Efficient Wind Energy Systems

Challenges and Opportunities to Enable a Clean Energy Future

Lucy Pao

Electrical, Computer, & Energy Engineering Department

Renewable & Sustainable Energy Institute

University of Colorado Boulder

EINDHOVEN UNIVERSITY OF TECHNOLOGY

Jan. – Aug. 2024

Control Systems Technology Group

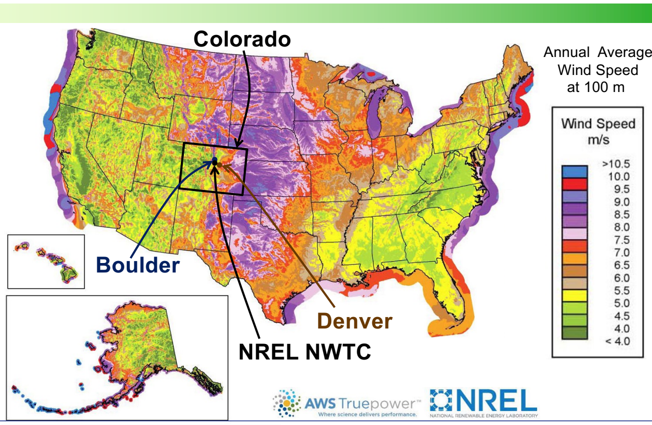
Mechanical Engineering Department

UNIVERSITY OF OXFORD one network

Seminar

13 February 2024

United States Wind Map

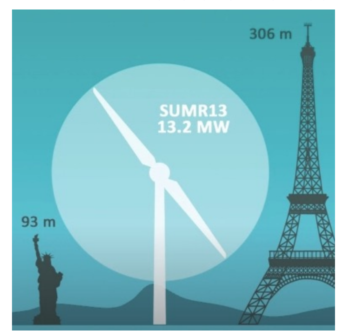


AWS Truepower NREL

Efficient Wind Energy Systems

Where are we now?

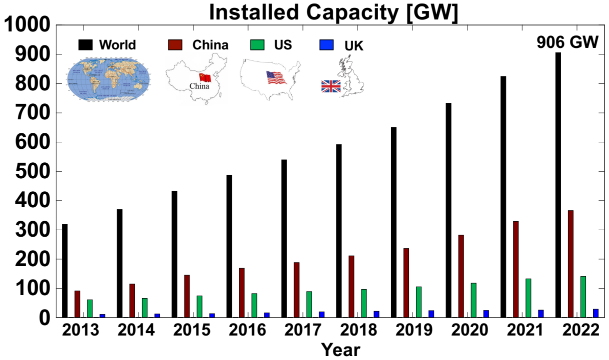
Where are we headed?



Growth of Wind Power

Since 2013, average annual growth of installed wind capacity has been:

- 12% globally
- 17% in China
- 9% in the US
- 13% in the UK



[data from irena.org, navigant.com, and US DOE Land-Based Wind Market Report (2023 edition)]

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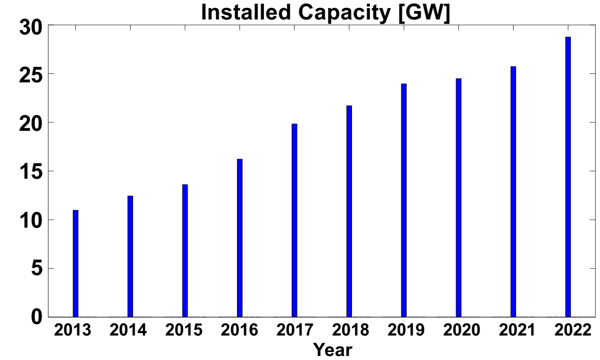

[data from gwec.net and irena.org]

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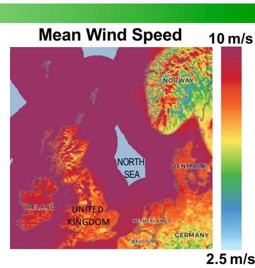

[from https://globalwindatlas.info]

