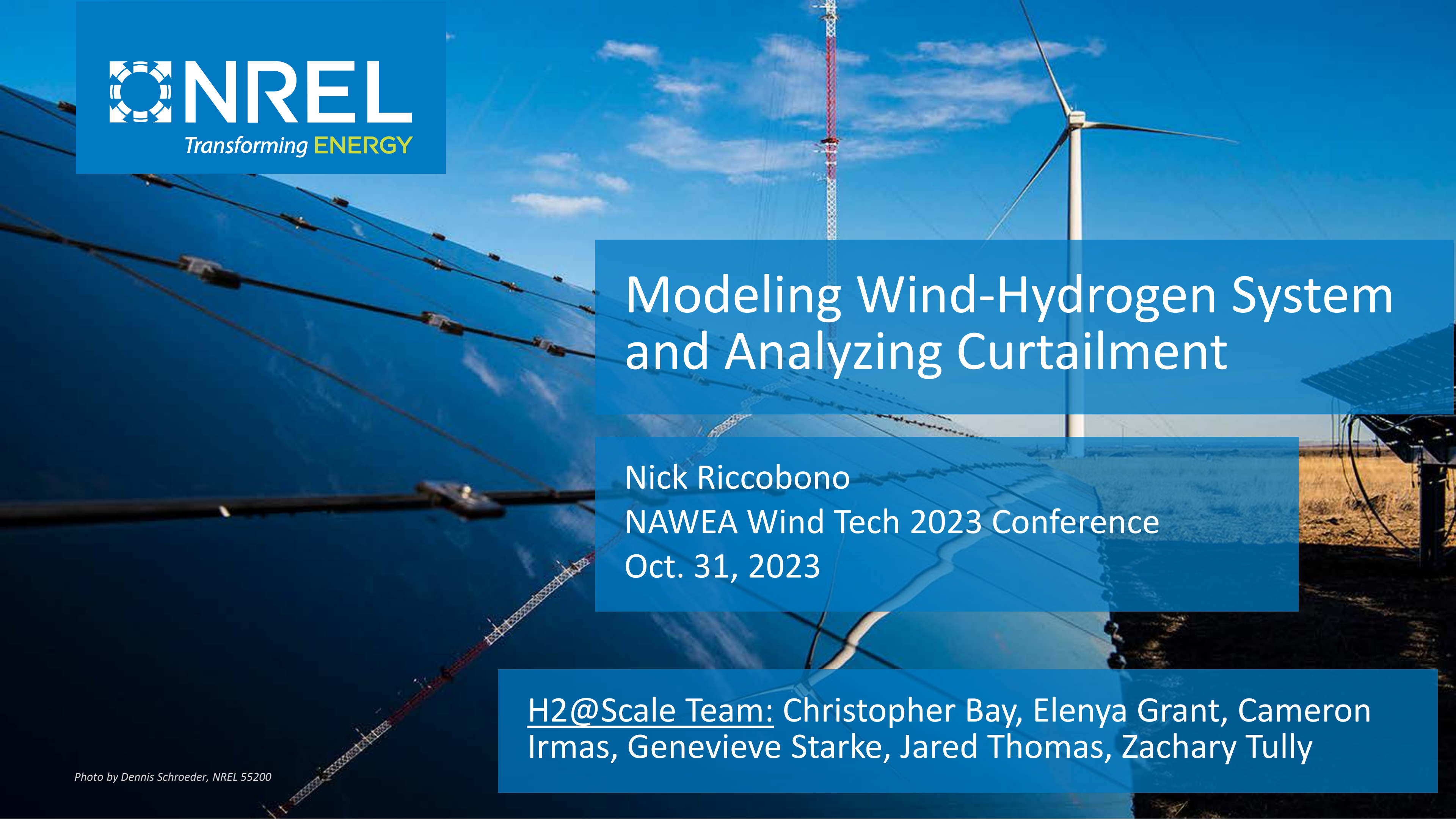


NREL
Transforming ENERGY

Modeling Wind-Hydrogen System and Analyzing Curtailment

Nick Riccobono
NAWEA Wind Tech 2023 Conference
Oct. 31, 2023

H2@Scale Team: Christopher Bay, Elenya Grant, Cameron Irmas, Genevieve Starke, Jared Thomas, Zachary Tully

Photo by Dennis Schroeder, NREL 55200

Contents

Motivation and Goals

5% U.S. Wind Energy Curtailed

(Musial 2021)

Curtailment: *To constrain or shut down operations of a system*

Research Question:

As we create new pathways to decarbonize our energy demand with hydrogen, are there benefits to specific hybrid configurations?

Background

Wind and Hydrogen System

Electrolysis System Configuration

Singlitico et al. (2021)

- Techno-economic analysis comparison study
- 1:1 system rating (varied configuration)

Mehta et al. (2022)

- Turbine optimization scheme
- 1:1.2 system rating (in-turbine)

No explicit mentions of curtailment and minimal defense to system rating decisions.

Is there any discernable different in H_2 performance between configurations?

