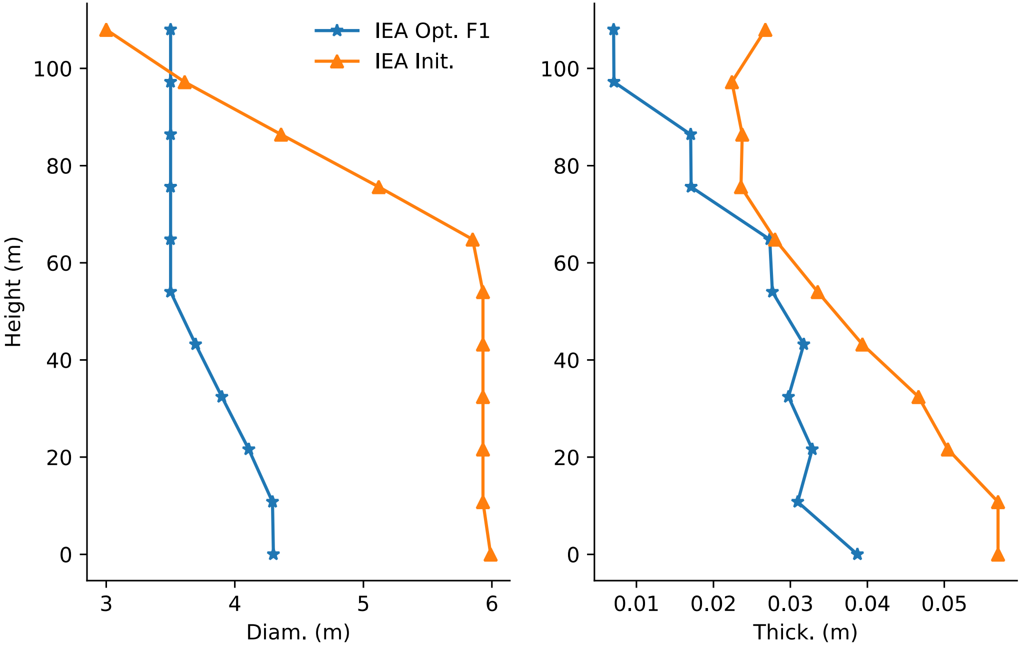
Constraints

Tower

- Stress
- Global buckling
- Shell buckling
- Slope
- First natural frequency

Preprocessing: Redesign IEA Baseline Tower for U.S. Transport

Maximum diameter for U.S. transport is 4.3 m



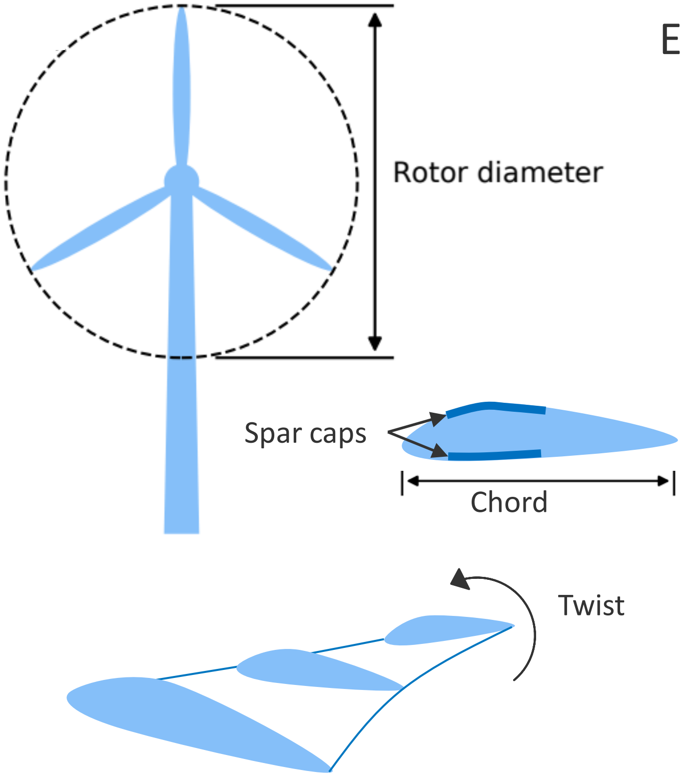
IEA 3.37-MW wind turbine tower design and redesigned tower diameter and thickness

m = meters

Two-Part Optimization Process

Subsystem(s) (Objective(s))	Design Variables
Tower + Blades (LCOE, LCOH)	Swept: rotor diameter (100 m to 200 m), electrolyzer rating Tower: Section thickness Blade: Chord, twist, spar cap
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

Rotor/Tower Optimization Specification



Electrolyzer

Design Variables	Constraints
Electrical rating (swept)	Max chord

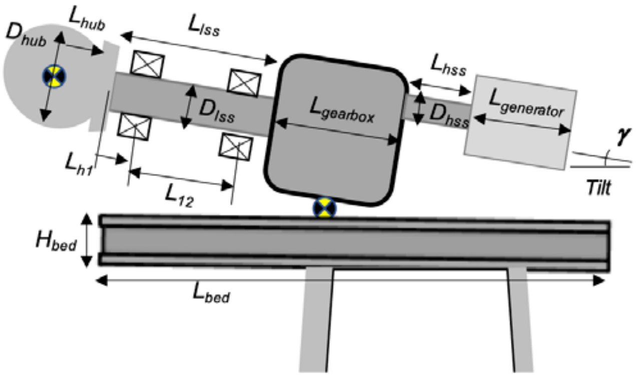
Rotor

Design Variables	Constraints
Rotor diameter (swept) Twist (8 locations) Chord (8 locations) Spar cap thickness (8 locations)	Stall Max chord Root circle diameter Spar cap strains Tip deflection

Tower

Design Variables	Constraints
Layer thickness (11 locations)	Stress Global buckling Shell buckling Frequency

Drivetrain Optimization

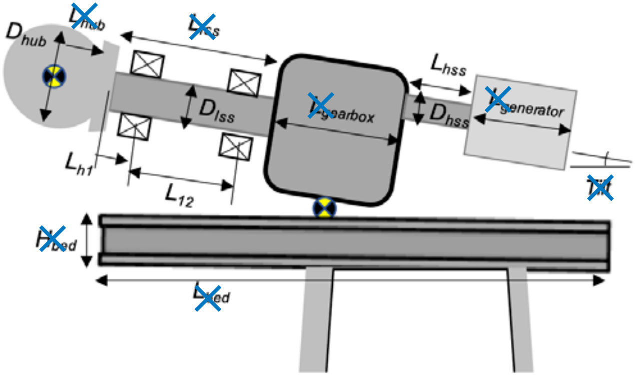


Geared drivetrain diagram for WISDEM

Design Variables	Constraints
***Shaft length from main bearing 1 to 2**	Low-speed shaft stress
Shaft length from hub flange to main bearing	High-speed shaft stress
High-speed shaft length	Bedplate stress
Hub diameter	Main bearing 1 deflection
Low-speed shaft diameter	Main bearing 2 deflection
Low-speed shaft wall thickness	Hub diameter
High-speed shaft diameter	Drivetrain length (tower top to hub overhang)
High-speed shaft wall thickness	Drivetrain height (tower top to hub height)
Bedplate web thickness	Shaft deflection
Bedplate flange thickness	Shaft angle
Bedplate flange width	Stator angle
	Low-speed shaft length

*Bold variables are also shown in the figure

Drivetrain Optimization



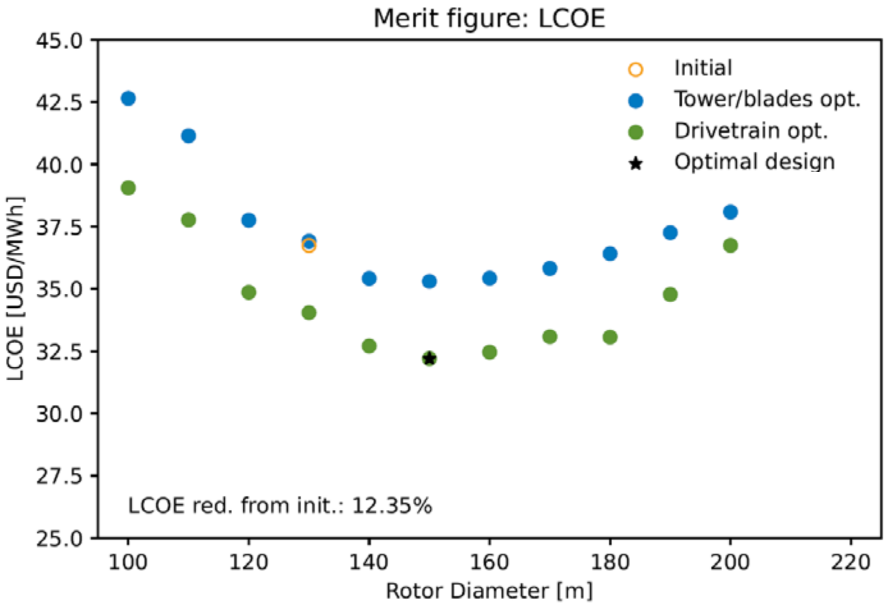
Geared drivetrain diagram for WISDEM

Design Variables	Constraints
***Shaft length from main bearing 1 to 2**	Low-speed shaft stress
Shaft length from hub flange to main bearing	High-speed shaft stress
High-speed shaft length	Bedplate stress
Hub diameter	Main bearing 1 deflection
Low-speed shaft diameter	Main bearing 2 deflection
Low-speed shaft wall thickness	Hub diameter
High-speed shaft diameter	Drivetrain length (tower top to hub overhang)
High-speed shaft wall thickness	Drivetrain height (tower top to hub height)
Bedplate web thickness	Shaft deflection
Bedplate flange thickness	Shaft angle
Bedplate flange width	Stator angle
	Low-speed shaft length