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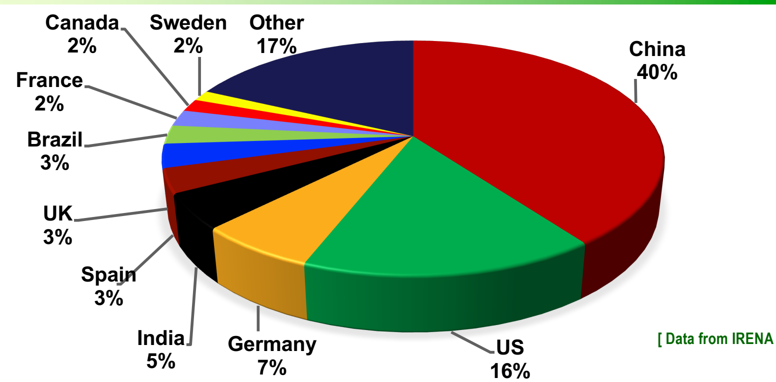
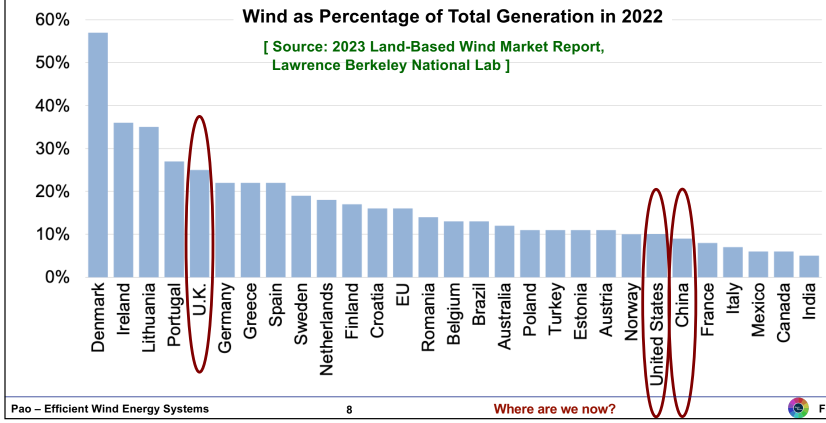
2022 Installed Wind Power Capacity by Country



[Data from IRENA]

Wind Energy Penetration



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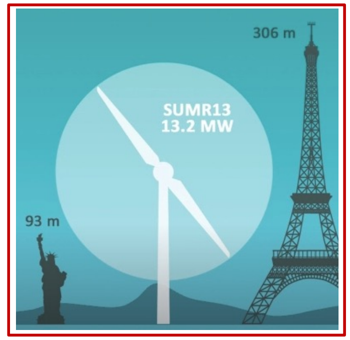


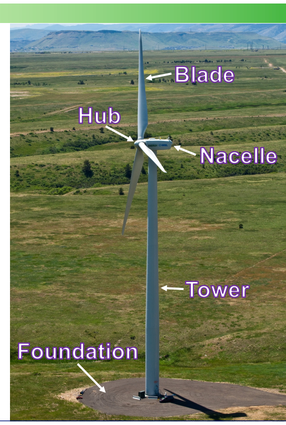
Land-Based Wind Turbines

DOE / NREL
1.5 MW Wind Turbine

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

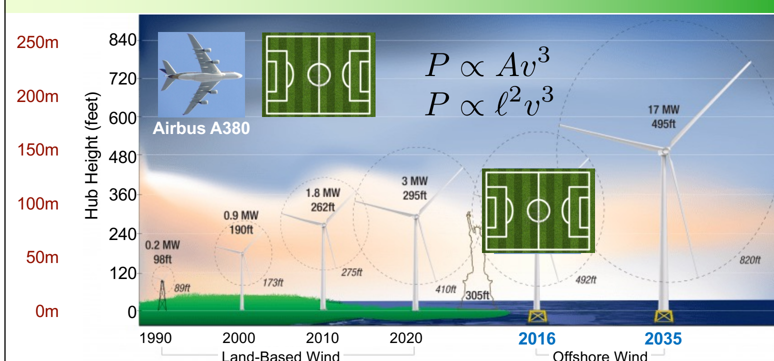
NWTC

wind



[Photo Credit:
Pat Corkery / NREL]

