A new approach to wind energy

John O. Dabiri
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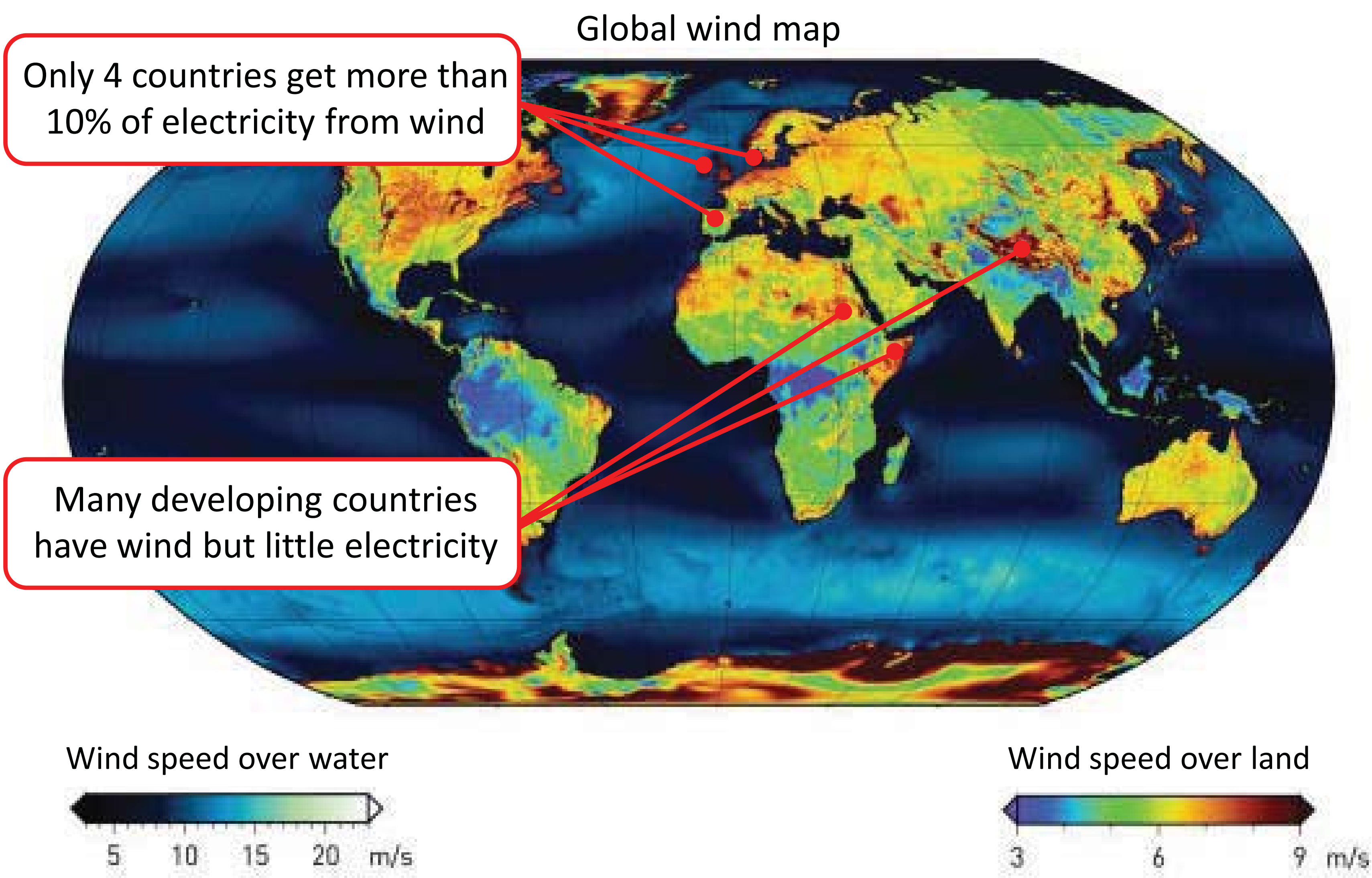
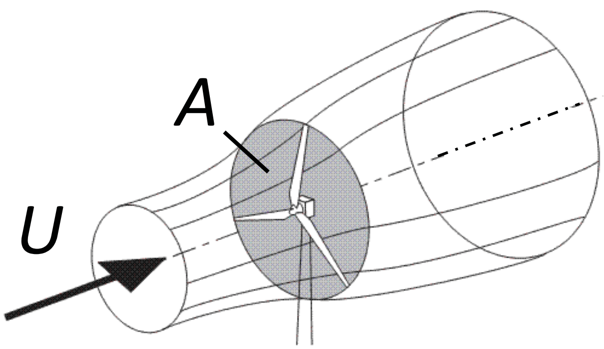
Our goal: *Develop wind energy technologies that match the global reach of the wind itself*