*Bold variables are also shown in the figure

The Rotor Diameter for the LCOE Design Is 15.4% (20 m) Larger Than for the initial Design

IEA-F1 3.37 MW Turbine
Ground clearance: 45.0 m
Blade root diameter approach: variable.



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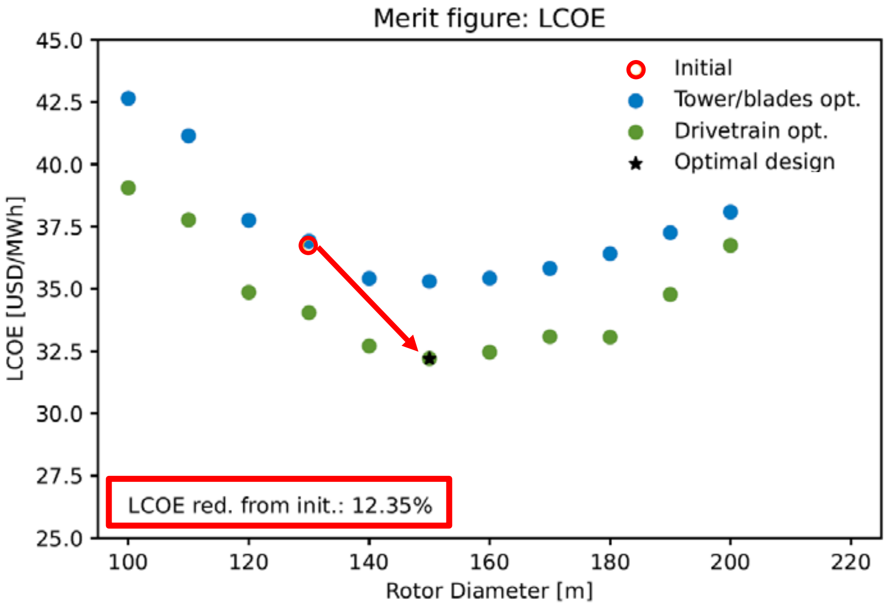
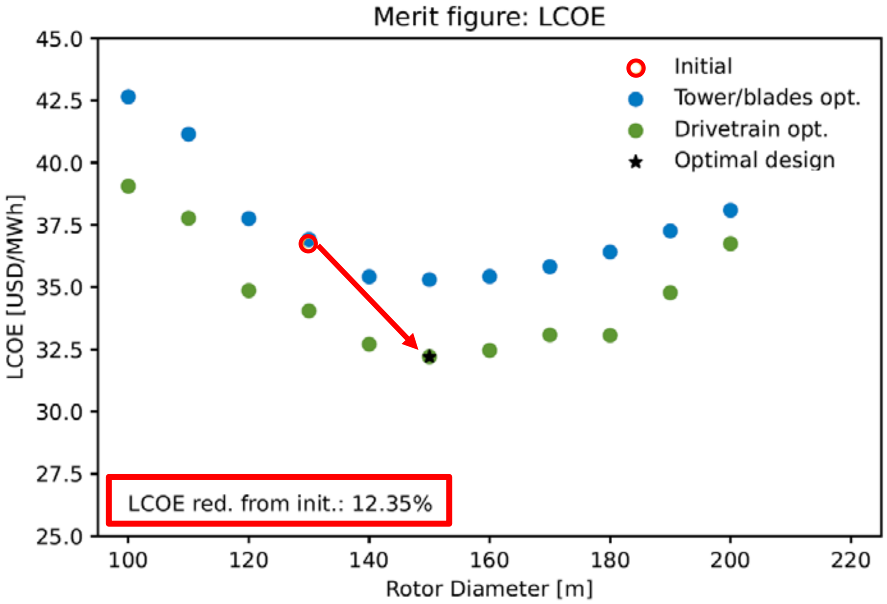
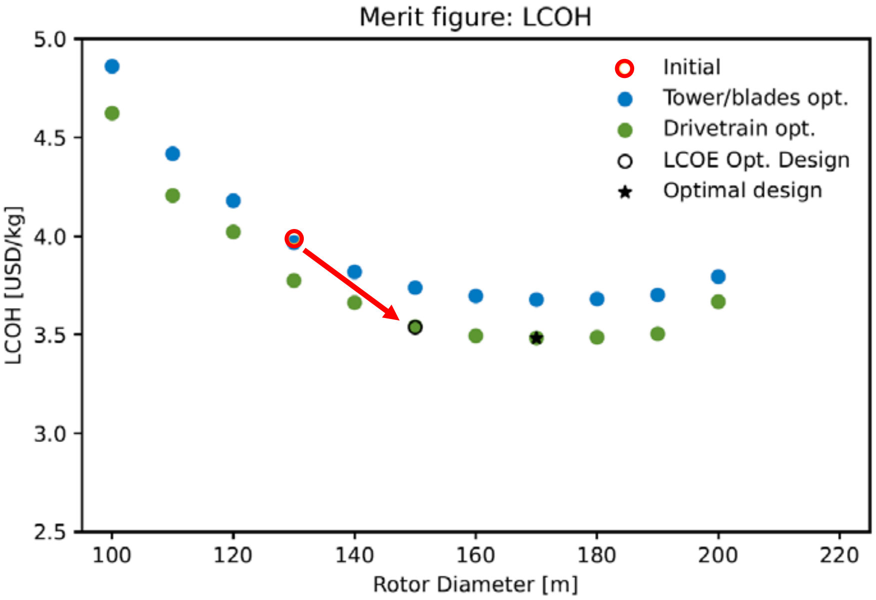


The LCOE Design Reduces LCOE and LCOH Compared With the Initial Design

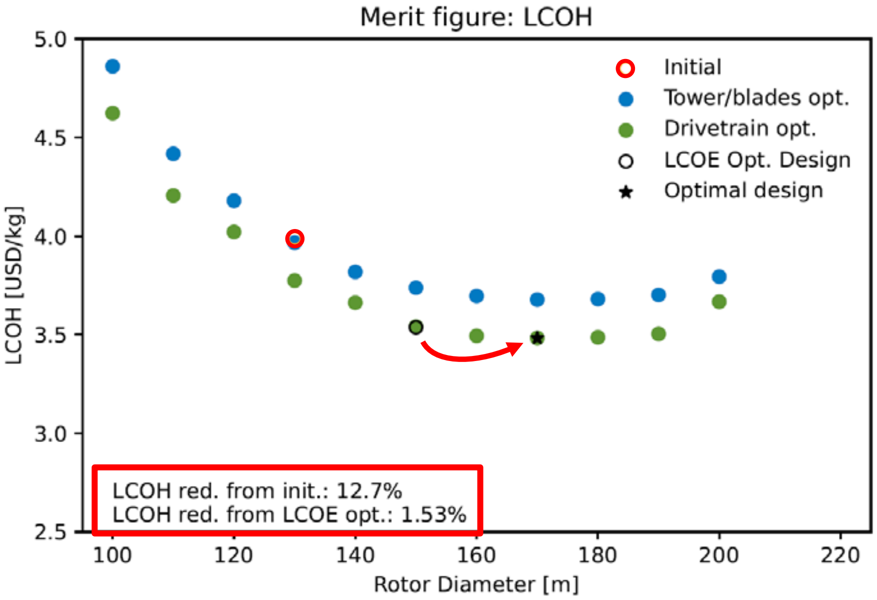
IEA-F1 3.37 MW Turbine
Ground clearance: 45.0 m
Blade root diameter approach: variable.





