Wind Turbine Design Optimization for Hydrogen Production

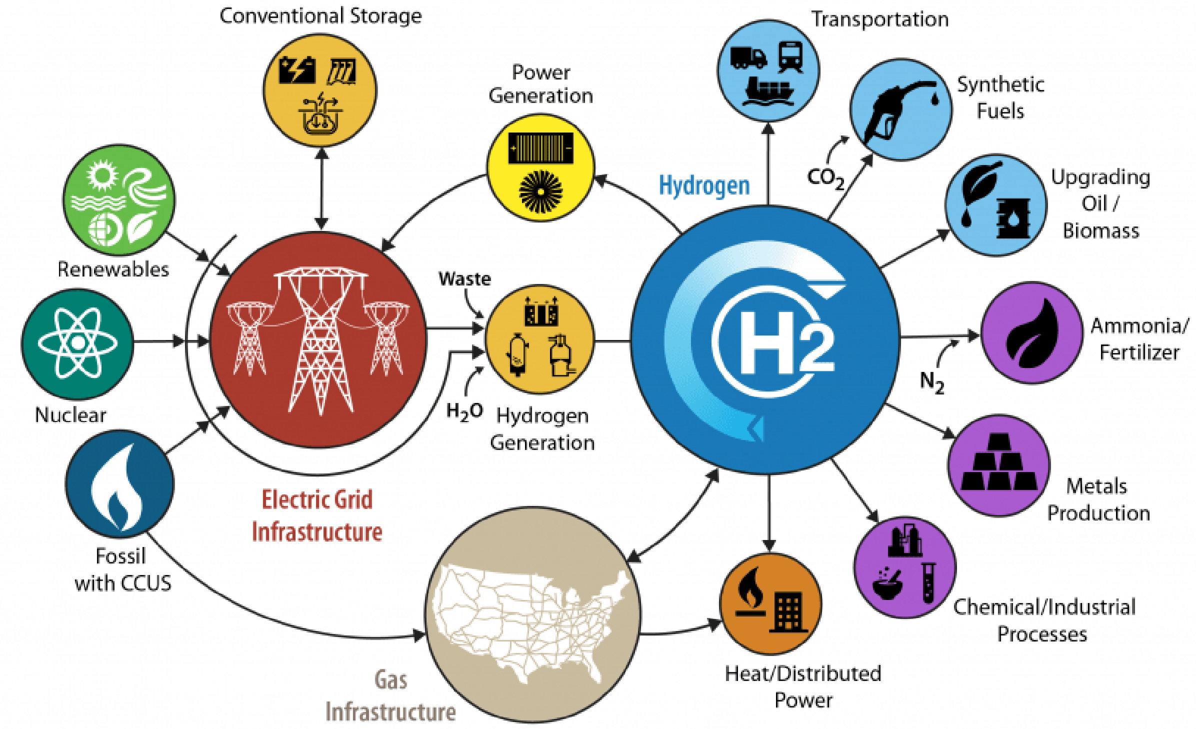
Jared Thomas, Cameron Irmas, Genevieve Starke, Elenya Grant, Nicholas Riccobono, Zach Tully, Pietro Bortolotti, Garrett Barter, Chris Bay

National Renewable Energy Laboratory (NREL)

Photo by Dennis Schroeder, NREL 55200

Outline

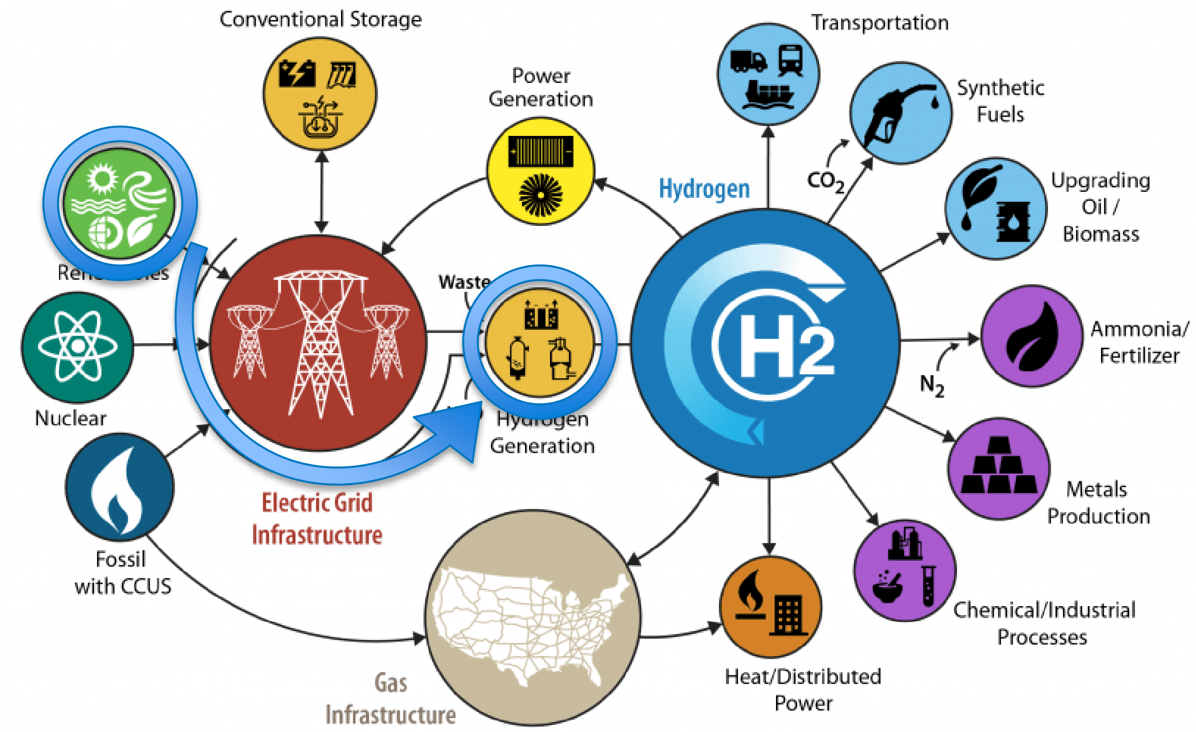
Background



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

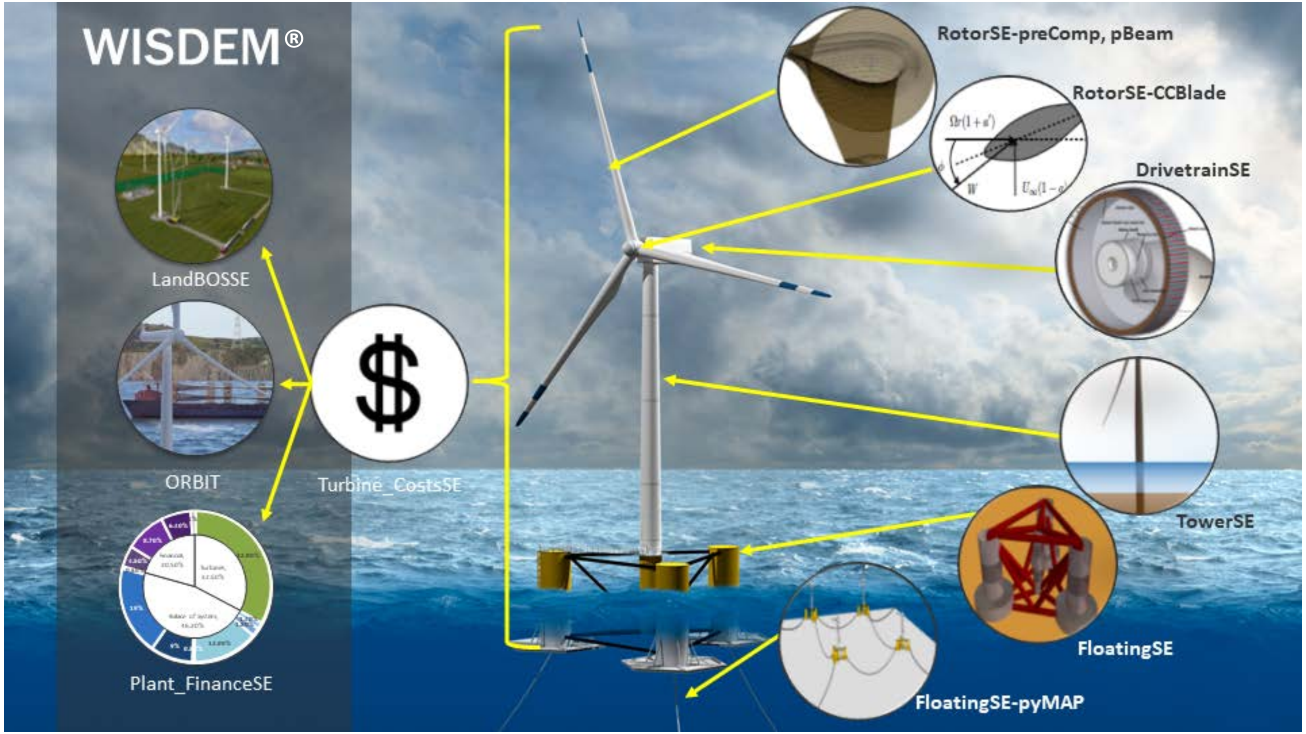
Background



In this project we are focused primarily 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