3Tier, Inc.

Evaluating Wind Energy Technologies

Turbine efficiency



$$C_p = \frac{P}{½\rho A U^3}$$

Wind farm power density

$$PD = \frac{P_{WF}}{A_{WF}}$$

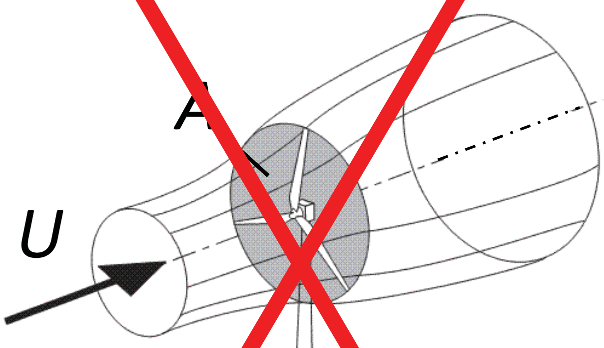
Cost of electricity

$

$$LCOE = \frac{¢}{kWh}$$

Evaluating Wind Energy Technologies

Turbine efficiency



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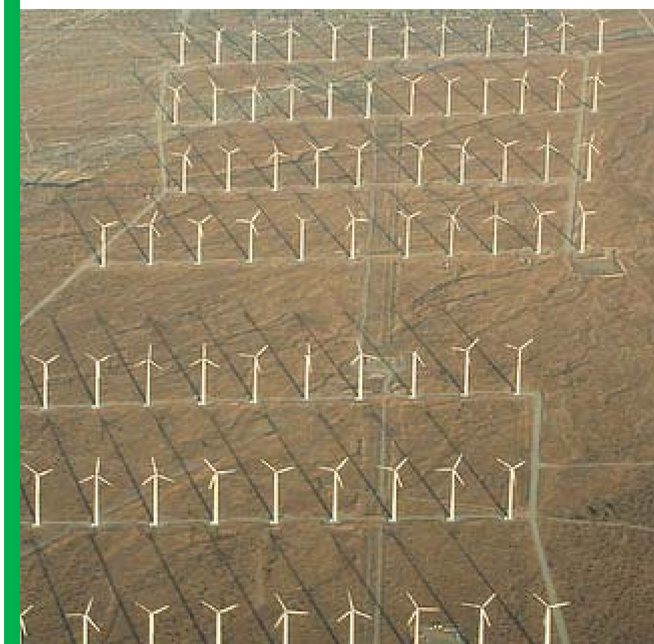


$$PD = \frac{P_{WF}}{A_{WF}}$$

Cost of electricity

\$

$$LCOE = \frac{¢}{kWh}$$

From closer spacing…to lower cost?