The Rotor Diameter for the LCOH Design Is 13.3% (20 m) Larger Than for the LCOE Design

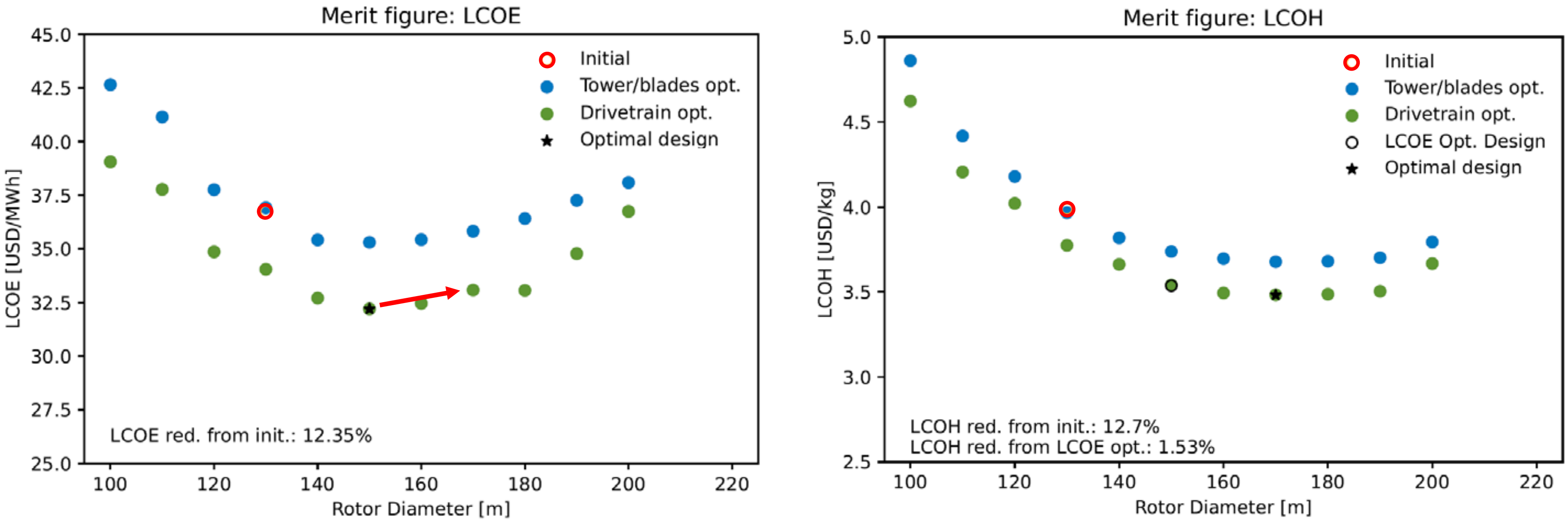
IEA-F1 3.37 MW Turbine
Ground clearance: 45.0 m
Blade root diameter approach: variable.



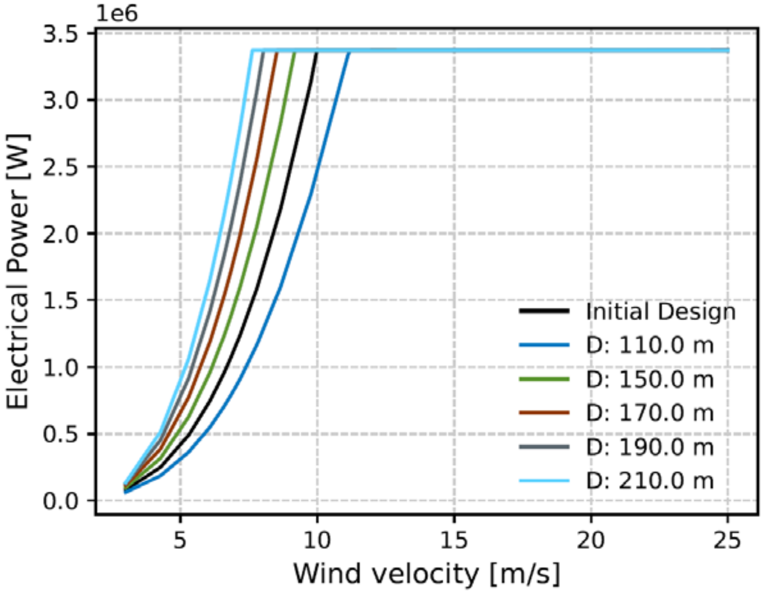
LCOH red. from init.: 12.7%
LCOH red. from LCOE opt.: 1.53%

LCOE for the LCOH Design Is Higher Than for the LCOE Design

IEA-F1 3.37 MW Turbine
Ground clearance: 45.0 m
Blade root diameter approach: variable.

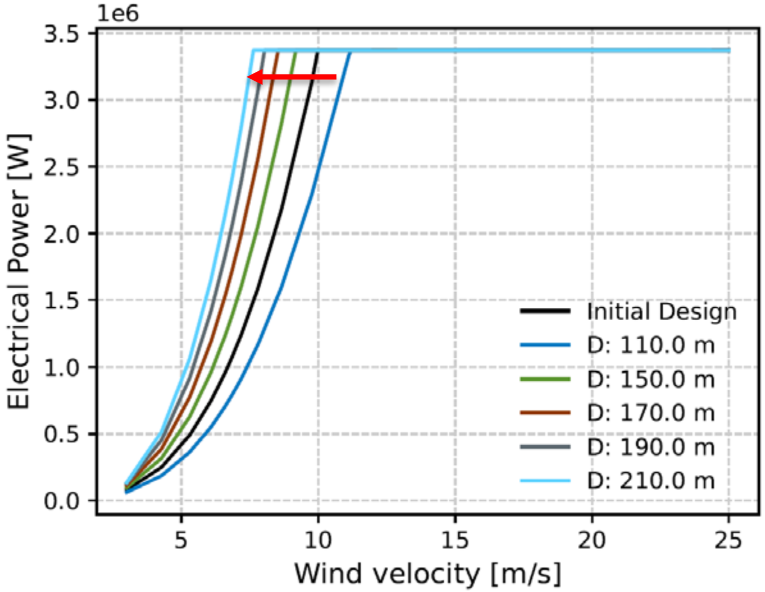


Larger Rotor Diameter Leads to Lower Rated Wind Speed



As rotor diameter increases, rated power is reached at lower wind speeds, which results in a less variable power output to the electrolyzer.

Rated Speed for LCOH Turbine Is Lower Than for LCOE



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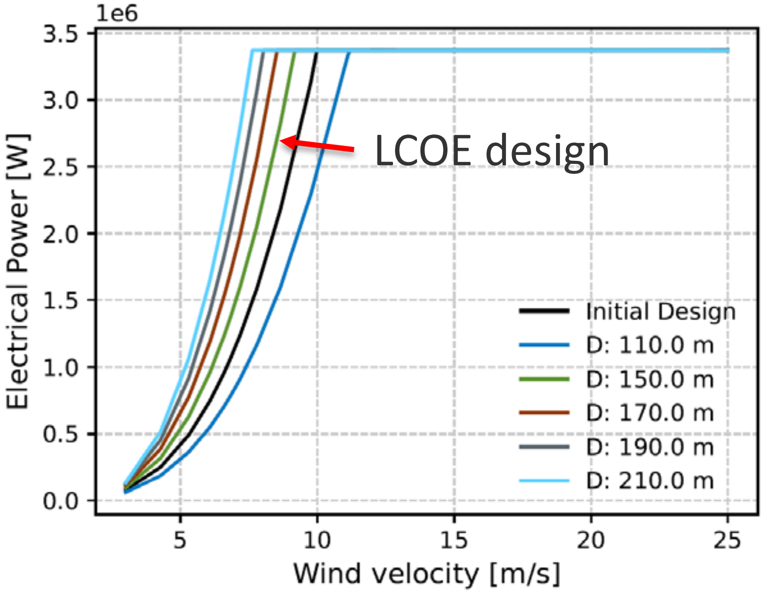
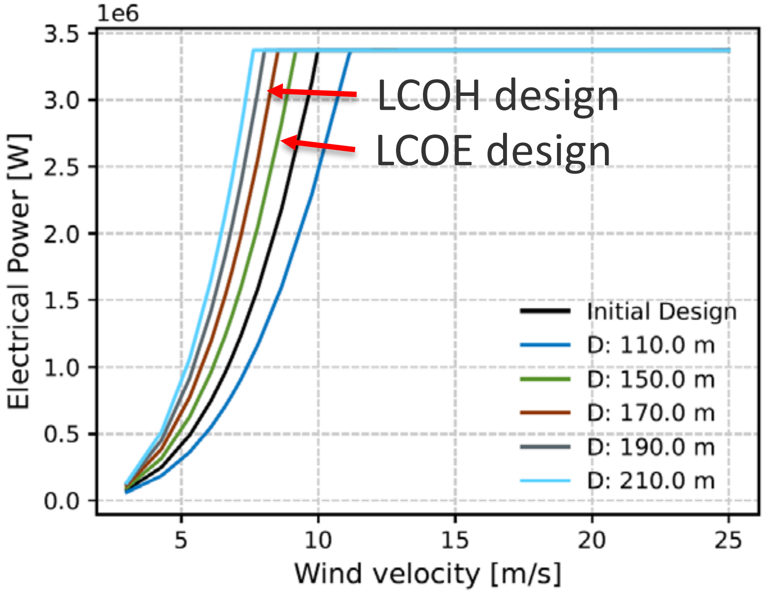