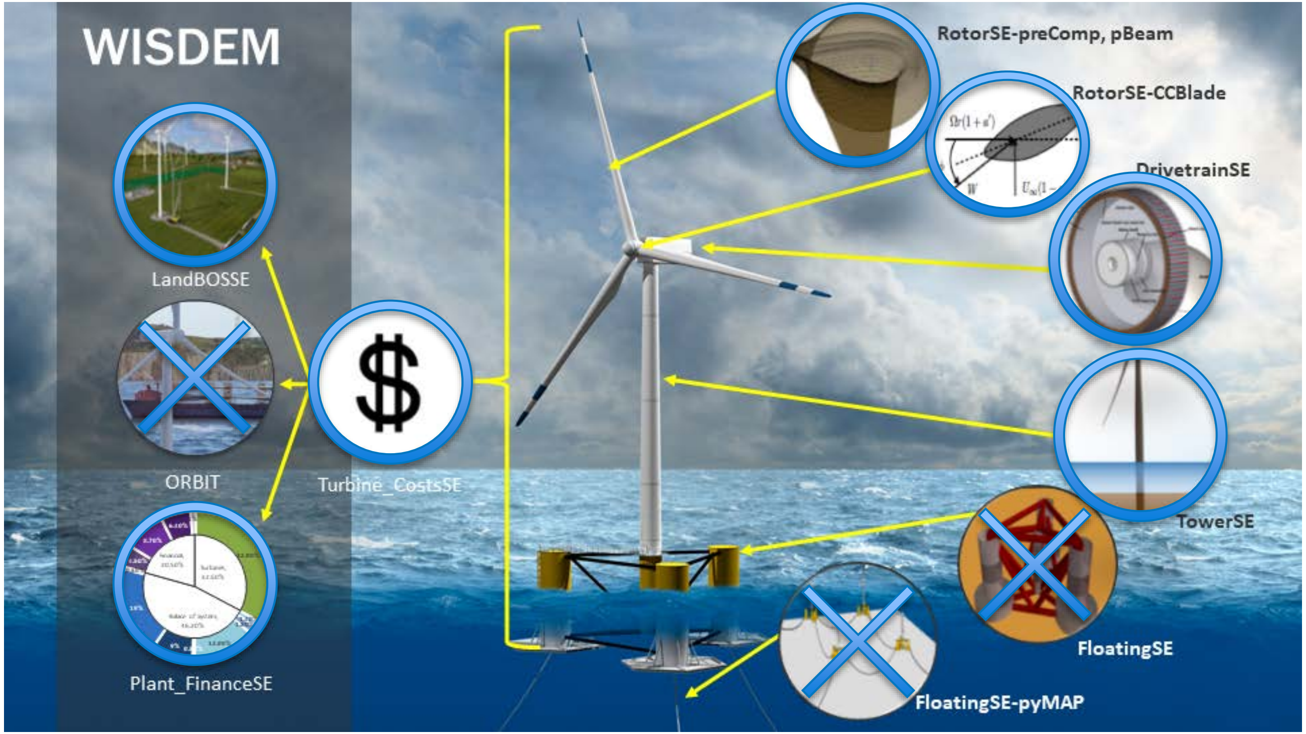
Wind turbine modeling



Overview of the WISDEM framework [5]

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

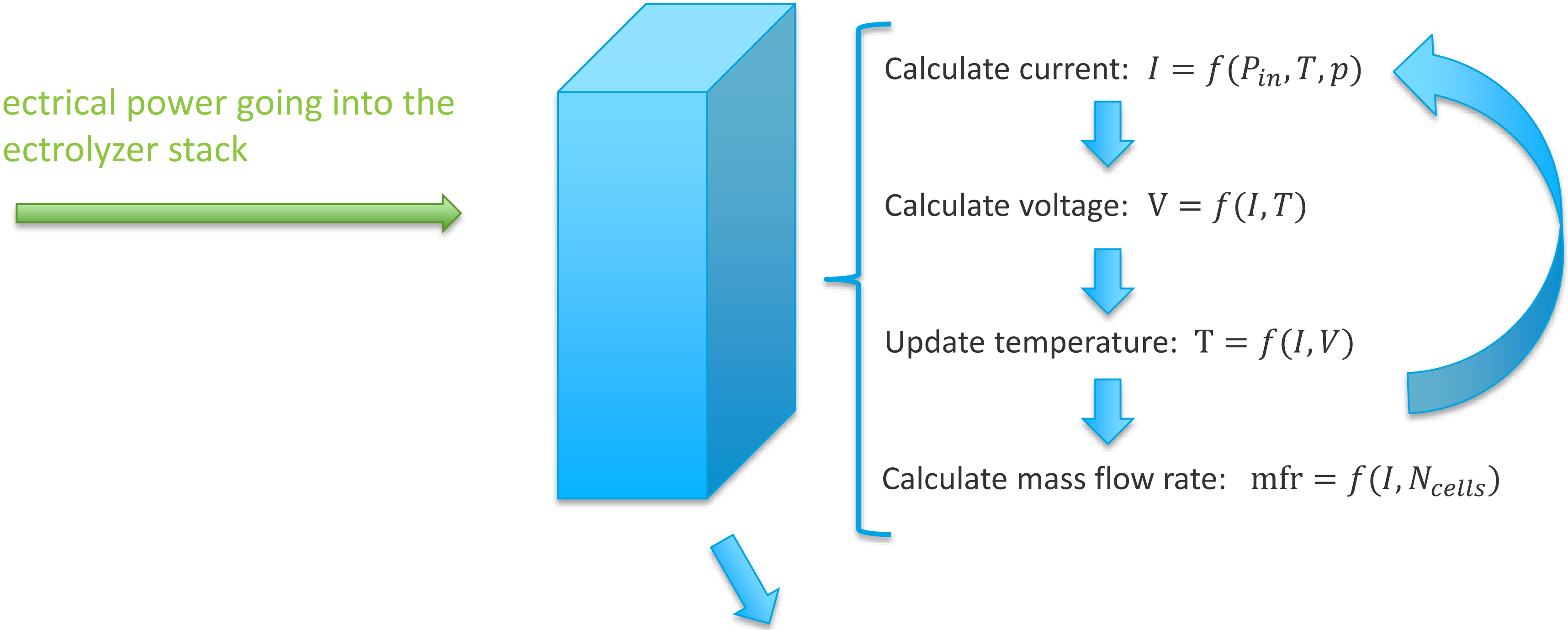
Wind turbine modeling – only onshore modules



Overview of the WISDEM framework [5]

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

Electrolyzer Model: Overview



Electrical power going into the electrolyzer stack

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

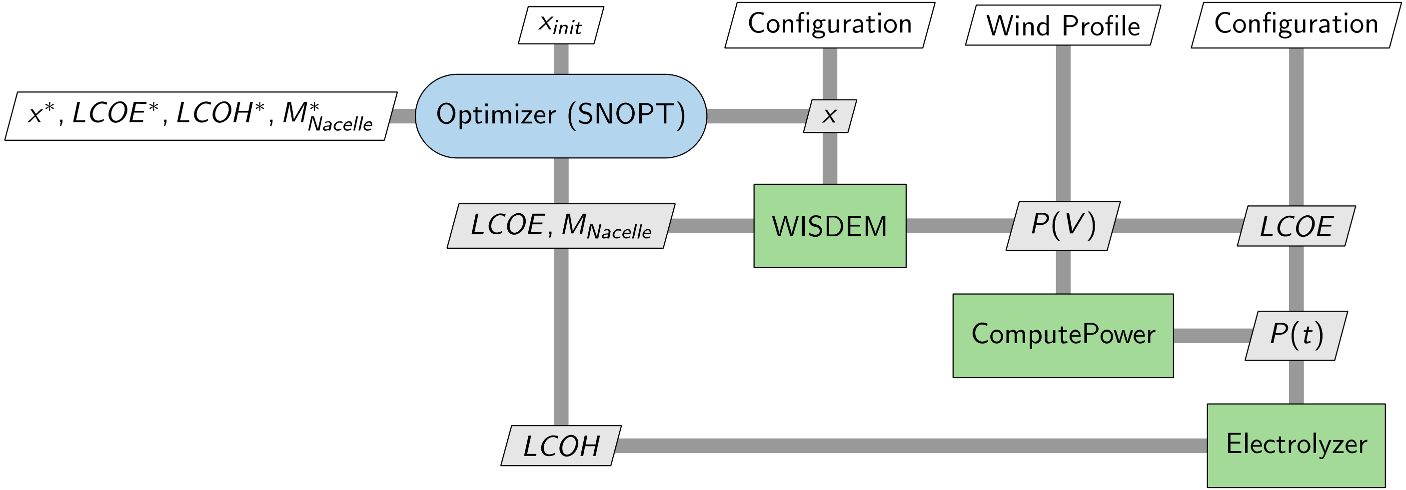
Calculate voltage: $\mathrm{V} = f(I, T)$