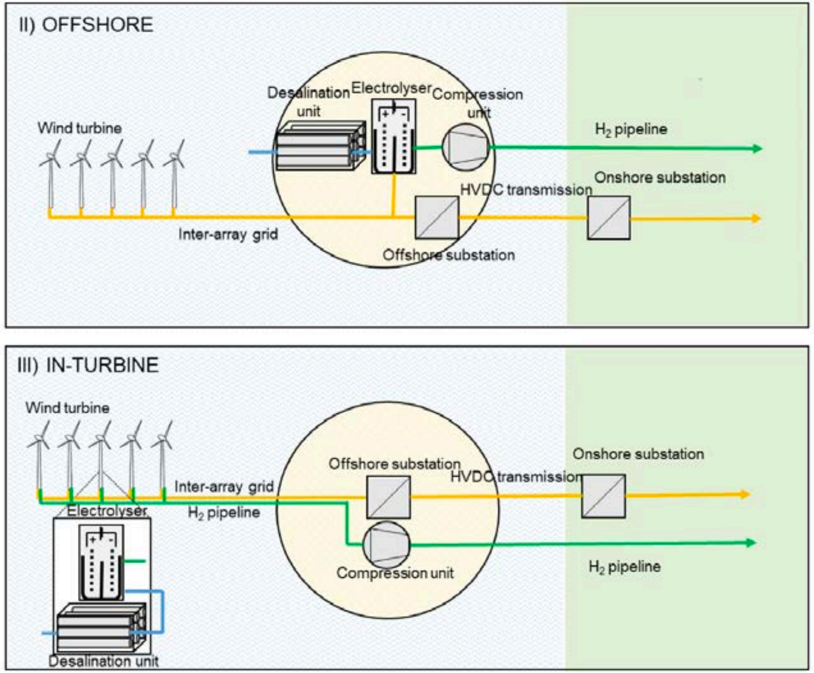
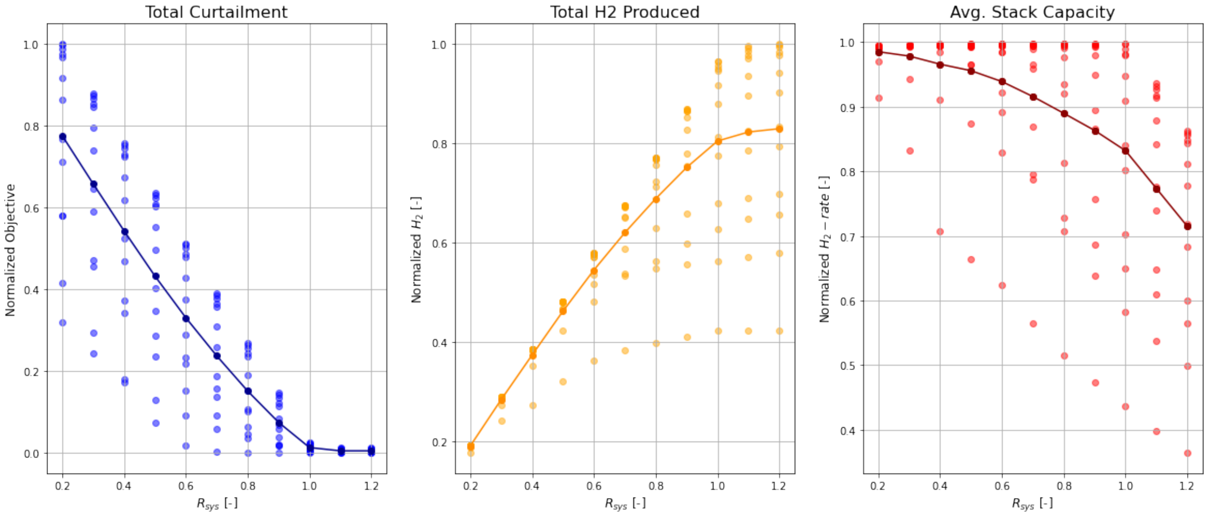


Figure from Singlitico et al. (2021). Figure describes electrolyzer/turbine configurations for an offshore wind farm.

Hybrid System Rating

Previous work's research goals

- End-use focused: minimize wind curtailment or guarantee hydrogen generation
- Vary system rating 20%–120%
- Determine how to reduce wind turbine loads.



"Undersized" electrolyzer guaranteed constant generation

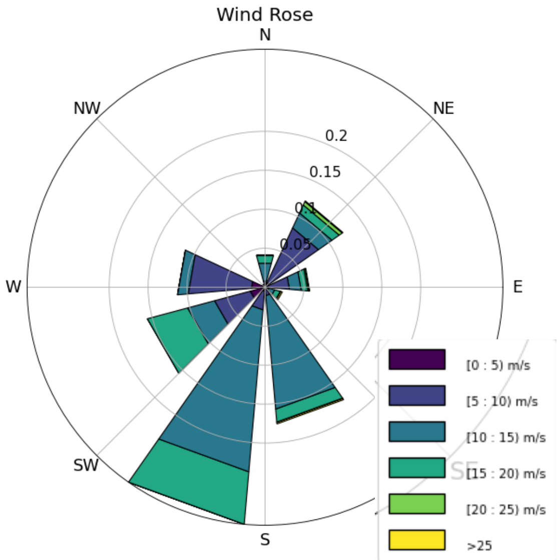
"Oversized" electrolyzer minimized curtailment

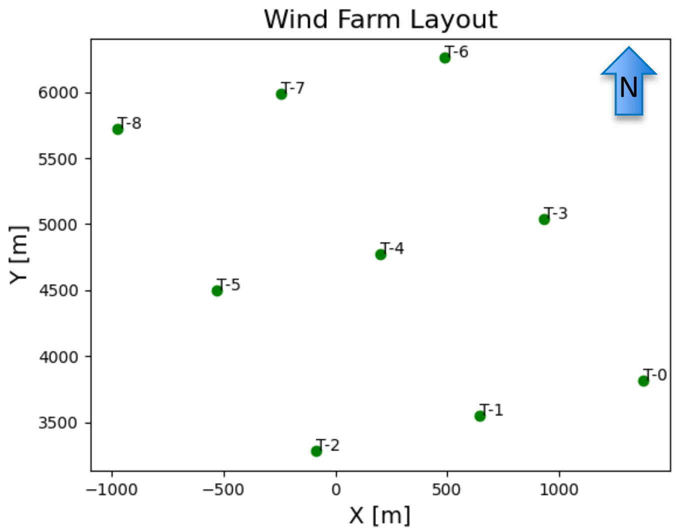
Figure from Riccobono (2023). Figure illustrates the results of the minimizing curtailment objective.