LCOE design

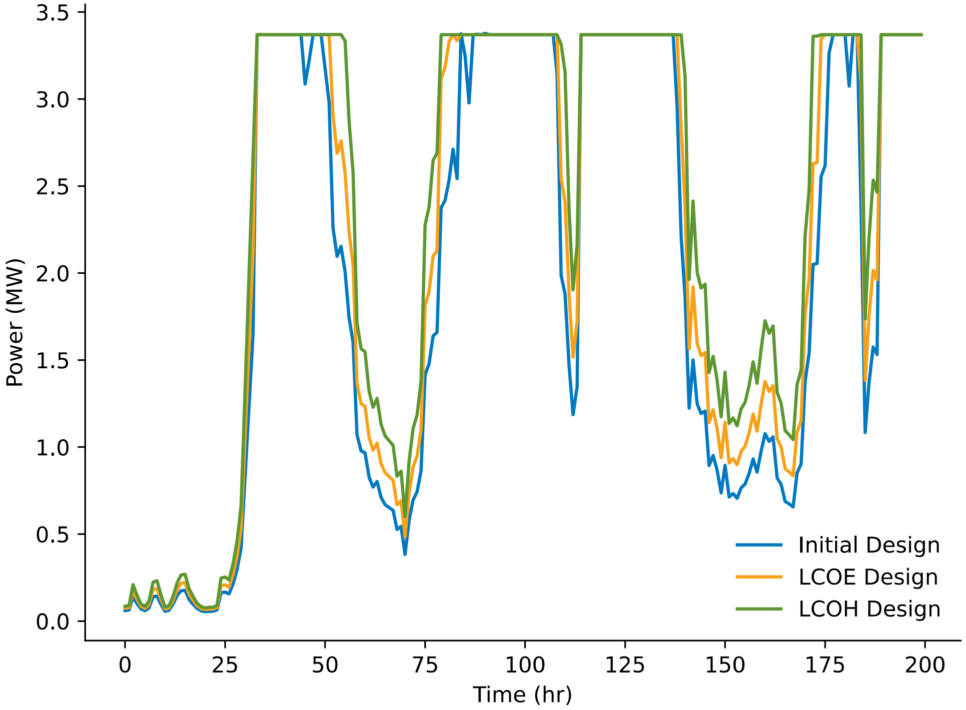
As rotor diameter increases, rated power is reached at lower wind speeds, which results in a less variable power output to the electrolyzer.

Rated Speed for LCOH Turbine Is Lower Than for LCOE



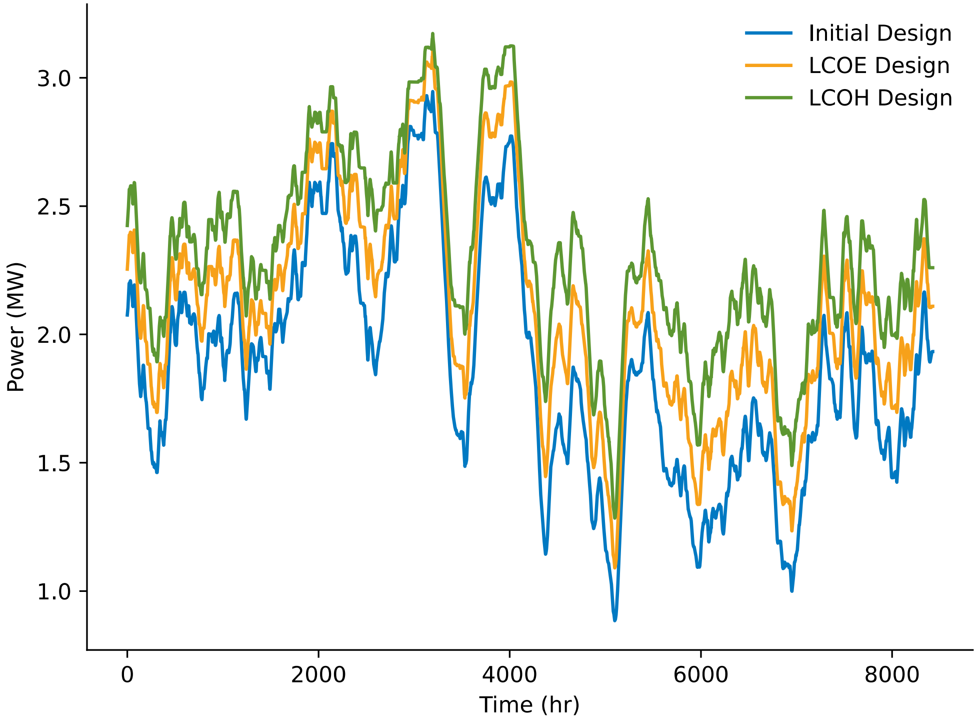
As rotor diameter increases, rated power is reached at lower wind speeds, which results in a less variable power output to the electrolyzer.

LCOH Design Gets to Rated Power Earlier and Stays at Rated Power Longer



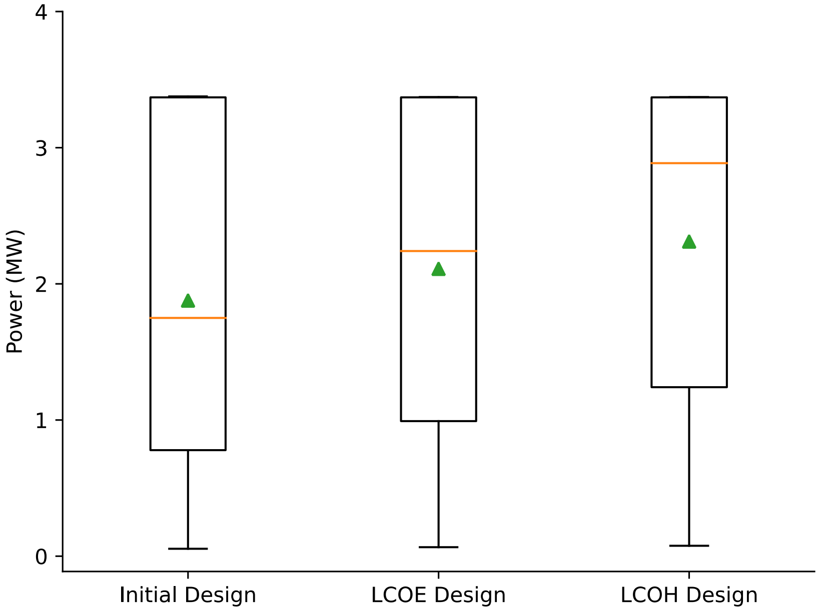
Detail of hourly power from the initial and optimal wind turbines shows that the LCOH design hits rated power earlier and ramps down later than the initial and LCOE designs

Power 2-Week Running Average for 1 Year



This 2-week averaged plot of power for each turbine design shows that the LCOH design produces more electricity