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

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

Hydrogen
(kilograms [kg])

Optimization Configuration



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
t: time
P(t): power as a function of time
$M_{Nacelle}$: nacelle mass

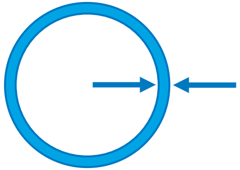
Simplified extended design structure matrix (XDSM) diagram of the simplified optimization framework.

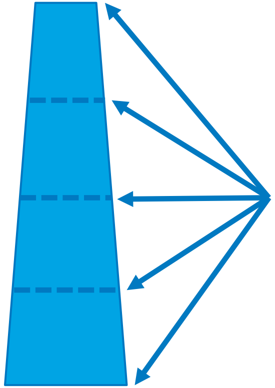
Three-Part Optimization Process

Subsystem(s) (Objective(s))	Design Variables
Tower (LCOE)	Tower: Section thickness, section diameter
Tower + Blades (LCOE, LCOH)	Swept: rotor diameter, 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

Tower Optimization Specification

Design Variables


Thickness (11 locations)

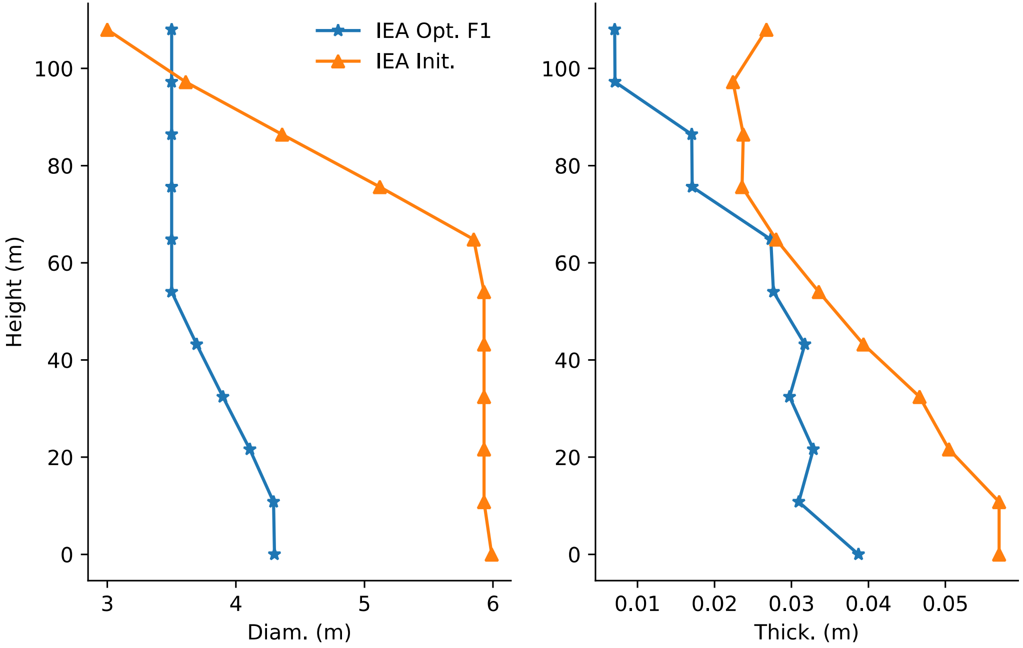

Diameter (11 locations)

Constraints

Tower

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

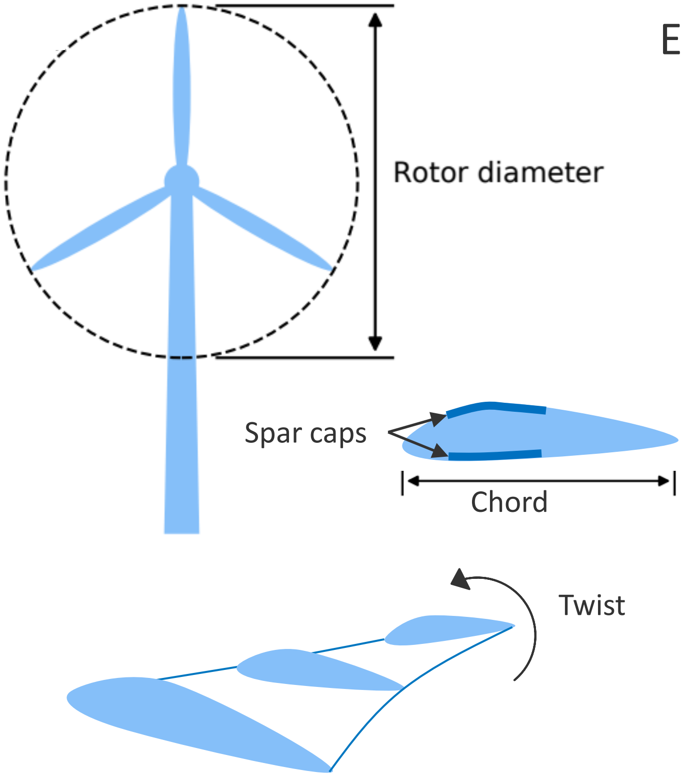
New International Energy Agency (IEA) Baseline Tower