Increasing Wind Turbine Sizes



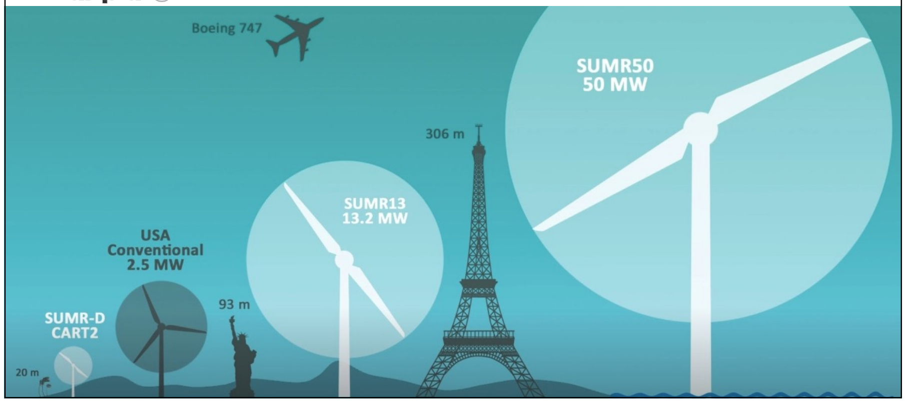
Wind Turbine Capacity (Megawatt) | Hub Height (feet)
Rotor Diameter (feet)

[from https://www.energy.gov/eere/articles/wind-turbines-bigger-better]

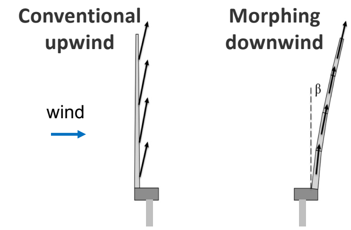
50 MW Segmented Ultralight Morphing Rotors (SUMR) for Wind Energy

[E. Loth, R. Damiani, D. T. Griffith, K. Johnson, N. Johnson, L. Pao, M. Selig]

arpa·e 2016 – 2022 [see www.SUMRwind.com for more information]



Segmented Ultralight Morphing Rotors (SUMR)



[Kirner, 2007]

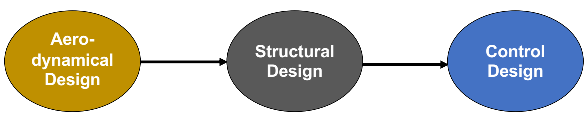
Morphing via downwind load alignment to:

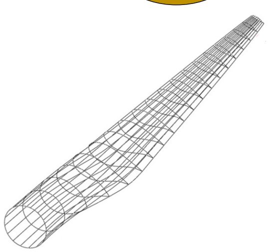
- Maximize capture area and power at low winds
- Minimize fatigue & failure at high operational winds

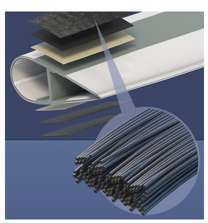
Morphing reduces cantilever loads which enables:

- **Blade segmentation** to reduce cost for fabrication, transport & assembly
- **Ultralight rotor mass** to reduce cost for fabrication, transport & assembly

Traditional Wind Turbine Design Process







[images from Lee, Jhan, & Chung, Composites: Part B, 2012; NREL; and brainline.org]