Methodology

Hybrid Energy Plant (Wind and Hydrogen)

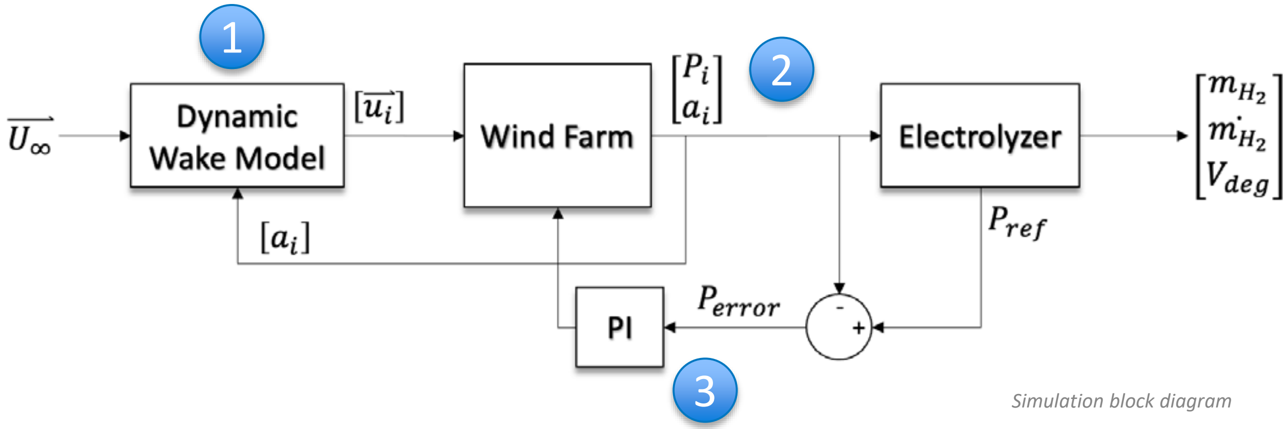
Wind Farm Layout





Site Info	Wind Farm
Lubbock, Texas	10 by 6 rotor diameters (D)
1 hour at dt: 1 second	Heading: 165°

m = meters
m/s = meters per second

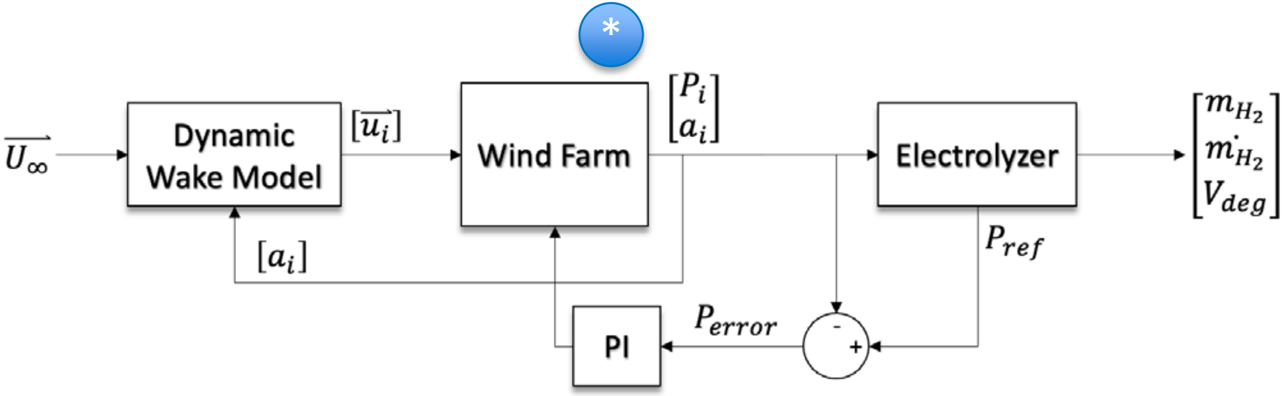


Simulation block diagram

Simulation Architecture

Highlights

1) Network-based estimation algorithm (Starke et al. [2021])
2) System rating: 90% [27-megawatt (MW) electrolyzer: 30-MW wind farm]
3) Apply proportional integral (PI) control: centralized (farm level) (Wingerden et al. 2017); distributed (turbine level).



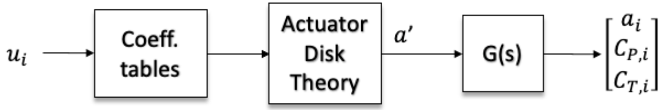
Wind Turbine Model

IEA 3.4-MW-Reference Wind Turbine (Bortolotti et al. [2019])