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

m = meters

Rotor/Tower Optimization Specification



Electrolyzer

Design Variables	Constraints
Electrical rating (swept)	Max chord

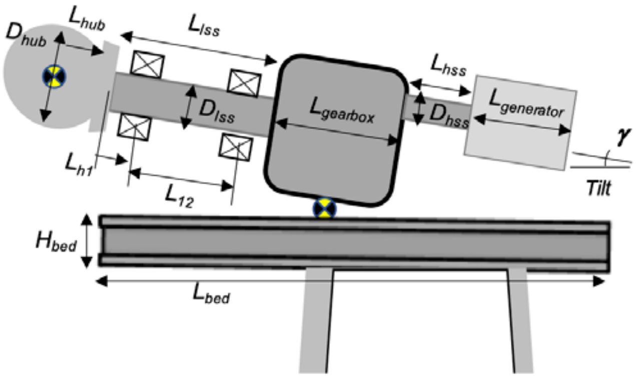
Rotor

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

Tower

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

Drivetrain Optimization

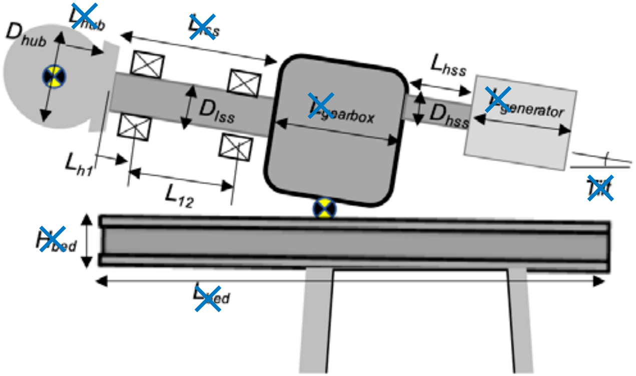


Geared drivetrain diagram for WISDEM

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

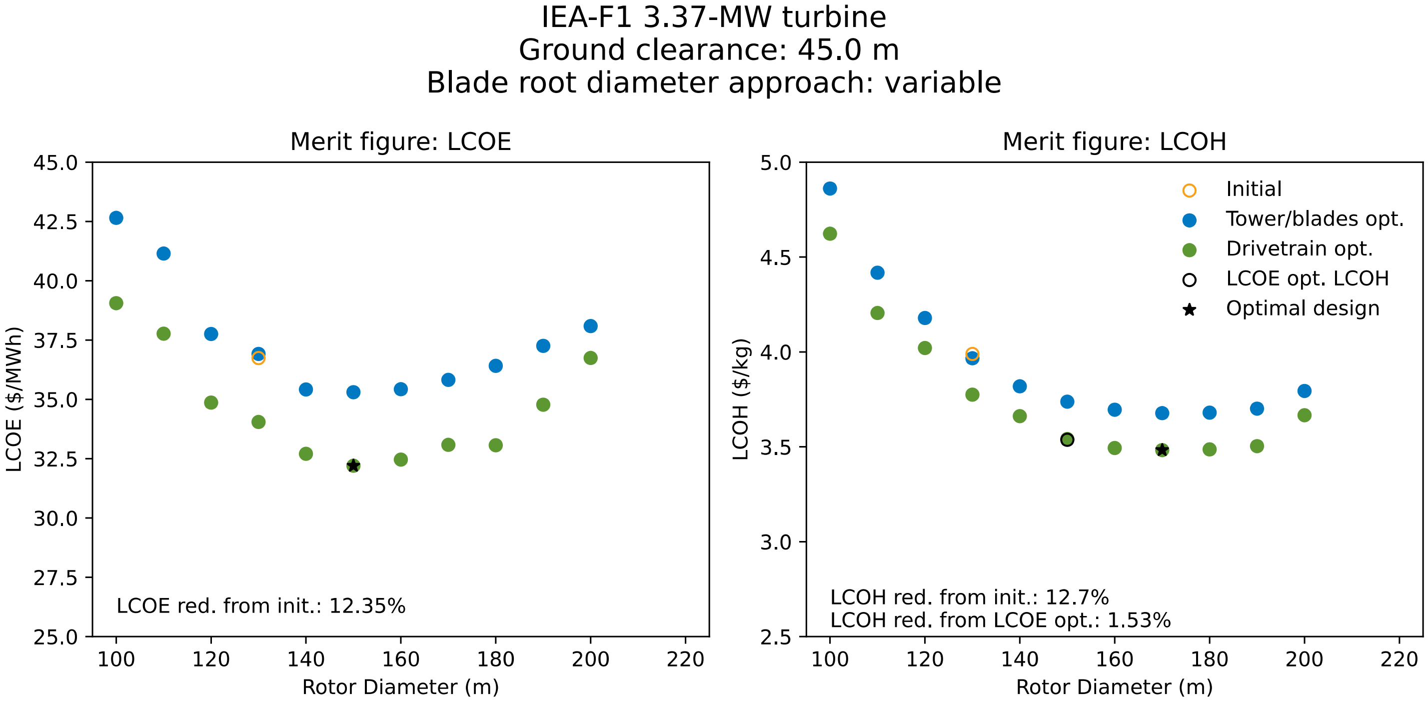


Geared drivetrain diagram for WISDEM

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

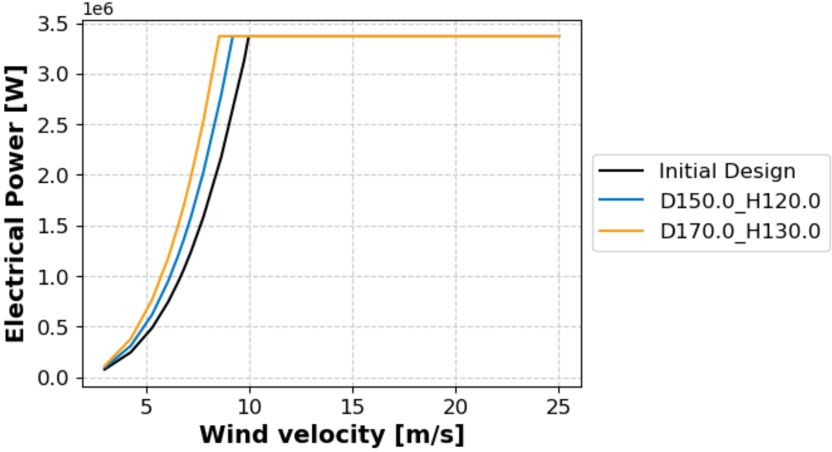
Optimal Rotor Diameter: LCOE vs LCOH



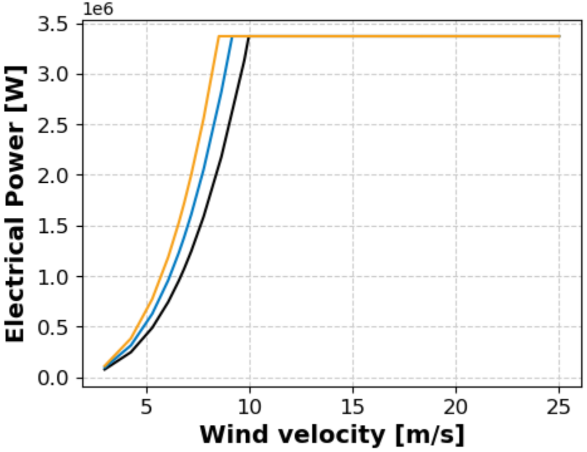
Results showing that the optimal rotor diameter for hydrogen is about 20 m larger than for electricity. Constant wind turbine rating was set at 3.37 megawatts (MW). Constant electrolyzer rating was set at 3.4 MW. MWh = megawatt-hour.

LCOE and LCOH power curves match at optimal rotor diameters

LCOE

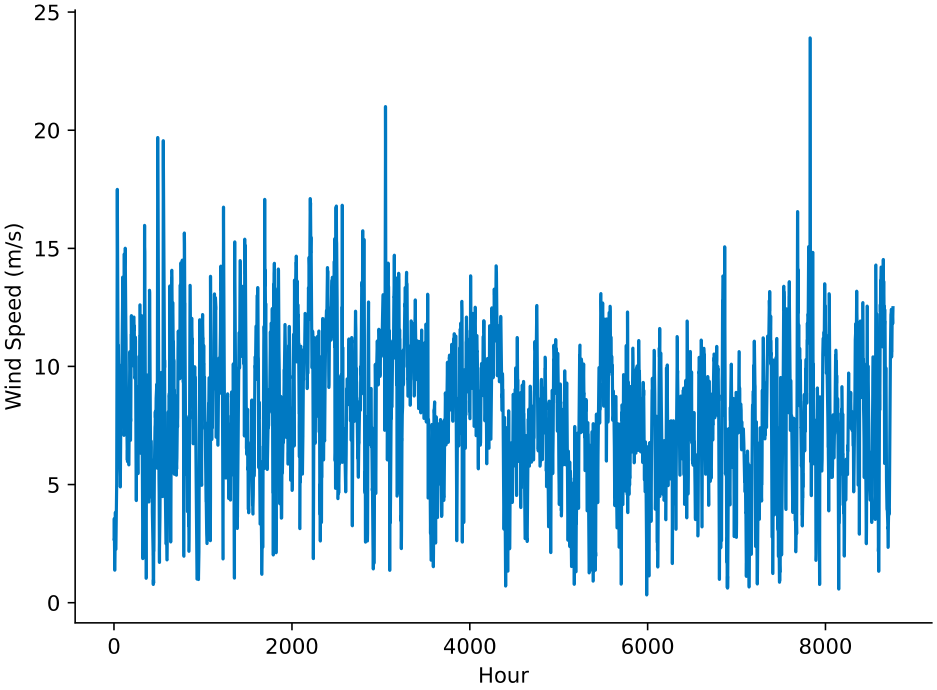


LCOH



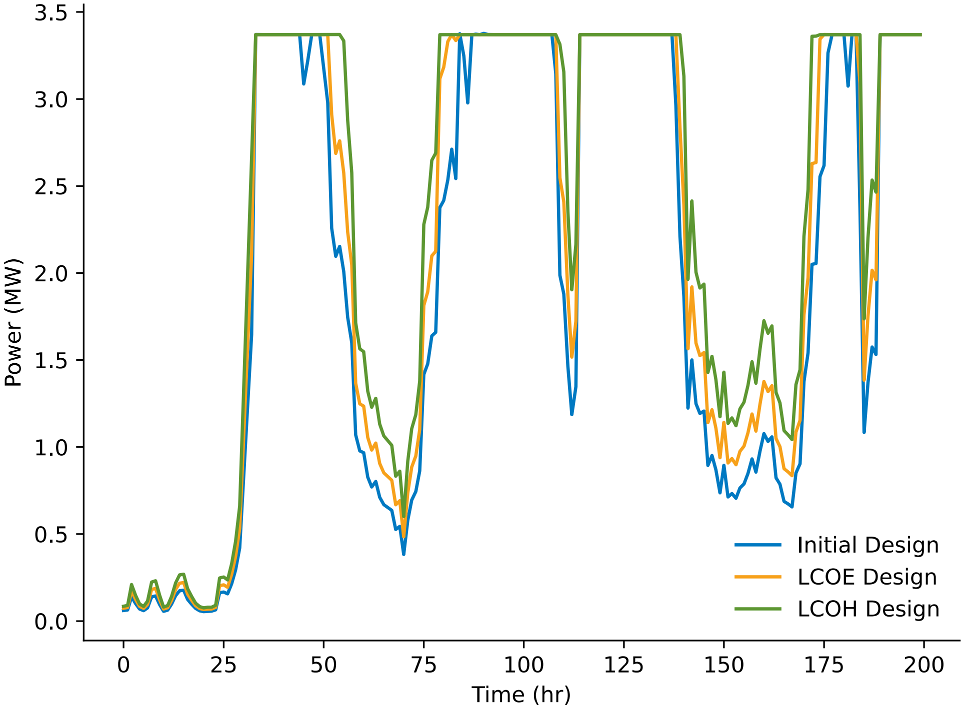
Simplified power curves from WISDEM for each of the optimal rotor diameters. These power curves were not used for loads analysis. W = watts. m/s = meters per second.