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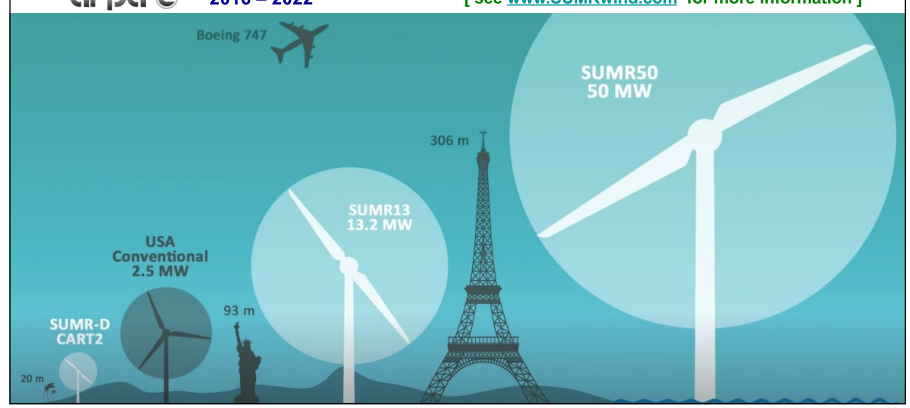
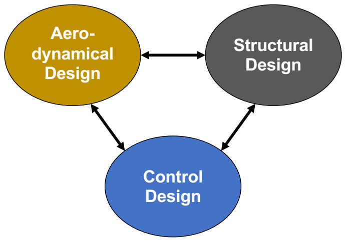
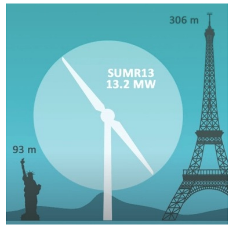


Wind Turbine Systems Engineering Co-Design





Design Goal: minimize Cost of Wind Energy

Result: 25% reduction in Cost of Wind Energy

[Pao, Zalkind, Griffith, Chetan, Selig, Ananda, Bay, Stehly, and Loth, *Annual Reviews in Control*, 2021]

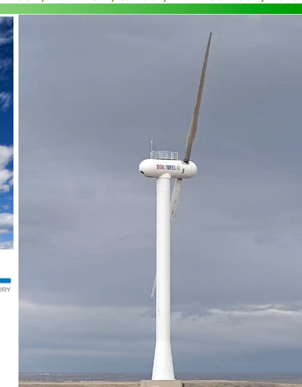
Design and Testing of a Scaled Demonstrator Turbine at the National Wind Technology Center

[Bay, Damiani, Fingersh, Chetan, Yao, Griffith, Ananda, Selig, Zalkind, Pao, Martin, Johnson, Kaminski, & Loth, *AIAA SciTech*, 2019]

[Photos courtesy of L. Fingersh]

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

- **Field testing campaign (November 2019 – August 2020)**



[Video courtesy of L. Fingersh]

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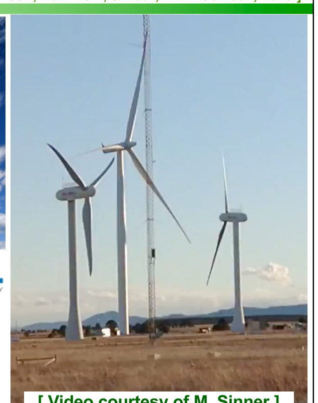


[Video courtesy of M. Sinner]

Advanced Wind Turbine Control Development

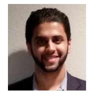
[Zalkind, Nicotra, & Pao, *Wind Energy,* 2022; Phadnis, Zalkind, & Pao, *Wind Energy,* 2023]

- **Key approach to decrease the cost of wind energy is to increase power production whenever possible while ensuring that structural loads are kept below desired thresholds**
- **Used field test results to improve our simulation models for this highly flexible wind turbine.**
  - **Developed advanced controller that can estimate and predict when wind conditions and structural loads are "steady" or "highly variable"**
    - If "steady" and "safe" conditions are predicted, greedier-control boosts power production.
    - If "highly variable" conditions are predicted, more conversative control may even de-rate power production as needed.