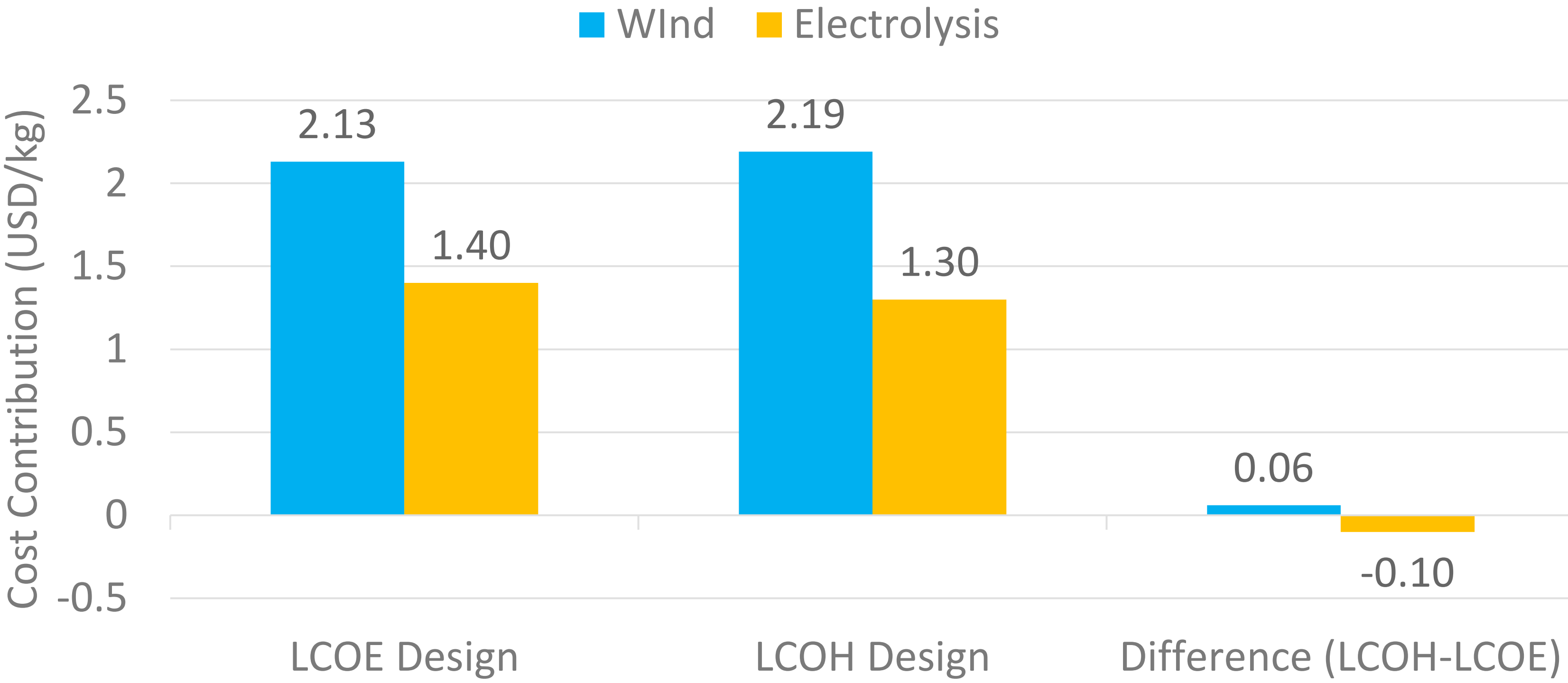
LCOH Design Raises Mean and Median Power



Capacity factor	0.39	0.44	0.48

Wind turbine capacity factors and power distributions for the initial, LCOE, and LCOH optimal designs. Green triangles represent the mean, and colored horizontal lines indicate the median.

The LCOH Design Lowers the LCOH by Using the Electrolyzer More Efficiently, Despite a Higher LCOE

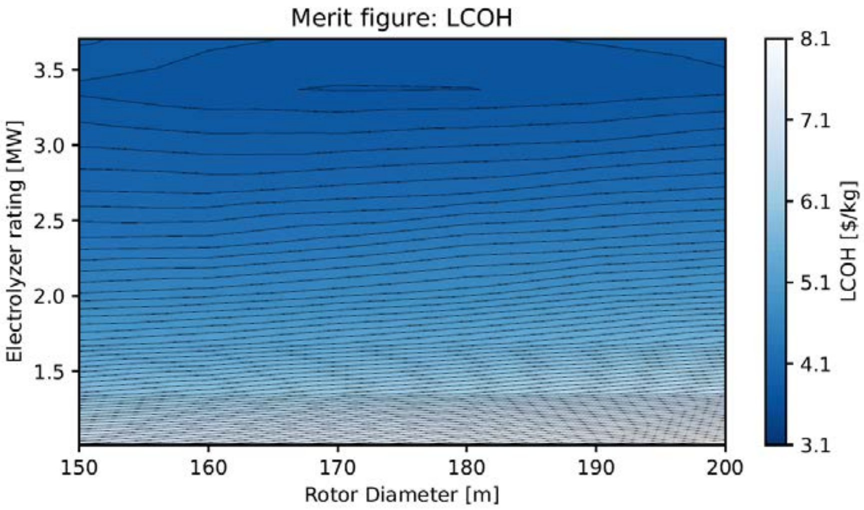


Total:	3.53 USD/kg	3.49 USD/kg	-0.04 USD/kg

Sweeping Rotor Diameter and Electrolyzer Rating While Optimizing Tower Thickness and Blades

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

IEA-F1 3.37 MW Turbine
optimized for LCOH at set rotor diameters.
Ground clearance: 45.0 m
Blade root diameter approach: variable.



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- Electrolyzer rating has a stronger influence than rotor diameter on LCOH.
- There is a range of rotor diameters that achieve near-optimal LCOH values; these simulations indicate that the electrolyzer rating should be close to the turbine rating.

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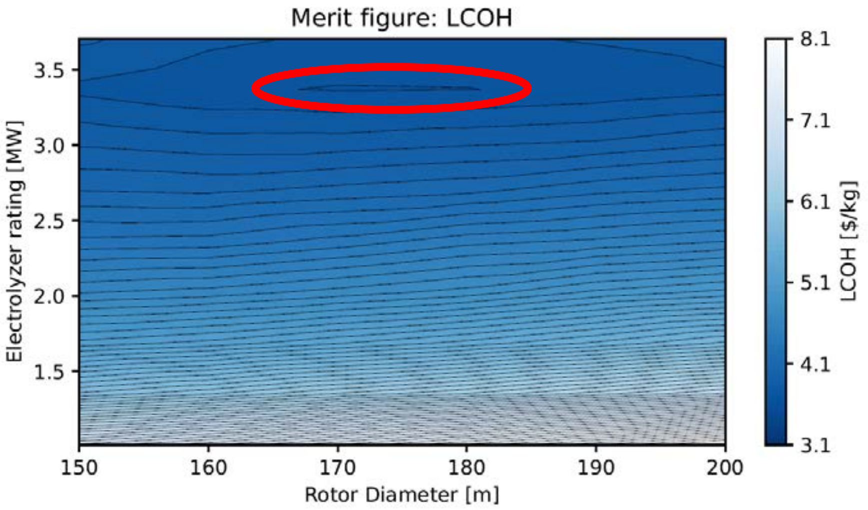
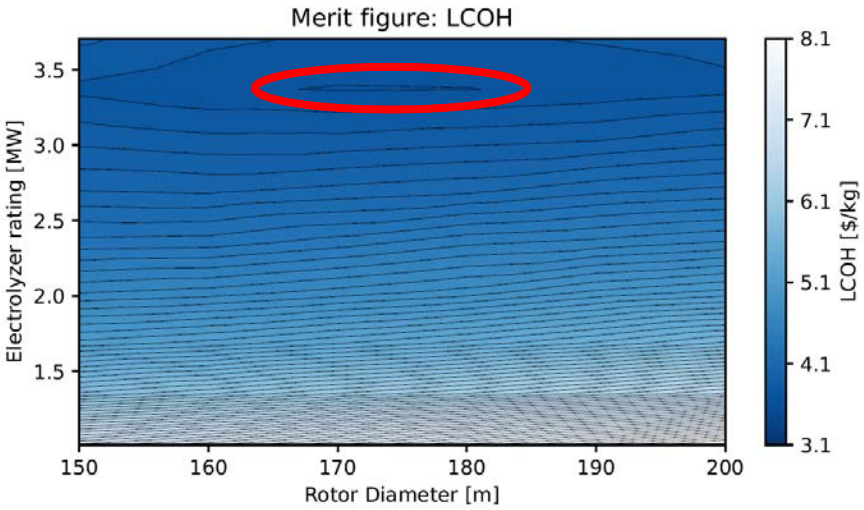


Sweeping Rotor Diameter and Electrolyzer Rating While Optimizing Tower Thickness and Blades

- Electrolyzer rating has a stronger influence than rotor diameter on LCOH.
- There is a range of rotor diameters that achieve near-optimal LCOH values; these simulations indicate 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.

IEA-F1 3.37 MW Turbine
optimized for LCOH at set rotor diameters.
Ground clearance: 45.0 m
Blade root diameter approach: variable.



Conclusions

Wind turbines designed for LCOH may benefit from larger rotor diameters than wind turbines designed for LCOE.

The increased cost associated with increased rotor diameter can be offset by more efficient use of electrolysis equipment through a less variable power profile.

Electrolysis equipment should likely be sized to match the wind turbine rating (for a grid-disconnected system with no storage available).

Future Work

Evaluate and optimize a full hybrid energy park including wind, solar, and battery with the optimized turbine designs.

Examine designs with higher-fidelity tools (e.g., OpenFAST, ROSCO).

Update electrolyzer cost analysis.

Improve electrolyzer sizing approach.