Wind Resource



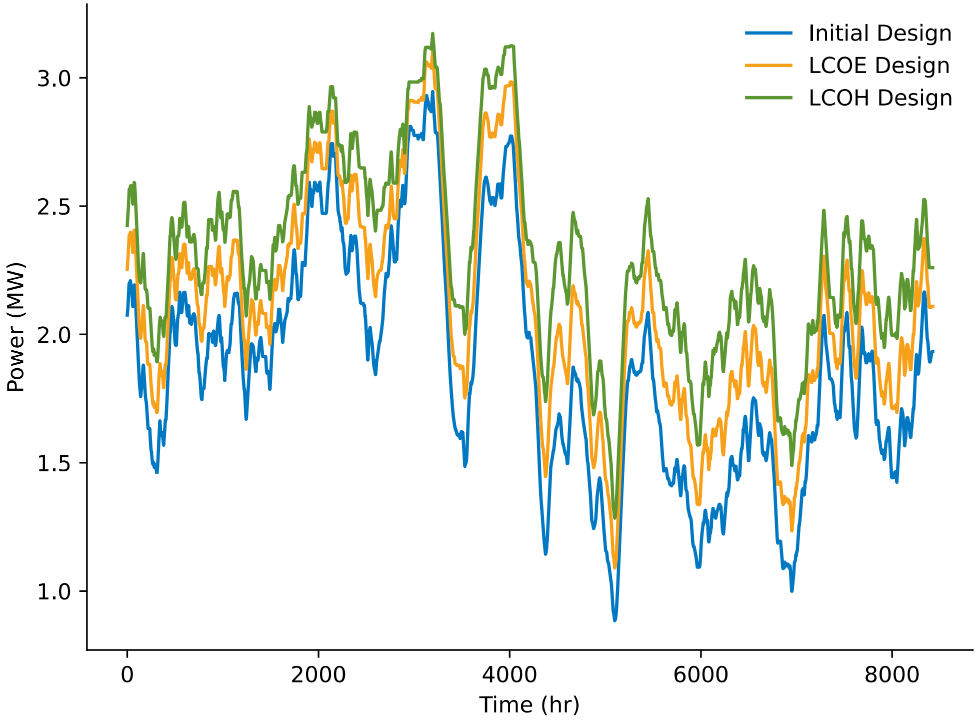
Hourly wind resource over a single year used to estimate hydrogen production for the wind turbines.

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



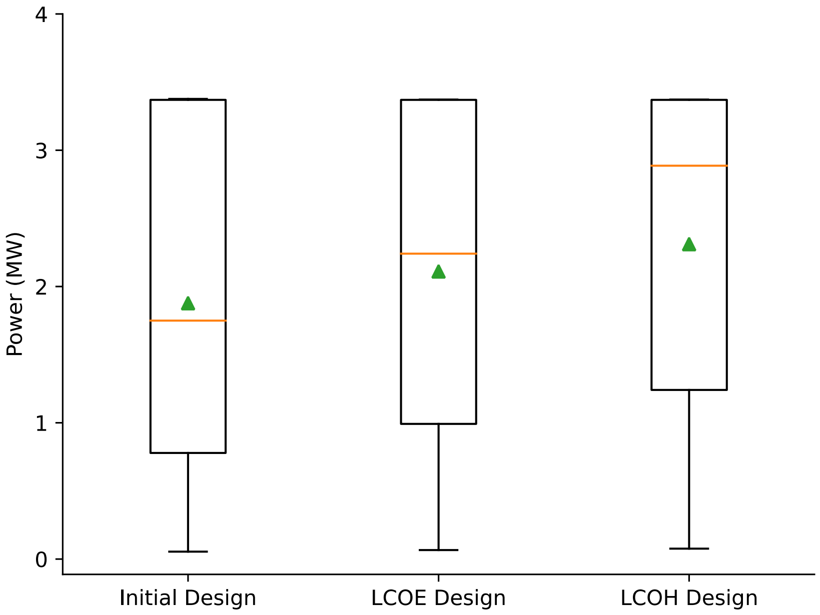
Detail of hourly power from the initial and optimal wind turbines show that the LCOH design hits rated power earlier and ramps down later than the initial and LCOE designs

Power 2-Week Running Average for 1 Year



This two-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 (CF) and power distributions for the initial, LCOE, and LCOH optimal designs. Green triangles represent the mean and colored horizontal lines indicate the median.

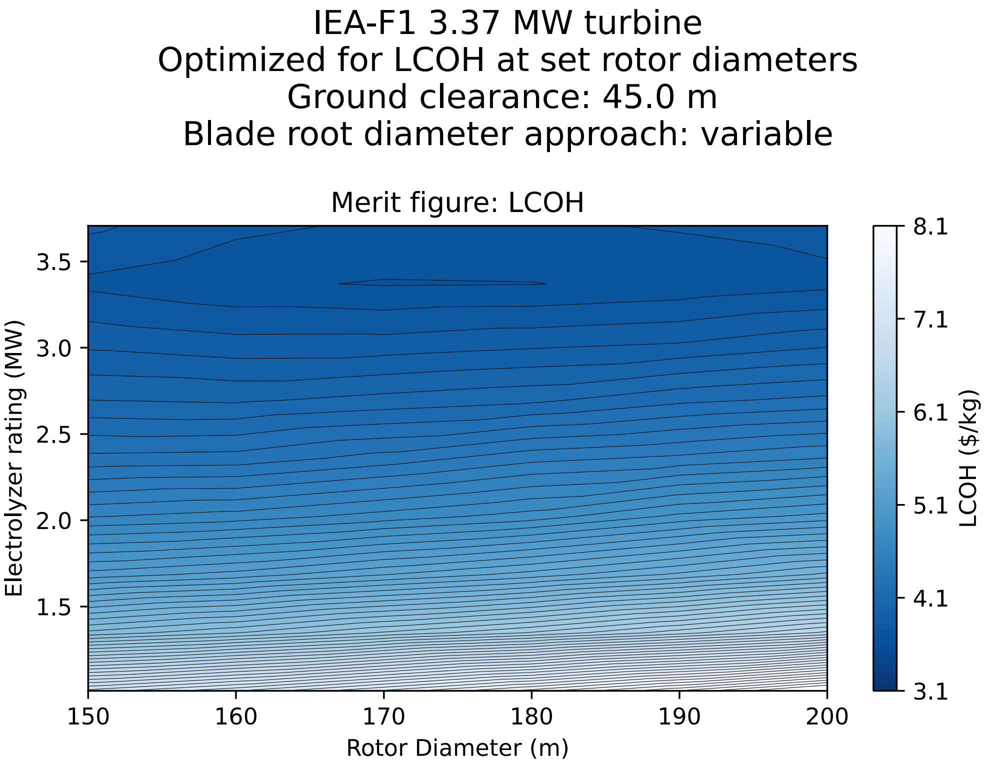
LCOH Design Leads to Higher Energy Cost but Lower Overall Cost

LCOH Contributions

	LCOE Design	LCOH Design	Difference
Electrolyzer Capital Expenditures (USD/kg)	0.88	0.81	-0.07
Energy Cost (USD/kg)	2.13	2.19	0.06
Other Costs (USD/kg)	0.52	0.49	-0.03

The energy cost for the LCOH design is higher on a per-kg basis than the LCOE design, but the other costs reduce sufficiently to offset the increased energy costs.