[Video courtesy of M. Sinner]

Collaboration with ForWind

❖ Planning to test this advanced controller in ForWind wind tunnel facility (Feb. – Mar. 2024)



Mandar Phadnis, DAAD research fellowship

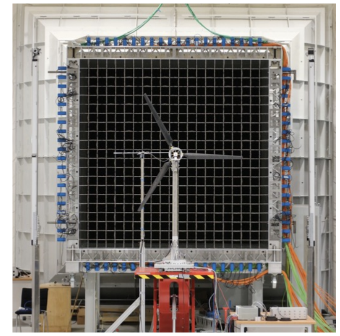
MoWiTO 1.8 = 1.8 m rotor diameter Model Wind Turbine Oldenburg

Collaboration with ForWind

❖ Planning to test this advanced controller in ForWind wind tunnel facility (Feb. – Mar. 2024)

❖ Less expensive than field testing

❖ Repeatable turbulent wind conditions can allow more thorough evaluation of controller



[Photos from Frederik Berger and Vlaho Petrović]

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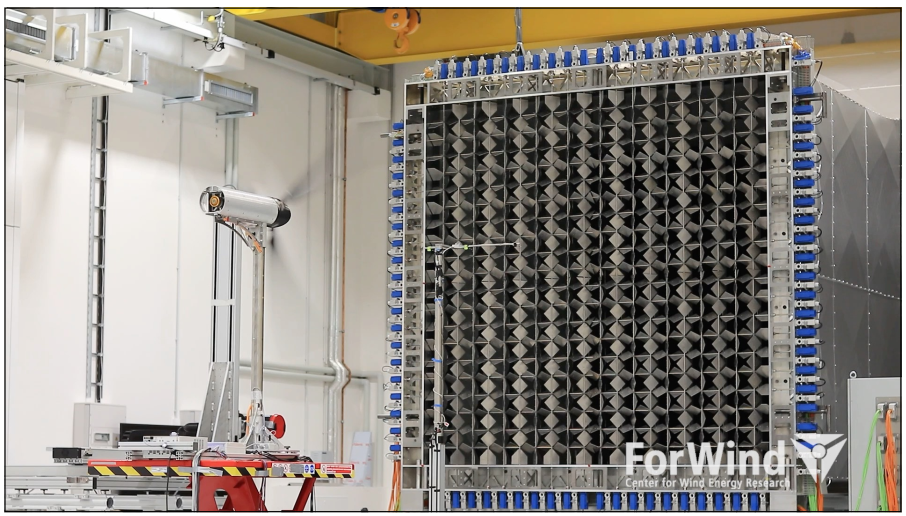

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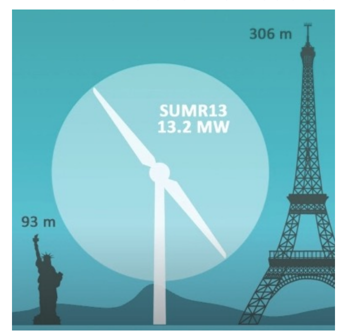
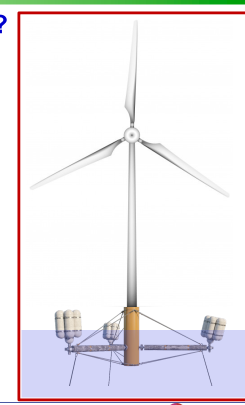
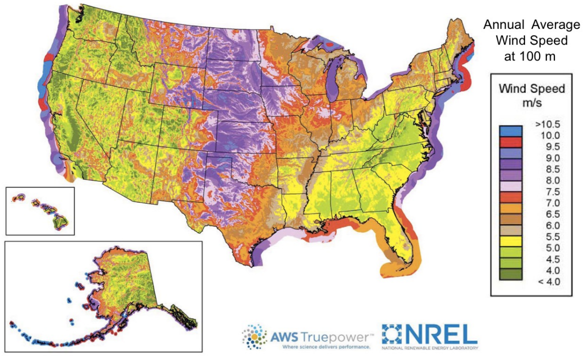




Interest in Offshore Wind Energy



- Stronger, more consistent winds offshore
- Coastal population centers
- Fewer limitations on turbine size