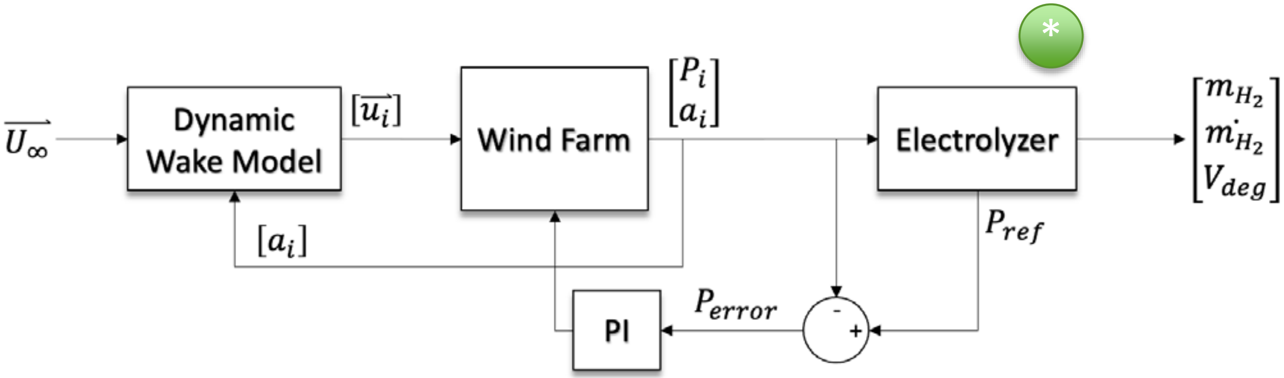
3.37 MW at 9.8 m/s

Rotor diameter: 130 m; tower height: 110 m

https://github.com/IEAWindTask37/IEA-3.4-130-RWT



Individual turbine signal path



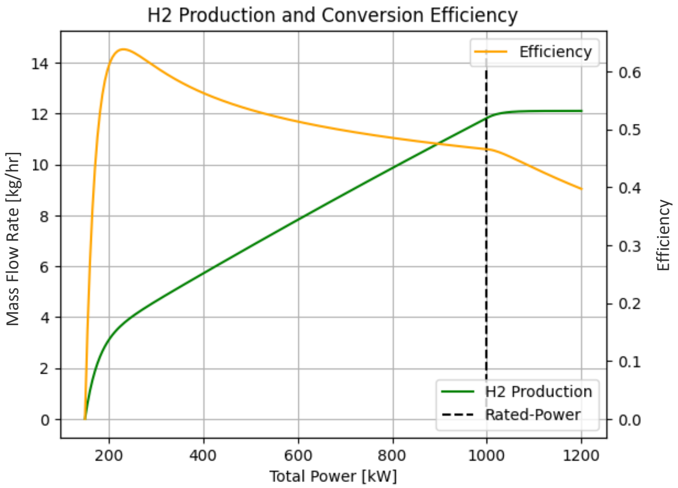
Electrolyzer Model

NREL Proton Exchange Membrane (PEM) Electrolyzer

1 MW per stack

200 cells; 1,500 cm^2; 60°C

https://github.com/NREL/electrolyzer



PEM electrolyzer performance

kg/hr = kilograms per hour

Results 1

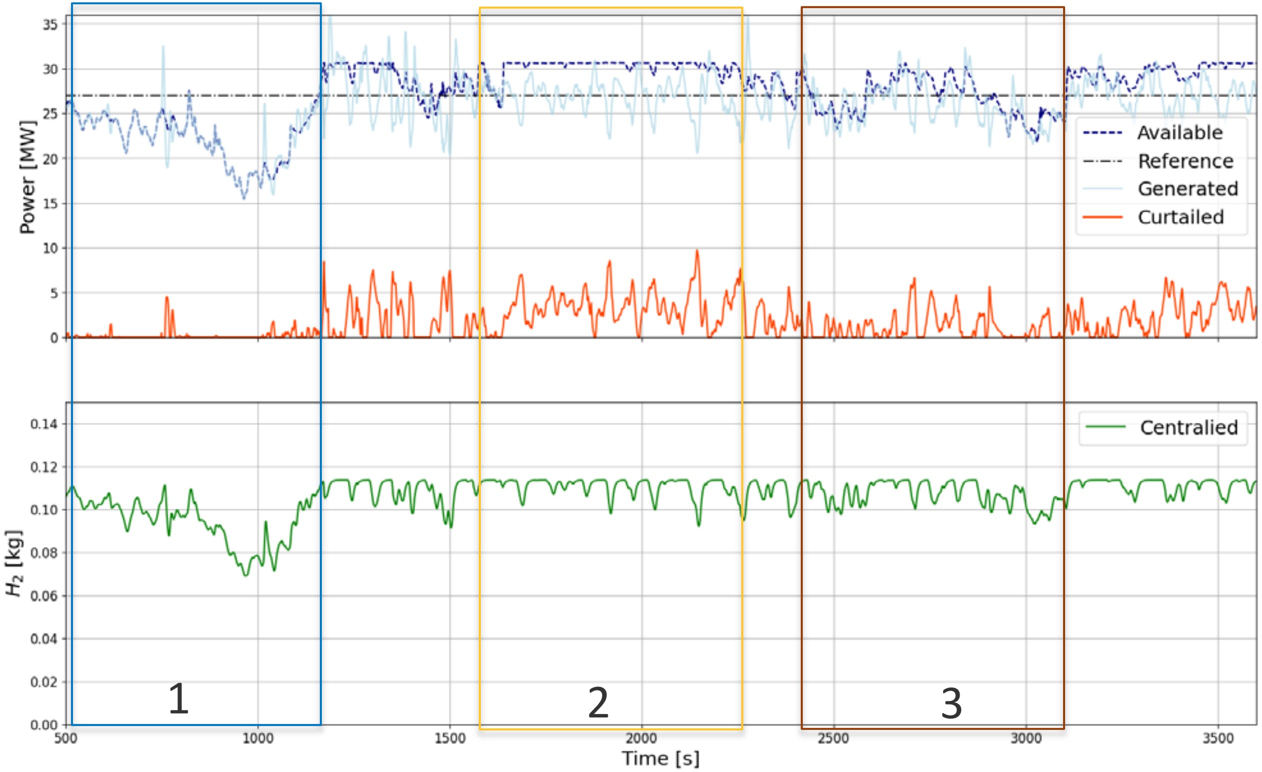
Centralized vs. Distributed Electrolysis

Centralized Configuration

1) Below-rated wind speed, below reference power

2) Above-rated wind speed, above reference power (steady)

3) Above-rated wind speed, above reference power (unsteady)