Equal Turbine-Electrolyzer Ratings Are Best for a Grid-Disconnected System Without Storage


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

Merit figure: LCOH

Optimal electrolyzer rating appears to be near the wind turbine rating when part of a grid-disconnected system without storage capacity

Conclusions

Wind turbines designed for LCOH may benefit from larger rotor diameters

Electrolysis equipment should 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, ROSCOE)

Update electrolyzer cost analysis

Improve electrolyzer sizing approach

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

Thank you

www.nrel.gov

NREL/PR-5000-87788

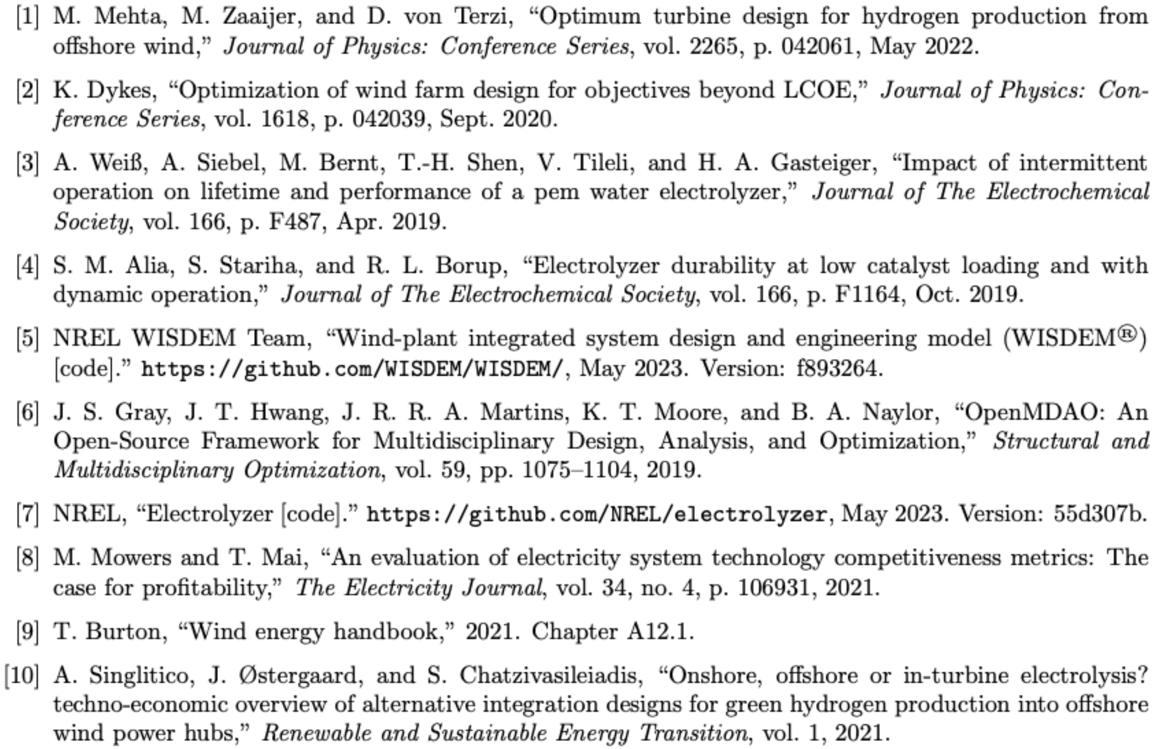
This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen 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.

This work was completed with input from GE and NEL

NREL

Transforming ENERGY

References



[1] M. Mehta, M. Zaaijer, and D. von Terzi, "Optimum turbine design for hydrogen production from offshore wind," *Journal of Physics: Conference Series*, vol. 2265, p. 042061, May 2022.

[2] K. Dykes, "Optimization of wind farm design for objectives beyond LCOE," *Journal of Physics: Conference Series*, vol. 1618, p. 042039, Sept. 2020.

[3] A. Weiß, A. Siebel, M. Bernt, T.-H. Shen, V. Tileli, and H. A. Gasteiger, "Impact of intermittent operation on lifetime and performance of a pem water electrolyzer," *Journal of The Electrochemical Society*, vol. 166, p. F487, Apr. 2019.

[4] S. M. Alia, S. Stariha, and R. L. Borup, "Electrolyzer durability at low catalyst loading and with dynamic operation," *Journal of The Electrochemical Society*, vol. 166, p. F1164, Oct. 2019.

[5] NREL WISDEM Team, "Wind-plant integrated system design and engineering model (WISDEM®) [code]." `https://github.com/WISDEM/WISDEM/`, May 2023. Version: f893264.

[6] J. S. Gray, J. T. Hwang, J. R. R. A. Martins, K. T. Moore, and B. A. Naylor, "OpenMDAO: An Open-Source Framework for Multidisciplinary Design, Analysis, and Optimization," *Structural and Multidisciplinary Optimization*, vol. 59, pp. 1075–1104, 2019.

[7] NREL, "Electrolyzer [code]." `https://github.com/NREL/electrolyzer`, May 2023. Version: 55d307b.

[8] M. Mowers and T. Mai, "An evaluation of electricity system technology competitiveness metrics: The case for profitability," *The Electricity Journal*, vol. 34, no. 4, p. 106931, 2021.

[9] T. Burton, "Wind energy handbook," 2021. Chapter A12.1.

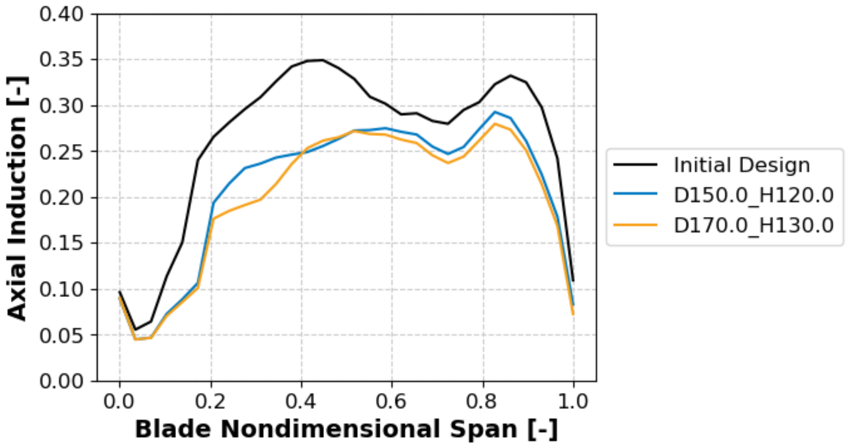
[10] A. Singlitico, J. Østergaard, and S. Chatzivasileiadis, "Onshore, offshore or in-turbine electrolysis? techno-economic overview of alternative integration designs for green hydrogen production into offshore wind power hubs," *Renewable and Sustainable Energy Transition*, vol. 1, 2021.