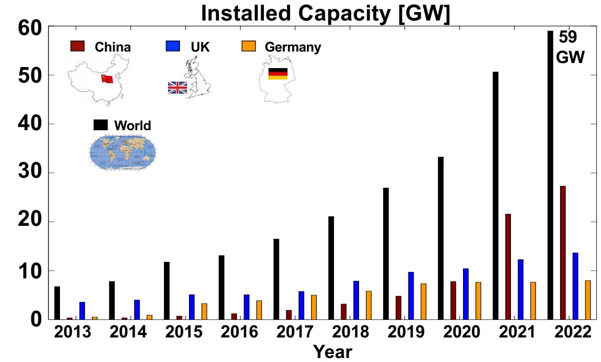
Total Global Wind: 906 GW (+12% annually)

Growth of Offshore Wind Power

Since 2013, average annual growth of installed offshore wind capacity is:

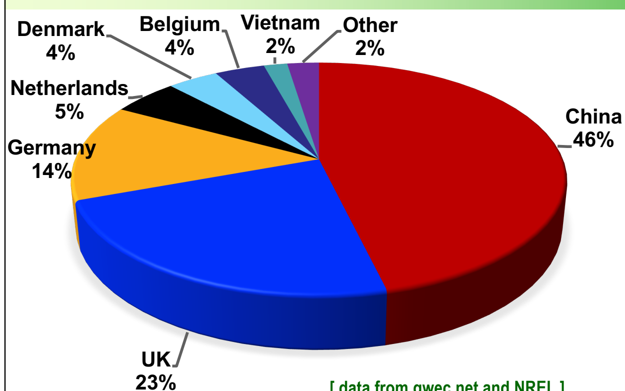
- 33% globally
- 63% in China
- 24% in the UK
- 78% in Germany

Percentage of total installed wind power capacity at end of 2022



[data from US DOE Offshore Wind Market Report: 2023 Edition]

2022 Installed Offshore Wind Power Capacity by Country

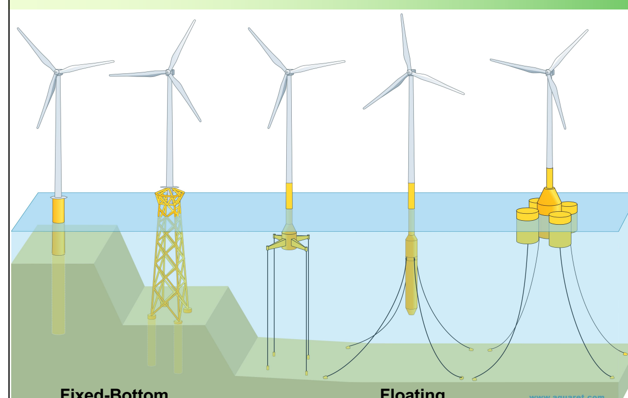


Other regions expected to have > 2 GW of offshore wind by 2026:

- US (> 5 GW)
- Taiwan (> 8 GW)
- South Korea (> 2 GW)

[data from gwec.net and NREL]

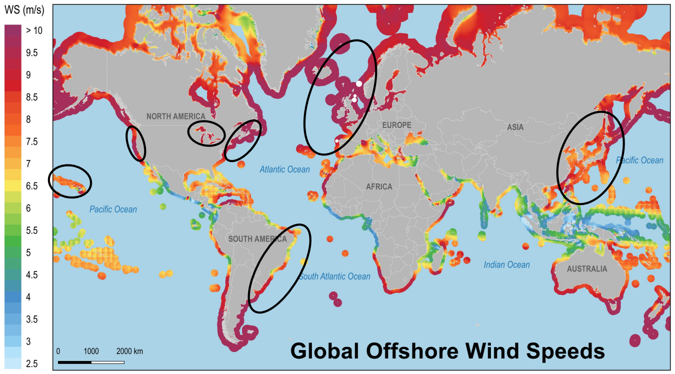
Offshore Wind Turbines



[Image from www.aquaret.com]

- In water depths of greater than ~60m, floating support structures may be more economical
  - Both wind and waves can cause oscillations …
  - Many control issues …

Worldwide Floating Offshore Wind Locations



Globally, majority of offshore wind resources are in water depths greater than 60m