Explore different wind turbine design approaches (e.g., materials, jointed blades).

Thank you

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NREL/PR-5000-92347

This work was completed with input from GE Vernova and Nel

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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Appendix

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Three-Part Optimization Process Using a Modified WISDEM

Tower optimization

$$
\begin{aligned}
\text{minimize} \quad & LCOE(t, d) \\
\text{tower subject to} \quad & 0.004\text{ m} \leq t_k \leq 0.2\text{ m}, \quad k = 1...11 \\
& 3.5\text{ m} \leq d_k \leq 4.3\text{ m}, \quad k = 1...11 \\
& b_{g,i} < 1, i = 1...8 \\
& b_{s,i} < 1, i = 1...8 \\
& C_{\sigma,i} < 1, i = 1...8 \\
& 0.13 \leq \lambda_{1,i} \leq 0.4, i = 1...8,
\end{aligned} \qquad (4)
$$

Rotor/tower optimization

$$
\begin{aligned}
\text{minimize} \quad & Objective(T_i, c_j, t_k, \theta_l) \\
\text{rotor subject to} \quad & 100\text{ m} \leq D_i \leq 200\text{ m} \\
& 0.8c_o \geq c_i \leq 2.0c_o, i = 1...8 \\
& \theta_i \geq \theta_{i,o} - 0.0872\text{ rad}, i = 1...8 \\
& \theta_i \leq \theta_{i,o} + 0.0872\text{ rad}, i = 1...8 \\
& 0.2T_o \geq T_i \leq 2.0T_o, i = 1...8 \\
& L_i \leq 0.0035, i = 1...7 \\
& U_i \leq 0.0035, i = 1...7 \\
& M_{s,i} \leq 0.05233\text{ rad}, i = 1...8 \\
& r_{d,i} \leq 1.1 \\
& d_r/c_r \leq 1.0 \\
\text{tower subject to} \quad & 0.004 \leq t \leq 0.2 \\
& C_{\sigma,i} < 1, i = 1...8 \\
& b_{g,i} < 1, i = 1...8 \\
& b_{s,i} < 1, i = 1...8 \\
& f/3P < 0.9 \vee f/3P > 1.1
\end{aligned} \qquad (5)
$$

Drivetrain optimization

$$
\begin{aligned}
\text{minimize} \quad & M_{nacelle}(L_{12}, L_{h1}, L_{hss}, d_h, d_{lss}, t_{lss}, d_{hss}, t_{hss}, \\
& t_{web}, t_{flange}, w_{flange}) \\
\text{subject to} \quad & 0.1\text{ m} \leq L_{12} \leq 1.0\text{ m} \\
& 0.1\text{ m} \leq L_{h1} \leq 2.0\text{ m} \\
& 0.1\text{ m} \leq L_{hss} \leq 1.5\text{ m} \\
& 2.0\text{ m} \leq d_h \leq 5.0\text{ m} \\
& 0.3\text{ m} \leq d_{lss} \leq 1.5\text{ m} \\
& 4 \times 10^-3\text{ m} \leq t_{lss} \leq 0.29\text{ m} \\
& 0.2\text{ m} \leq d_{hss} \leq 1.0\text{ m} \\
& 0.004\text{ m} \leq t_{hss} \leq 0.15\text{ m} \\
& 0.004\text{ m} \leq t_{web} \leq 0.5\text{ m} \\
& 0.004\text{ m} \leq t_{flange} \leq 0.5\text{ m} \\
& 0.1\text{ m} \leq w_{flange} \leq 1.0\text{ m} \\
& \sigma_{v,lss} \leq 1.0, \quad \sigma_{v,hss} \leq 1.0, \quad \sigma_{v,bp} \leq 1.0 \\
& \delta\theta_{b1} \leq 0.008\text{ rad}, \quad \delta\theta_{b2} \leq 0.008\text{ rad} \\
& d_h \geq 0.0\text{ m}, \quad M_l \geq 0.0, \quad M_h \geq 0.0 \\
& y_{sh} \leq 10^{-4}\text{ m}, \quad \theta_{sh} \leq 0.001\text{ rad} \\
& \theta_{st} \leq 0.001\text{ rad}, \quad L_{lss} \geq 0.1\text{ m}
\end{aligned} \qquad (6)
$$

Coupled Simulations and Code

- Developed electrolyzer model, made available as open-source on GitHub (https://github.com/NREL/electrolyzer)
  - Hysteretic switching on and off
  - Degradation-based switching order
  - Variable power distribution
  - Informed by NREL experimental data and by Nel input
- Coupled electrolyzer model to single turbine simulations (turbine simulated using WEIS, https://github.com/WISDEM/WEIS)

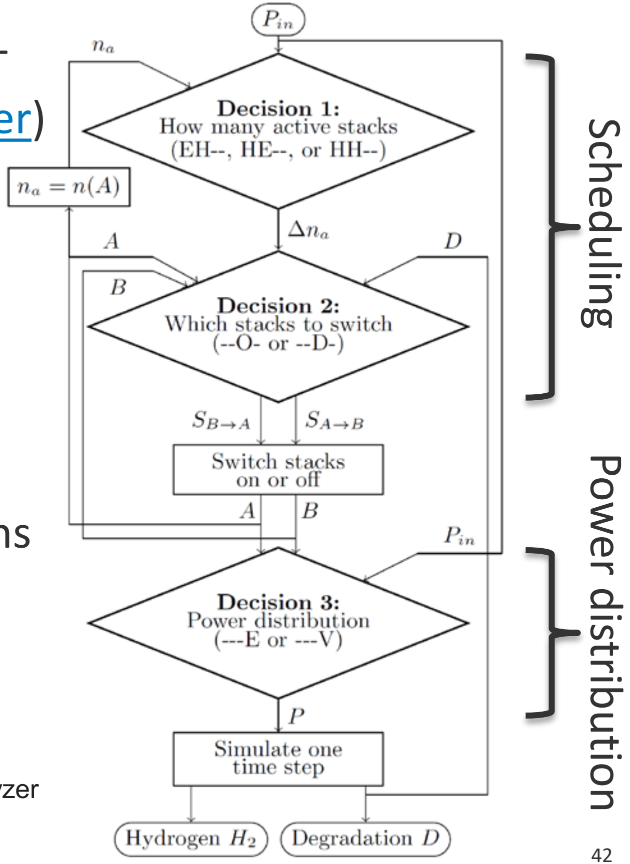
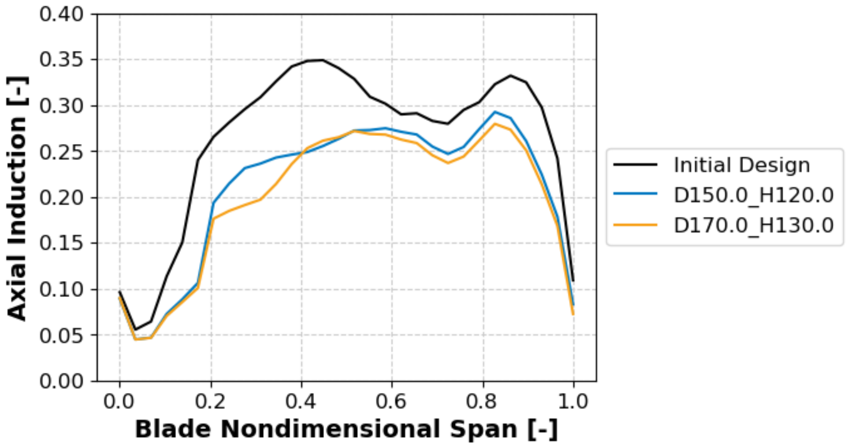


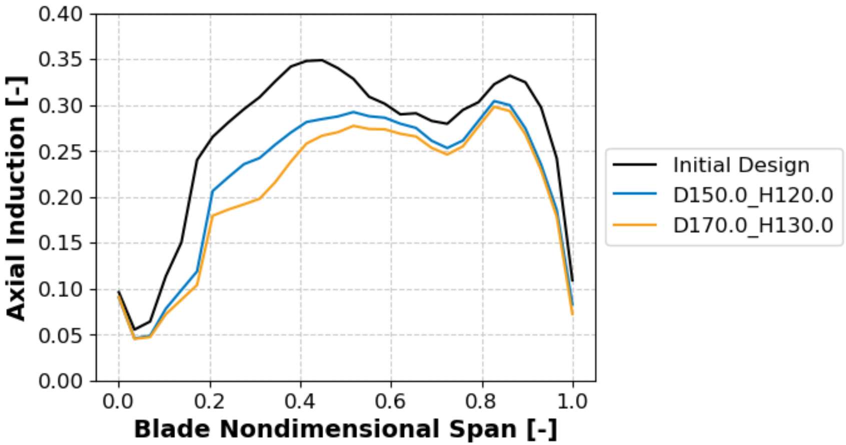
Figure taken from: Tully, Zachary, et al. "An Investigation of Heuristic Control Strategies for Multi-Electrolyzer Wind-Hydrogen Systems Considering Degradation." *2023 IEEE Conference on Control Technology and Applications (CCTA)*. IEEE, 2023.