Appendix

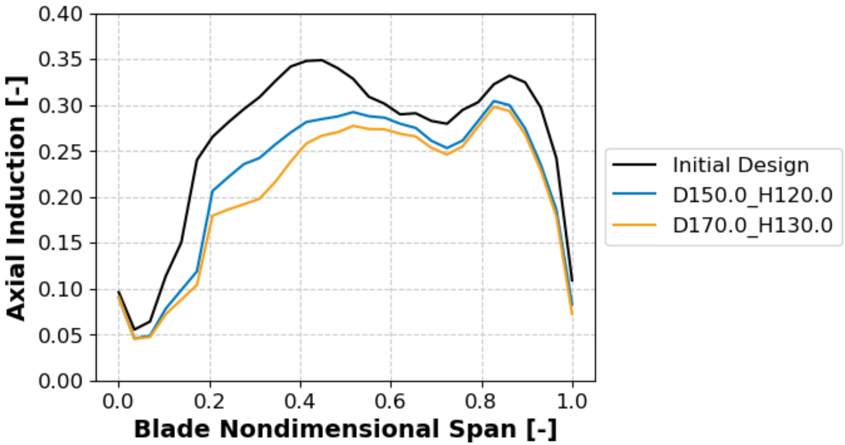
Photo from iStock-627281636

Induction

LCOE

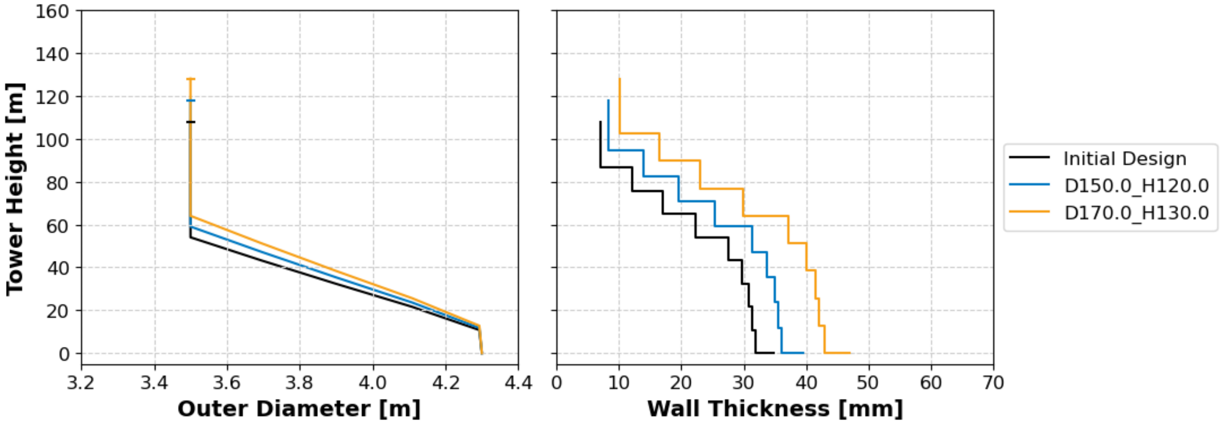


LCOH

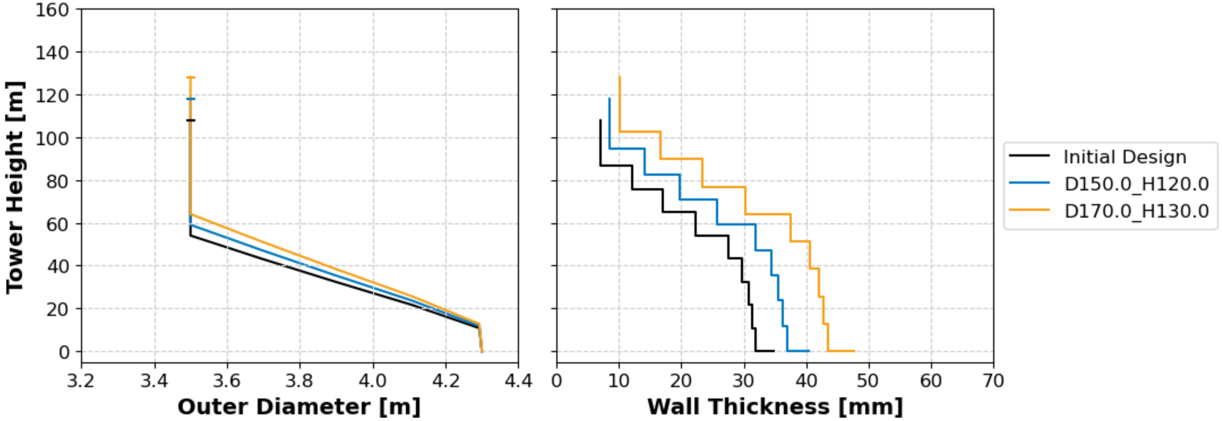


Axial induction for both the LCOE and LCOH designs follow a similar shape to the initial design.

LCOE



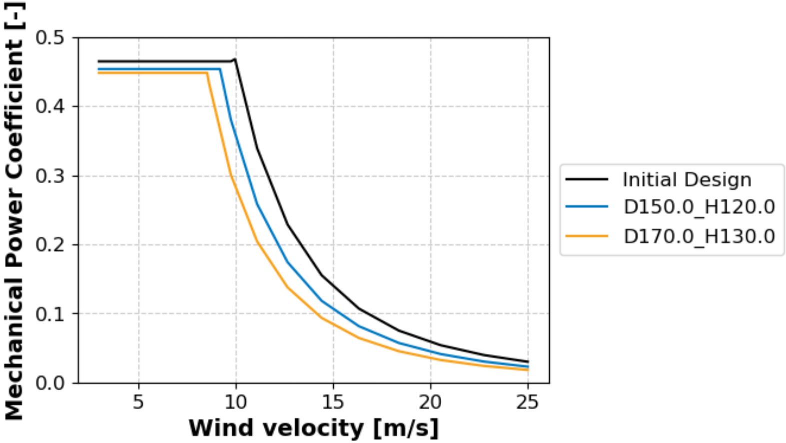
LCOH



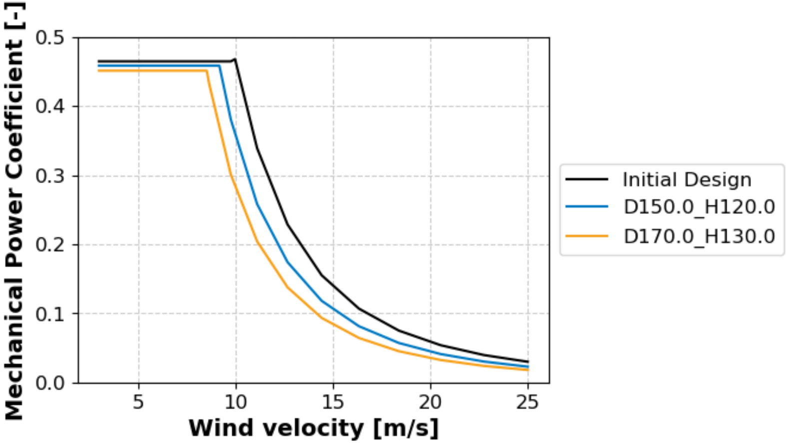
The tower designs for the LCOE and LCOH designs are nearly identical at a given rotor diameter. However, as expected, the larger rotor diameter requires a thicker tower with locally larger diameters.

CP Aero

Levelized Cost of Energy (LCOE)

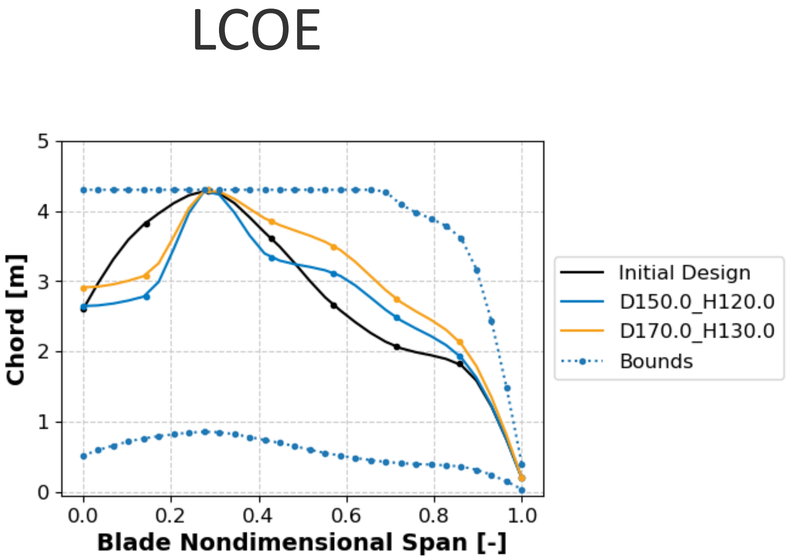


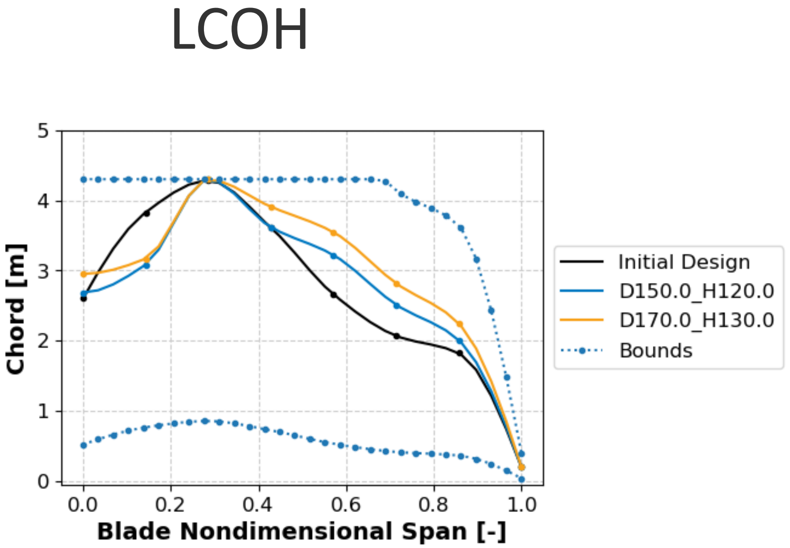
Levelized Cost of Hydrogen (LCOH)



As rotor diameter increases, rated power is reached at lower wind speeds, which results in a more consistent power output. m/s = meters per second.