Closer turbine spacing can be used to achieve…

↓

More efficient wind farms, which can generate sufficient power using…

↓

Smaller wind turbines, which can achieve on a per-watt basis…

↓

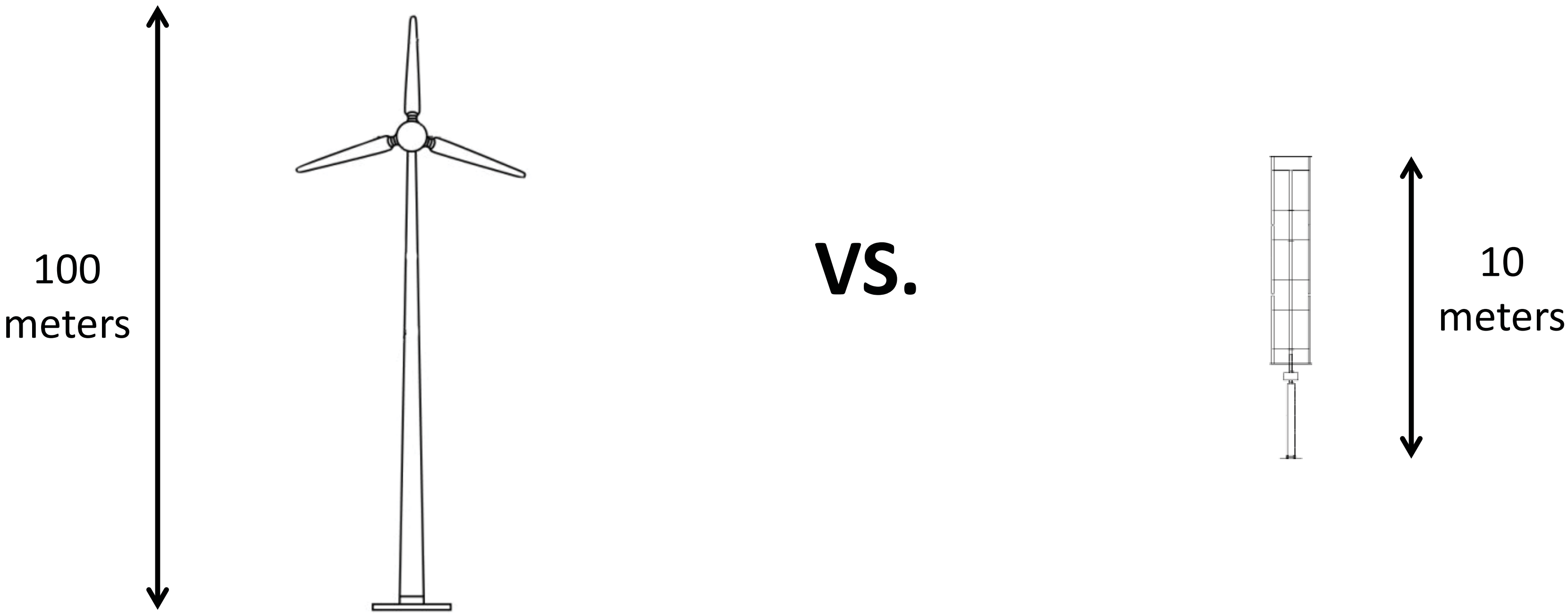
Lower costs for materials, manufacturing, installation, O&M