Induction

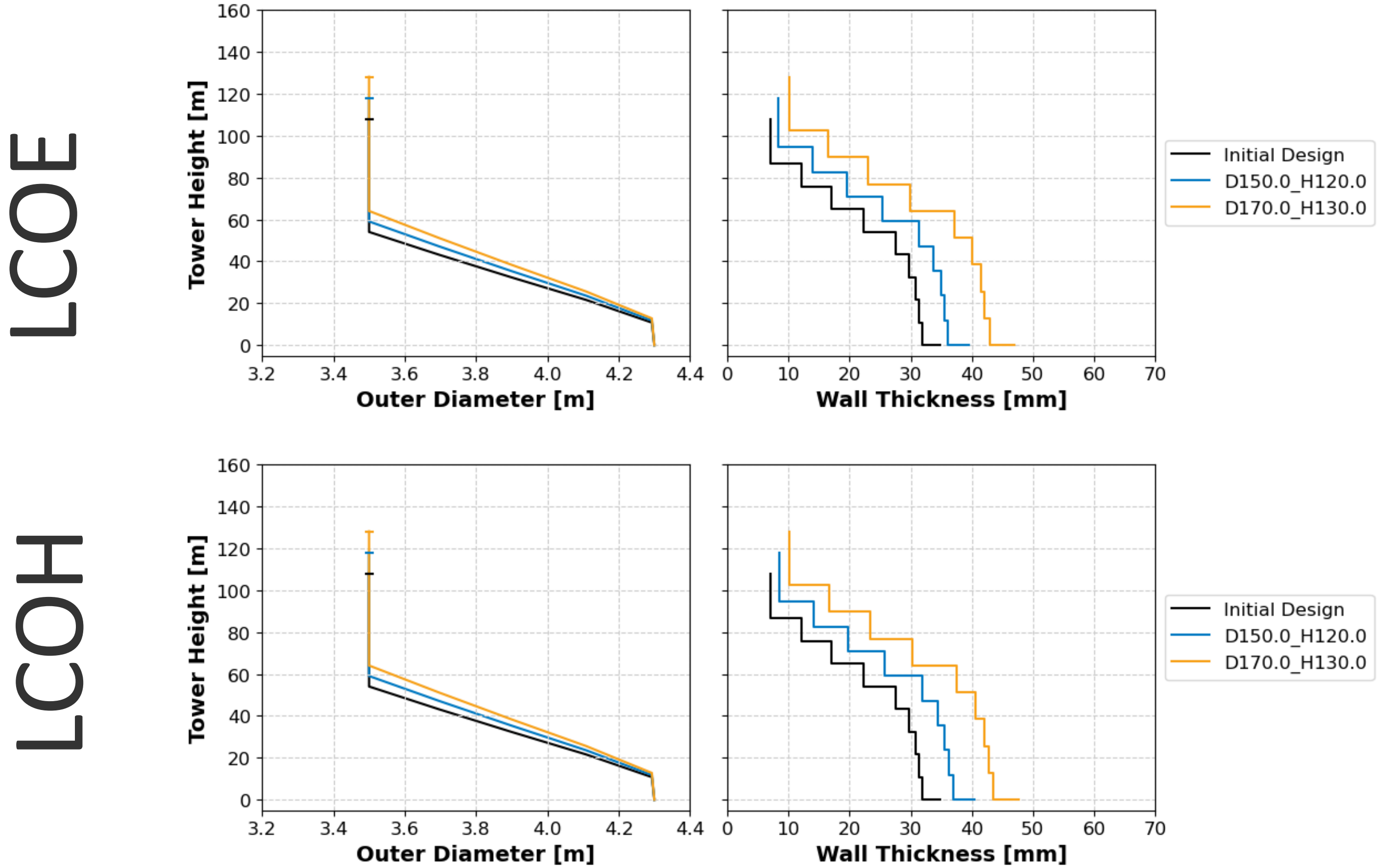
LCOE



LCOH



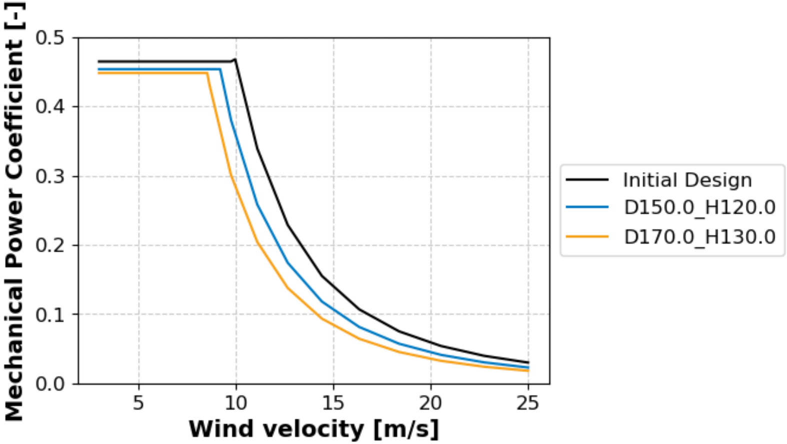
Axial induction for both the LCOE and LCOH designs follow a similar shape to the initial design.



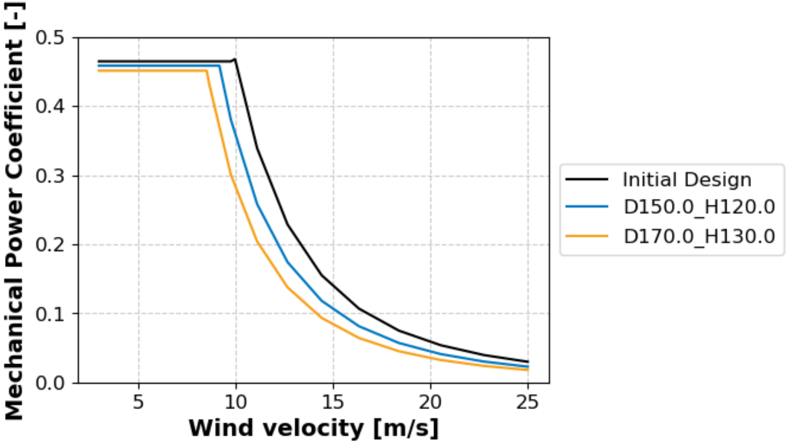
The tower designs for the LCOE and LCOH designs are nearly identical at a given rotor diameter. However, as expected, the larger rotor diameter requires a thicker tower with locally larger diameters.