There is currently only ~193 MW of installed floating wind power

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Wind Resource in the UK

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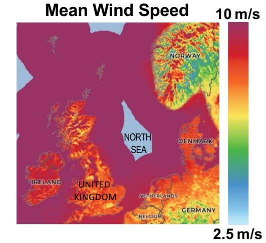

[from https://globalwindatlas.info]

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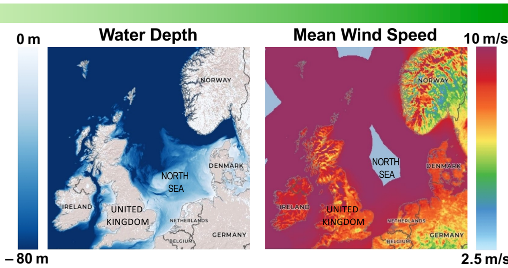
Wind Resource in the UK

UK currently has

- ~15 GW of onshore wind power capacity
- ~15 GW of shallow water offshore wind power capacity



[from https://globalwindatlas.info]

UK also has a lot of wind resources over deep water.

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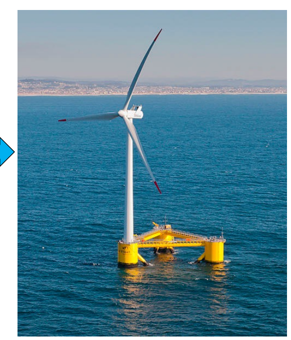
Initial Floating Offshore Wind Turbines (FOWTs)

[Photo from www.telegraph.co.uk/finance/newsbysector/energy/oilandgas/10978898/Life-on-an-oil-rig-in-pictures.html?frame=2980750]



[Image Source: jplourde umaine via North American Windpower]

- **Basic types of floating wind turbine platforms were derived from platforms used in the oil and gas industries**
  - Safe and relatively sturdy, but massive and expensive

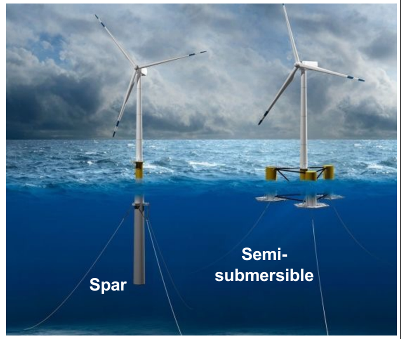
Hywind Scotland and Windfloat Atlantic Substructures

Hywind Scotland:
6.0 MW Turbines on Spars

[Photo by Brent Rice / NREL]

Windfloat Atlantic: 8.4 MW
Turbines on Semi-submersibles

[Photo from www.offshore-mag.com/renewable-energy/article/14188688/windfloat-atlantic-represents-major-offshore-wind-milestone]



[Illustration by J. Bauer, NREL]

Ultraflexible Smart FLoating Offshore Wind Turbine (USFLOWT)

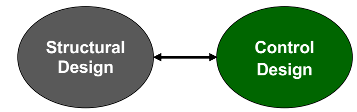
[S. Sirnivas, R. Damiani, K. Johnson, E. Loth, L. Pao]

arpa·e 2020 – 2022

[Wind Turbine Image from freepik.com

SpiderFLOAT Image Credit: J. Bauer, NREL]

- DTU 10 MW reference wind turbine
- Novel SpiderFLOAT substructure



- Structural-Control co-design
  - Minimize cost of SpiderFLOAT
    → Minimize mass

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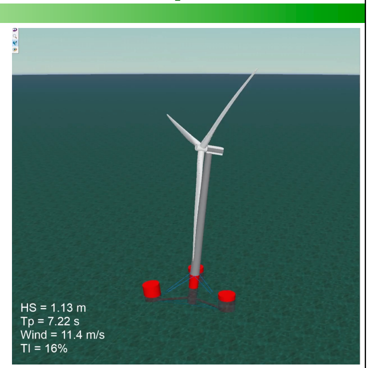
[Wind Turbine Image from freepik.com

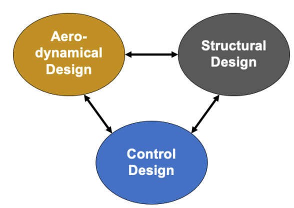
SpiderFLOAT Image Credit: J. Bauer, NREL]