s = seconds

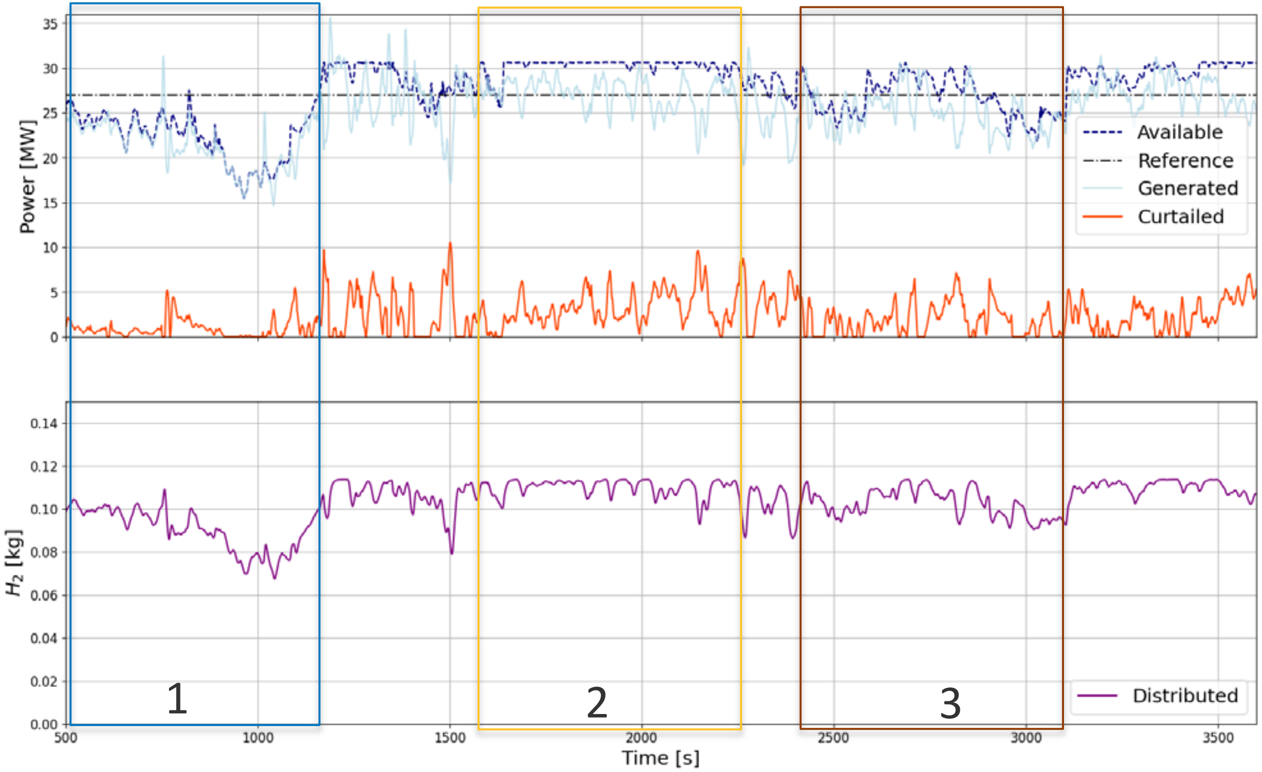
Centralized electrolyzer configuration performance

Distributed Configuration

1) Below-rated wind speed, below reference power

2) Above-rated wind speed, above reference power (steady)

3) Above-rated wind speed, above reference power (unsteady)

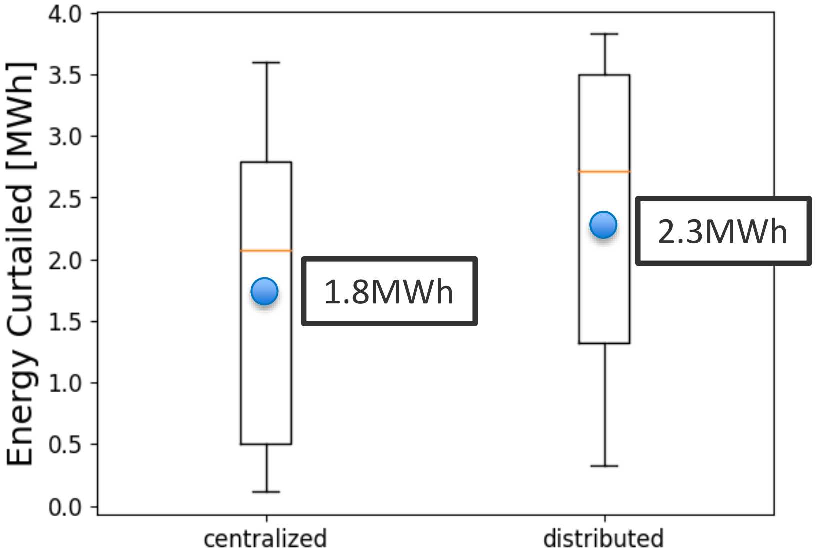


Distributed electrolyzer configuration performance

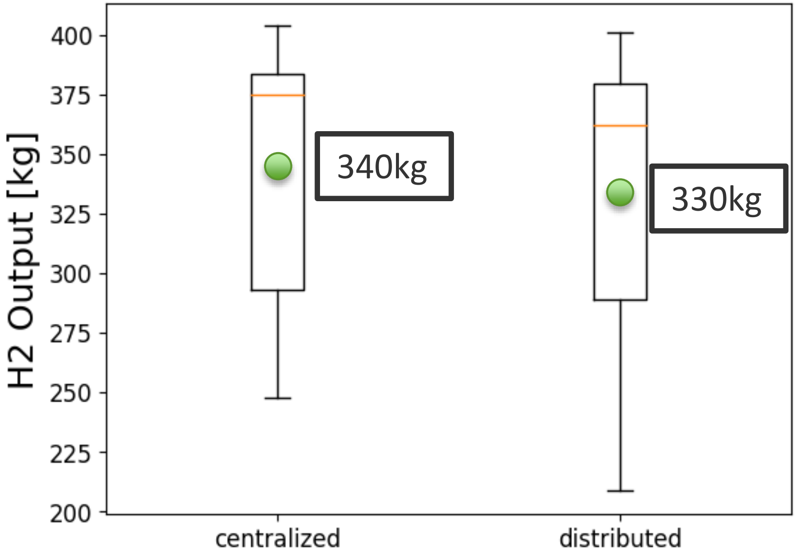
s = seconds

Results 2

Curtailment and Performance Trade-Offs

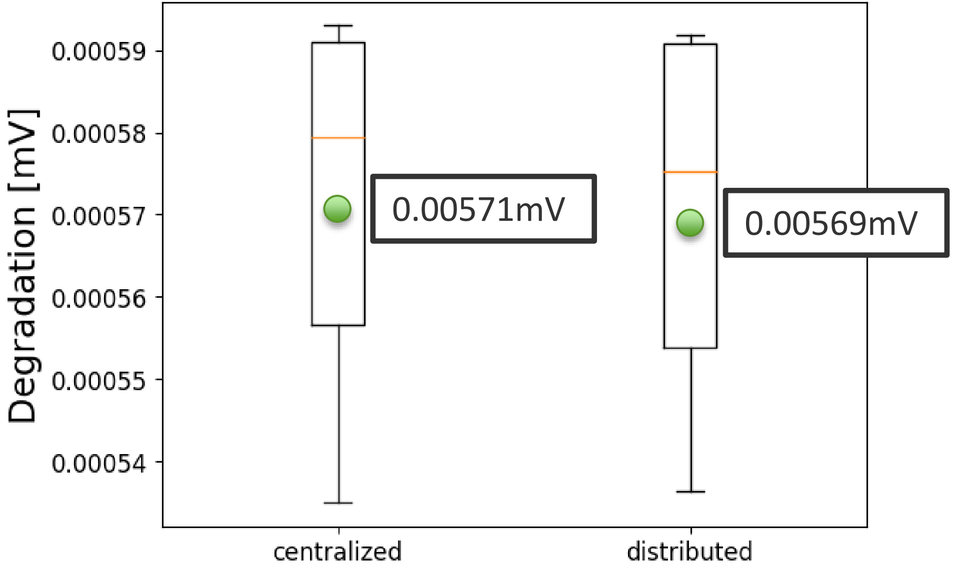


MWh = megawatt-hour



Curtailment and Hydrogen Output

- Distributed config. Curtailed more energy (or did not use as much)
- Distributed config. Produced less hydrogen



mV = millivolts

Electrolyzer performance

- Distributed configuration degraded slightly less than centralized configuration