CP Aero

LCOE

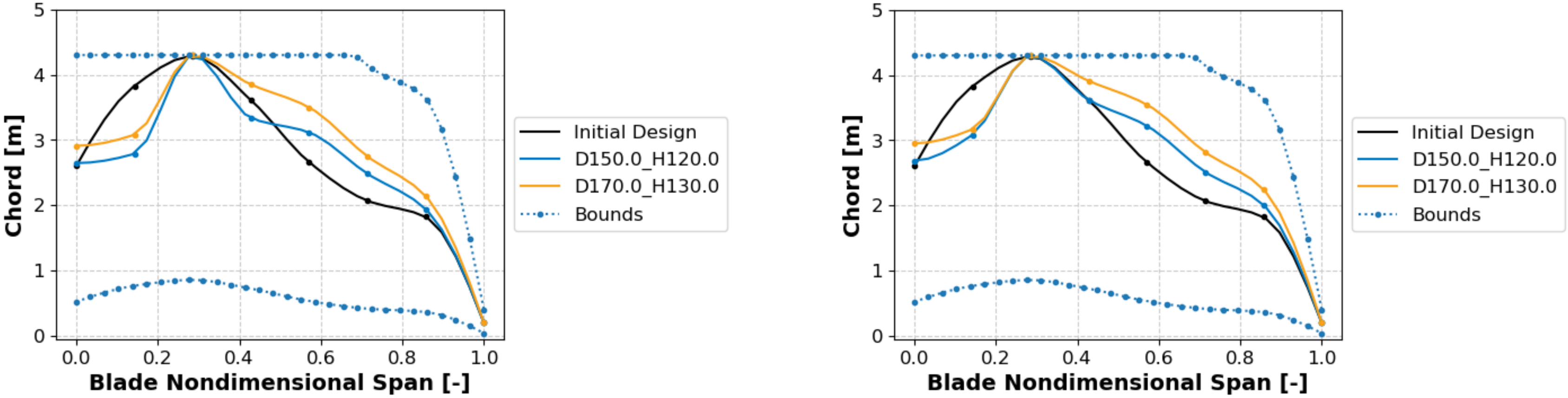


LCOH



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

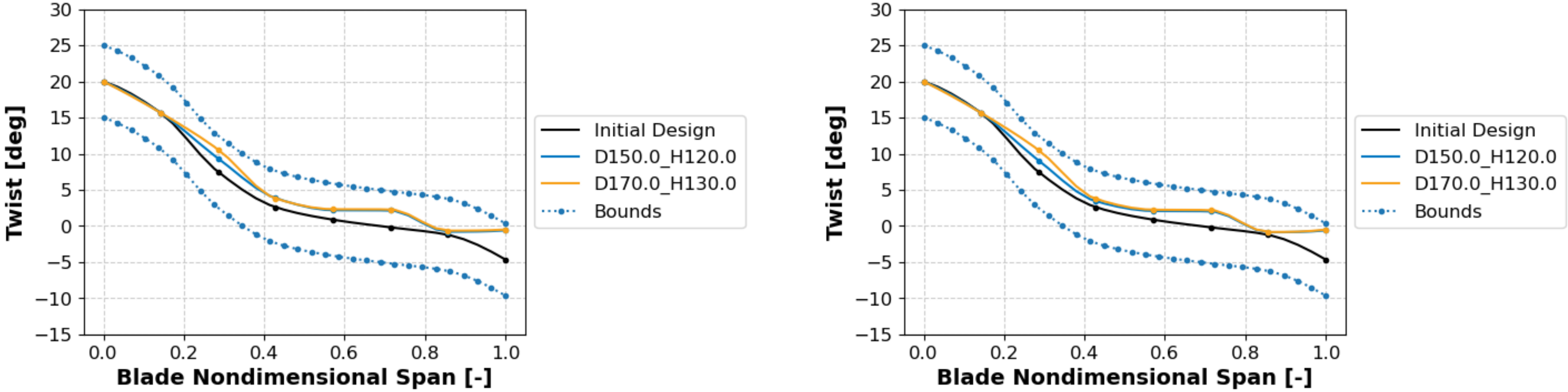
Chord


LCOE

LCOH

Chord along the blade for LCOE, LCOH, and initial designs.

Twist



LCOE

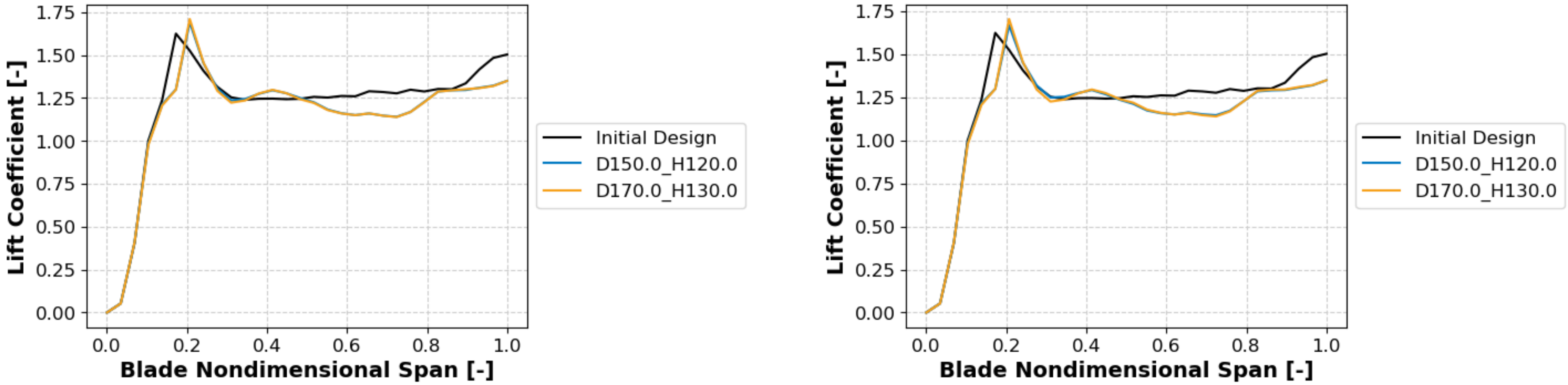
LCOH

Twist along the blade for LCOE, LCOH, and initial designs.

Lift

LCOE

LCOH

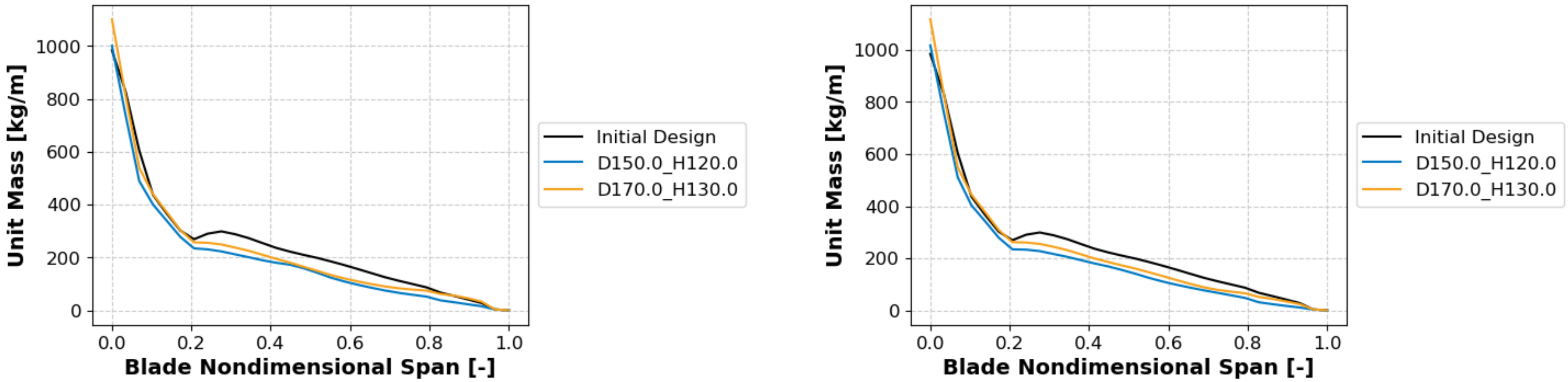


Lift coefficient along the blade for LCOE, LCOH, and initial designs.

Mass

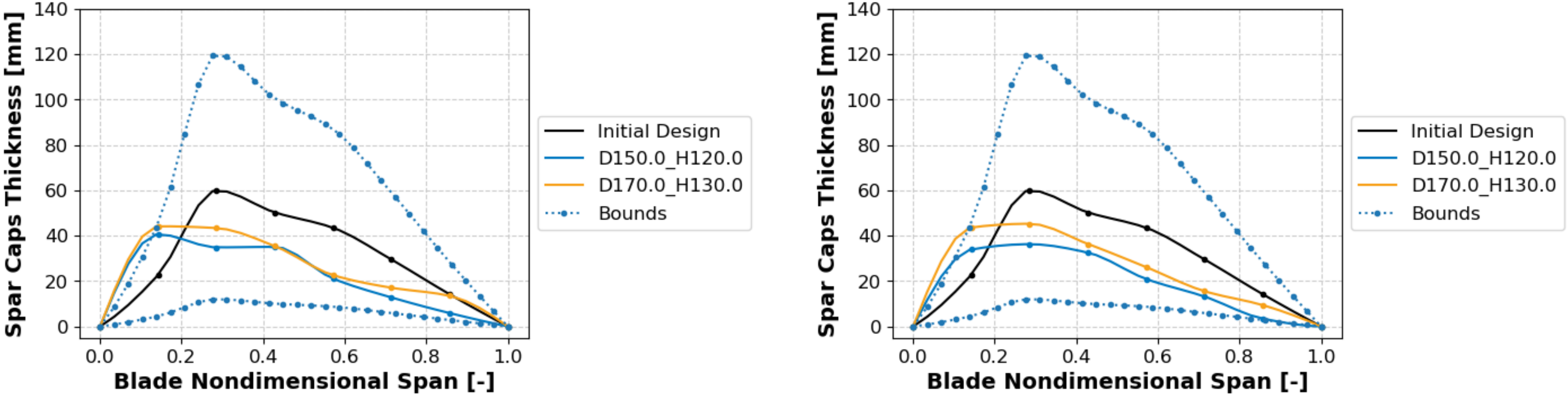
LCOE

LCOH



Unit mass along the blade for LCOE, LCOH, and initial designs.

Spar Cap Thickness


LCOE

LCOH

Unit mass along the blade for LCOE, LCOH, and initial designs.