↓

LOWER COST OF ENERGY

Evaluating Wind Energy Technologies

The usual starting point: *turbine efficiency*



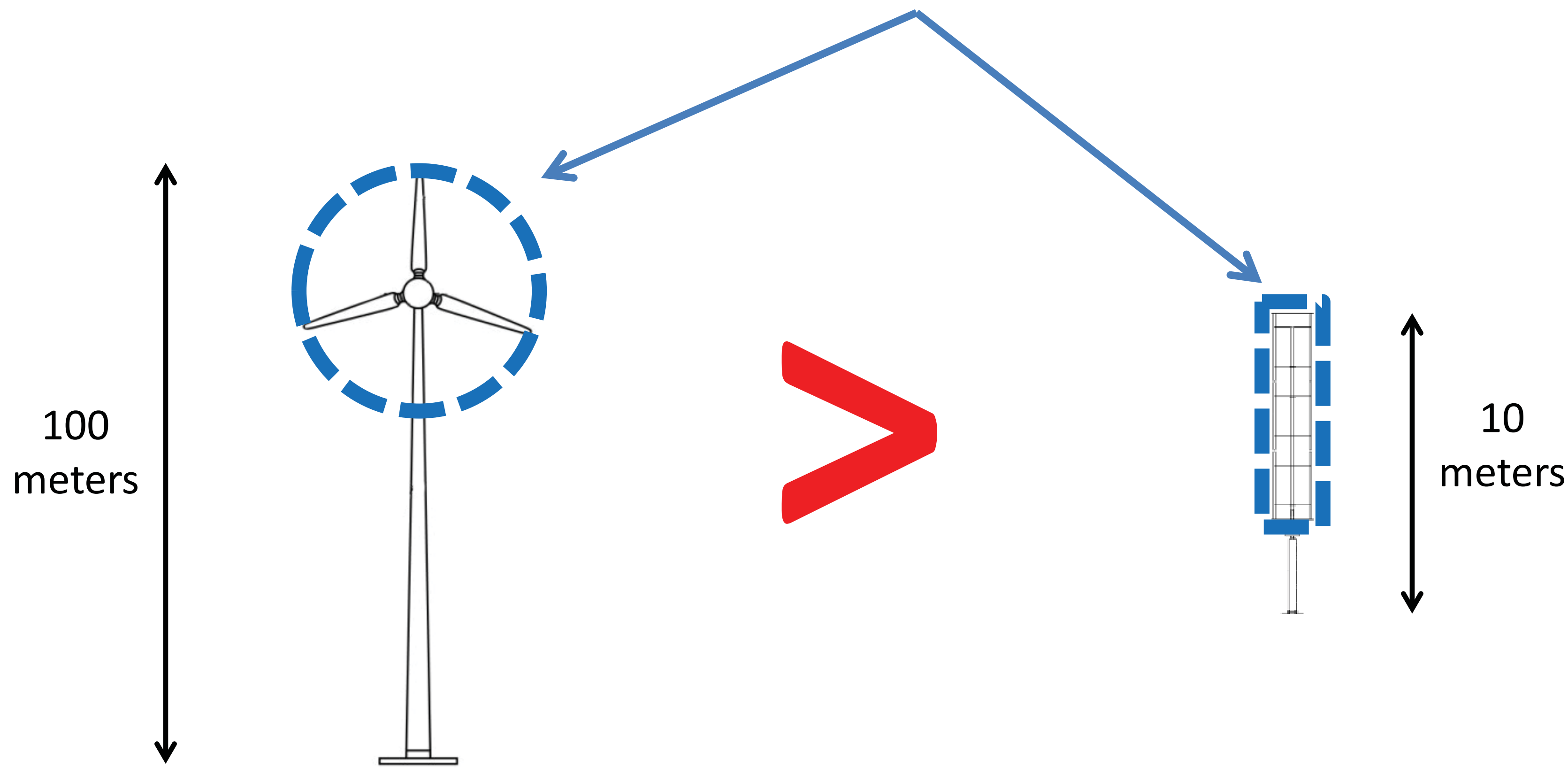
Horizontal-axis wind turbine
(HAWT)

Vertical-axis wind turbine
(VAWT)

Evaluating Wind Energy Technologies

The usual starting point: *turbine efficiency*

What fraction of wind energy flux through the swept area is converted to electricity?