Findings and Take-aways

- *Wake dynamics appear more present in the distributed configuration*
- *Distributed configuration converted less hydrogen and curtailed more energy.*
- *Distributed configuration degraded less*

Future Work

- Tuning controller and adjusting time scales
- Incorporating system losses
- Adding alternative storage/generation

Literature:
Bortolotti, Pietro, Helena Canet Tarres, Katherine Dykes, Karl Merz, Latha Sethuraman, David Verelst, and Frederik Zahle. n.d. "IEA Wind TCP Task 37: Systems Engineering in Wind Energy - WP2.1 Reference Wind Turbines," 138.

Mehta, Mihir, Michiel Zaaijer, and Dominic von Terzi. 2022. "Optimum Turbine Design for Hydrogen Production from Offshore Wind." *Journal of Physics: Conference Series* 2265 (4): 042061. https://doi.org/10.1088/1742-6596/2265/4/042061.

Riccobono, Nicholas. 2023. "Riding on Wind's Curtails: How Abundant Wind Energy Can Accelerate Green Hydrogen." ProQuest: 30425884 - Colorado University Boulder.

Singlitico, Alessandro, Jacob Østergaard, and Spyros Chatzivasileiadis. 2021. "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* 1 (August): 100005. https://doi.org/10.1016/j.rset.2021.100005.

Starke, Genevieve M., Paul Stanfel, Charles Meneveau, Dennice F. Gayme, and Jennifer King. 2021. "Network Based Estimation of Wind Farm Power and Velocity Data under Changing Wind Direction." In *2021 American Control Conference (ACC)*, 1803–10. https://doi.org/10.23919/ACC50511.2021.9483060.

Wingerden, Jan-Willem, Lucy Pao, Jacob Aho, and Paul Fleming. 2017. "Active Power Control of Waked Wind Farms." *IFAC-PapersOnLine* 50 (1): 4484–91. https://doi.org/10.1016/j.ifacol.2017.08.378.

References

Software models:

IEA-3.4MW RWT
https://github.com/IEAWindTask37/IEA-3.4-130-RWT

NREL PEM Electrolyzer
https://github.com/NREL/electrolyzer

Thank you

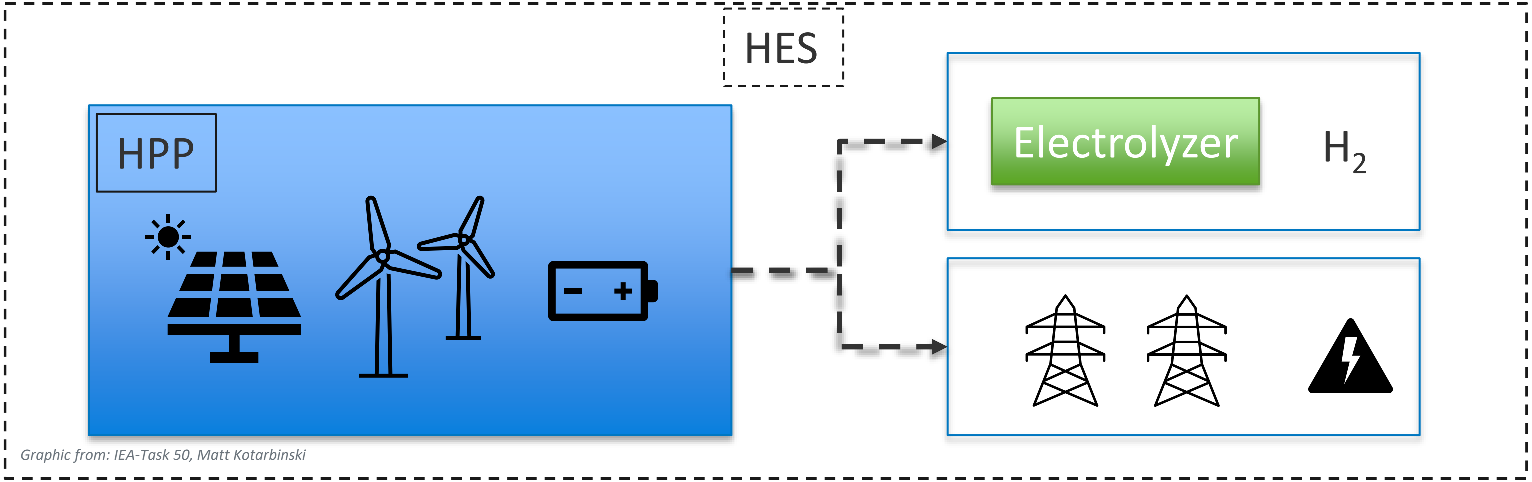
www.nrel.gov

NREL/PR-5000-87539

This work was authored 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 the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office and 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.