[Courtesy of S. Sirnivas, simulation and animation generated using OrcaFlex]

Wind Energy with Integrated Servo-control (WEIS) Phase 2: Toolset to Enable Controls Co-Design of Floating Offshore Wind Energy Systems

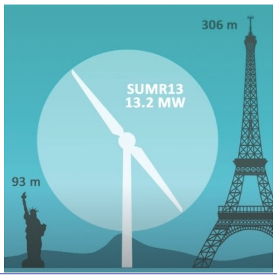
[D. Zalkind, J. Allison, D. Herber, L. Pao] arpa·e 2023 – 2025

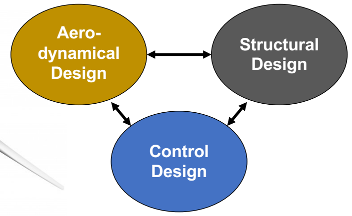


- Understand control co-design process
- Develop (semi-)automated controller tuning methods
  - Reference Open-Source Controller (ROSCO) released in 2021
  - Enable non-controls experts to explore different wind turbine designs
  - Allow controls experts to spend more time on developing advanced control methods for novel wind turbine concepts

Summary

- Aero-structural-control co-design with an interdisciplinary team can lead to better optimized wind turbine designs that reduce the cost of wind energy

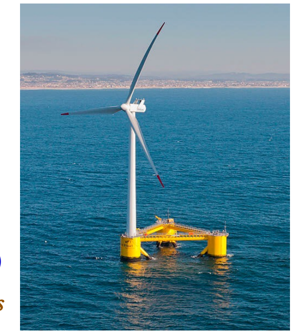




Summary

- Floating offshore wind installations expected to grow rapidly over the next several decades
  - Cost of floating offshore wind energy expected to decrease to similar levels as fixed-bottom wind energy
- Active research in trying to minimize cost of floating platform substructure
- Control Group seminar tomorrow (2pm, IEB LR8)

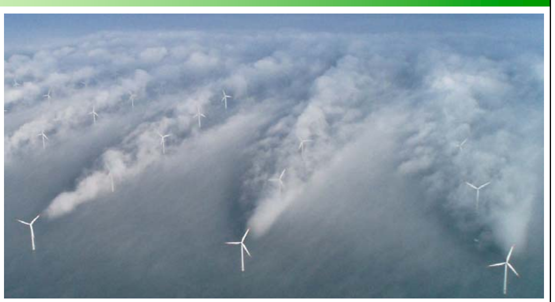
Sink or Swim: Control of Floating Offshore Wind Turbines



[Image Source: jplourde umaine via North American Windpower]

On-Going and Future Work

- Control of wind farms
  - Wind turbines interact with one another via their wakes
  - Coordinating the control of the individual wind turbines can lead to higher wind farm power production
  - How do wakes propagate behind floating offshore wind turbines?



Horns Rev 1 Shallow-Water Wind Farm, Denmark
[Photo credit: Christian Steiness]

On-Going and Future Work

- For floating offshore wind farms, would it be advantageous to control the turbines in such a way as to move them translationally to alter the layout of the wind farm to mitigate wake effects?

[Illustration by J. Bauer, NREL]

Acknowledgments

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Acknowledgments

SUMR
Project Team


August 2018

Acknowledgments

USFLOWT
Team

Mario Garcia-Sanz
Senu Sirnivas
Rick Damiani
Katie Johnson
Eric Loth


May 2022, ARPA-E Summit

Acknowledgments

Recent/Current Wind Energy Research Group

Mandar Phadnis (is at Uni Oldenburg until Apr 2024 on DAAD Research Exchange)

Nikhar Abbas (PhD 2022, received European Academy of Wind Energy's 2023 Excellent Young Doctor Award, now at SGRE)


Oct. 2021

Aoife Henry

David Stockhouse

Manuel Pusch (Postdoc 2021-2022, now Professor at Munich University of Applied Sciences)

Thank You!

Seminar

13 February 2024