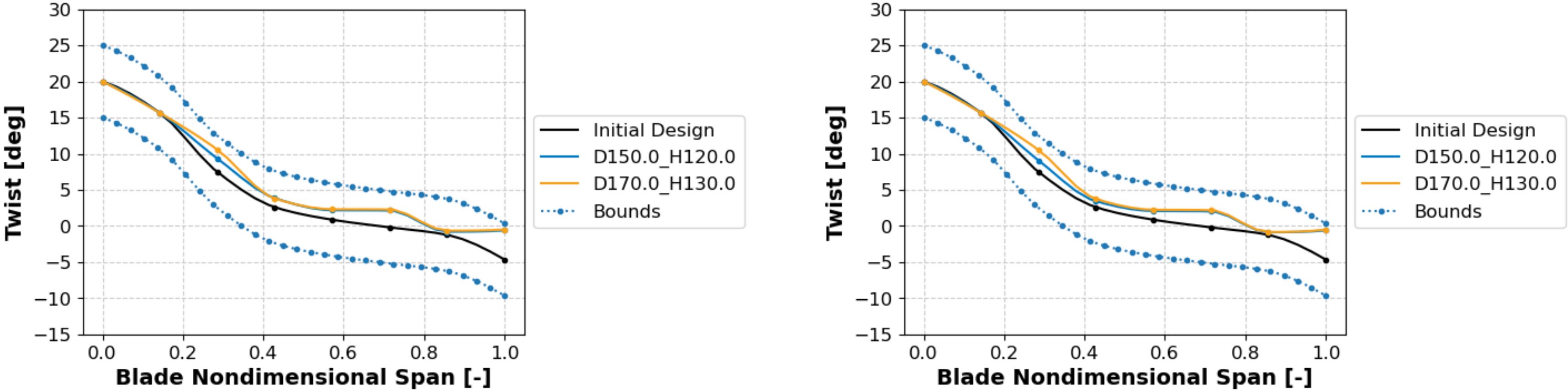
Chord





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

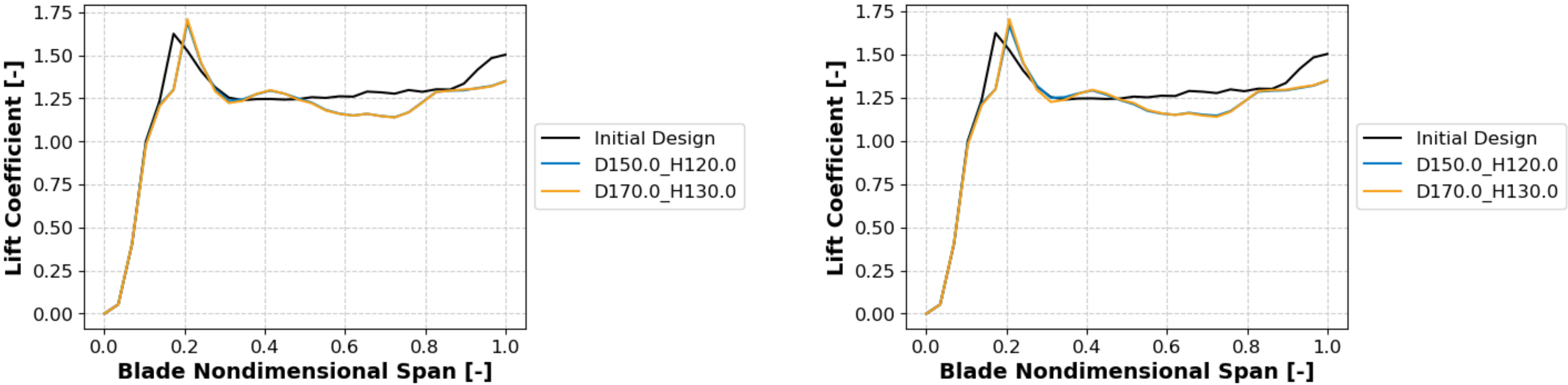
Twist


LCOE

LCOH

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

Lift

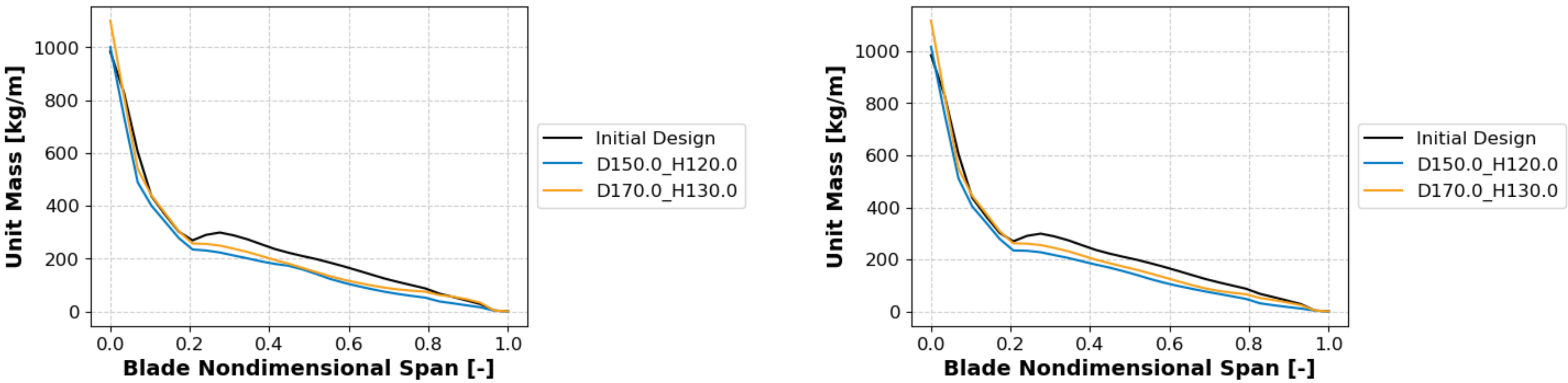


LCOE

LCOH

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

Mass



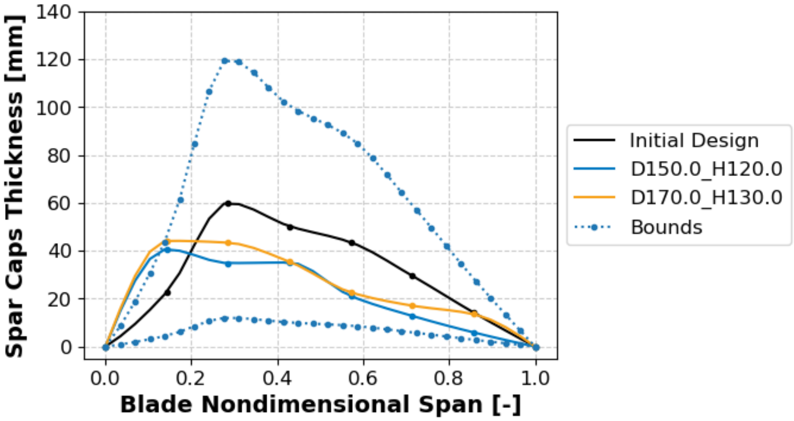
LCOE

LCOH

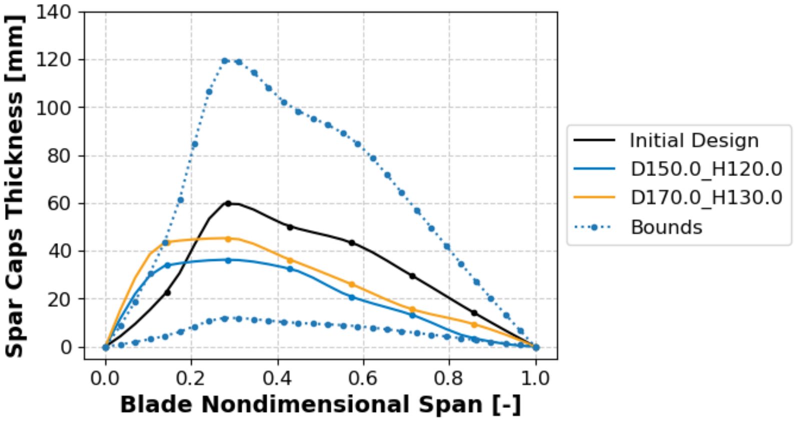
Unit mass along the blade for LCOE, LCOH, and initial designs. kg = kilograms

Spar Cap Thickness

LCOE



LCOH



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