NREL Transforming ENERGY

Extra slides



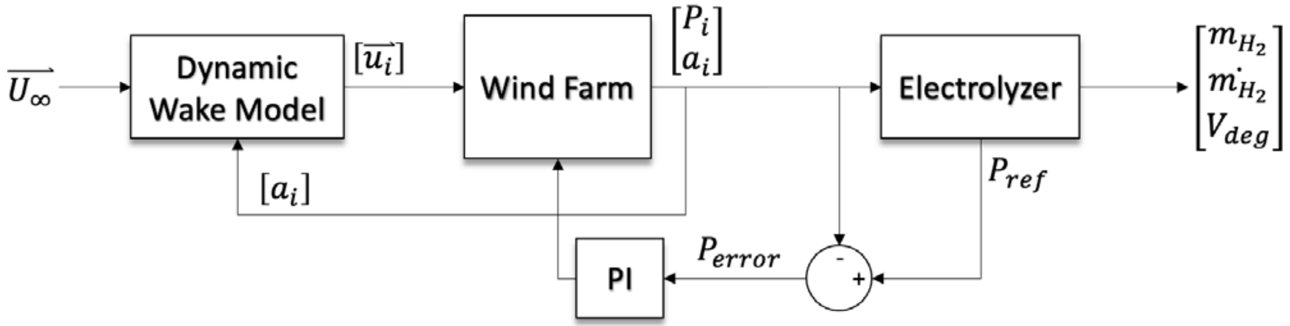
Hybrid Energy Taxonomy

Hybrid Power Plant (HPP)

"A combination of two or more electricity generation and/or two or more storage technologies used to provide electrical power services through coordinated bi-directional power flow." – IEA Task 50

Hybrid Energy System (HES)

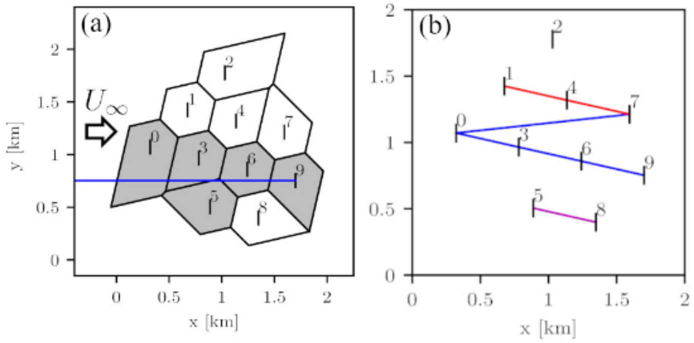
"A system that leverages one or more hybrid facilities to provide an energy and/or non-energy product to accommodate specific end-use needs in a coordinated way."



Dynamic Wake Model

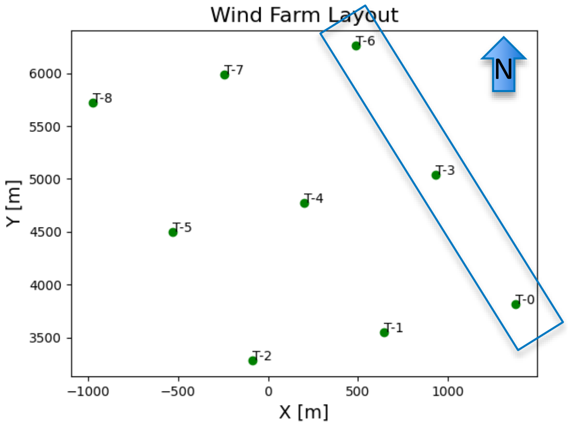
Starke et al. (2021)

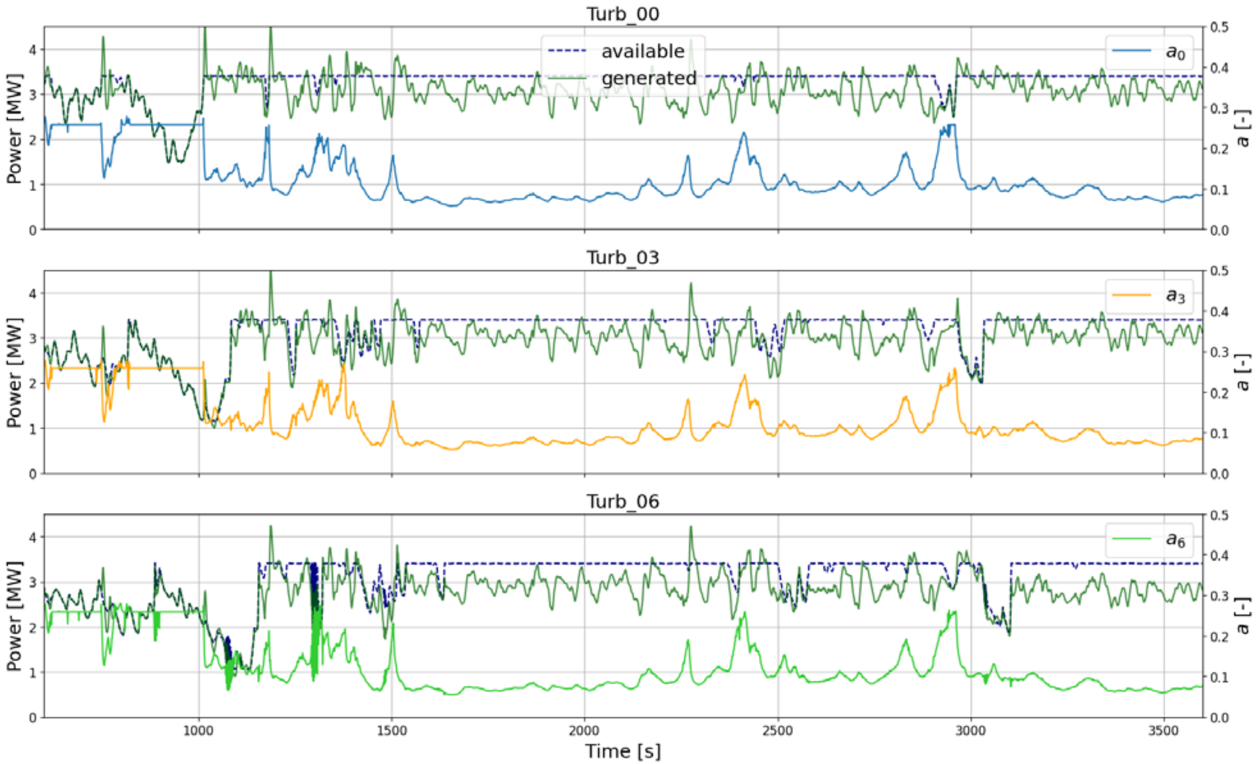
- Network-based estimation
- Time and space varying
- Varying wind speed and direction.



Depiction of Vouroni cells and how wake interaction matrix is tracked. From Starke et al. (2021)

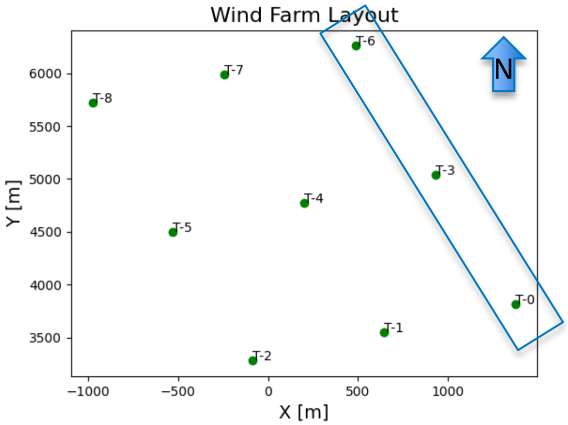
Centralized Configuration

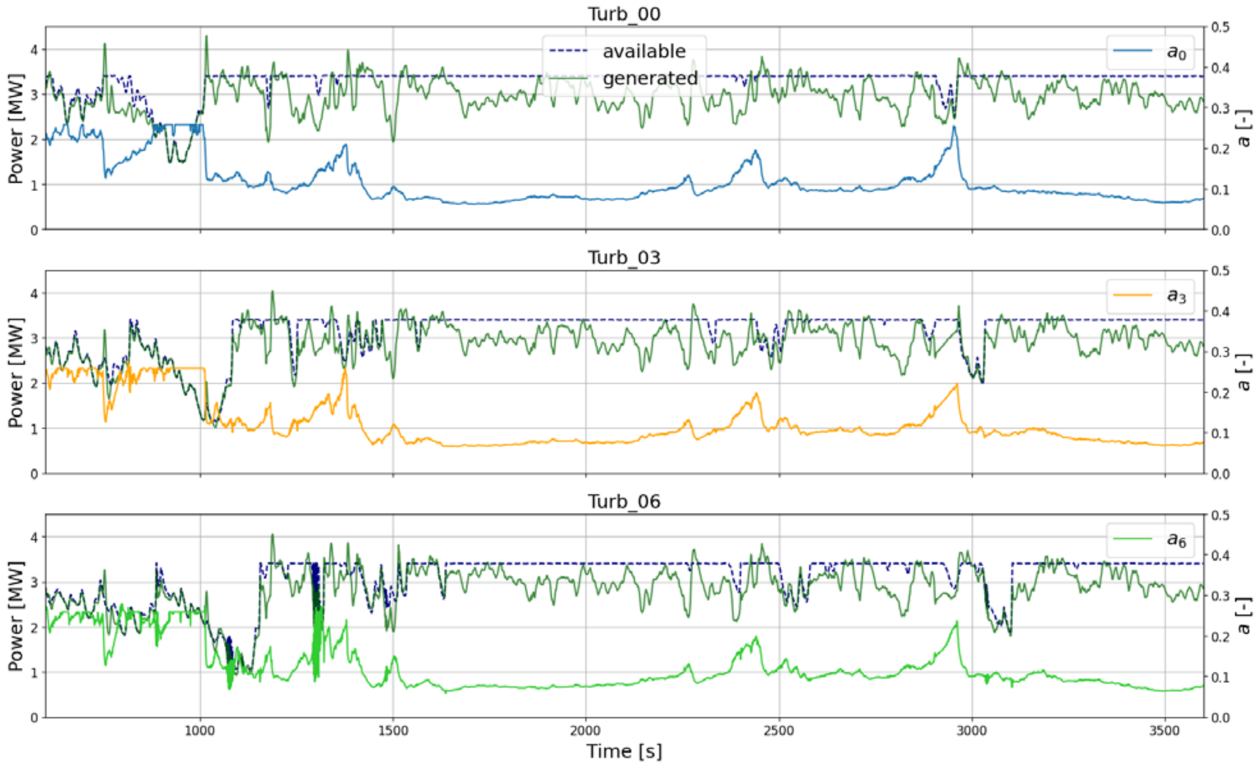




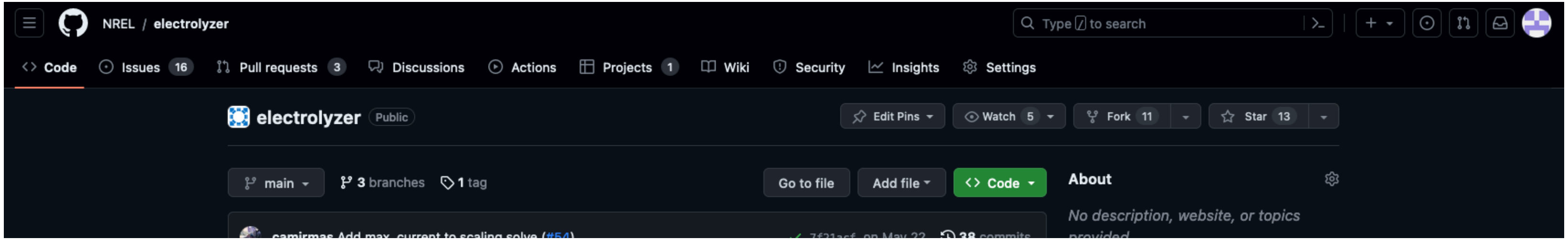
Centralized configuration single row individual turbine performance

Distributed Configuration





Distributed configuration single row individual turbine performance



https://github.com/NREL/electrolyzer

Electrolyzer Model (continued)

NREL Proton Exchange Membrane (PEM) Electrolyzer Capabilities
User-defined inputs
Variable time step
Levelized cost of hydrogen cost model
Integrates with NREL tools (Wind-Plant Integrated System Design & Engineering Model, Hybrid Optimization and Performance Platform)

Near-Term Upgrades
Alkaline electrolyzer
More user-defined inputs
New ideas?