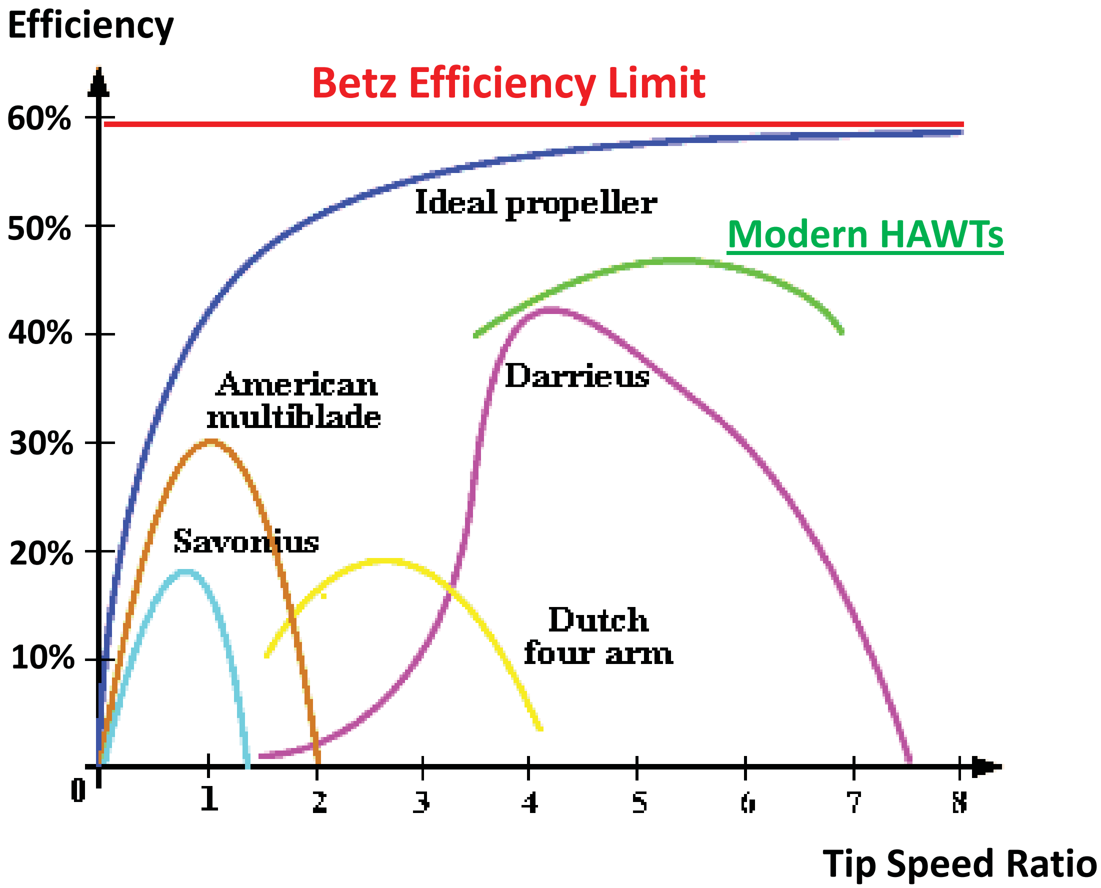
Horizontal-axis wind turbine (HAWT)

Vertical-axis wind turbine (VAWT)

Evaluating Wind Energy Technologies

The usual starting point: *turbine efficiency*

*What is the **maximum** fraction of wind energy flux through the swept area that can be converted to electricity?*



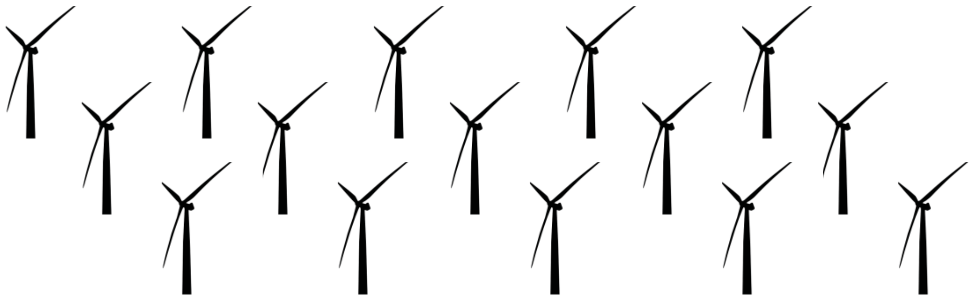
Modern HAWTs approach theoretical maximum efficiency

Is there room for fundamental improvement in wind energy?

netfirms.com

Evaluating Wind Energy Technologies

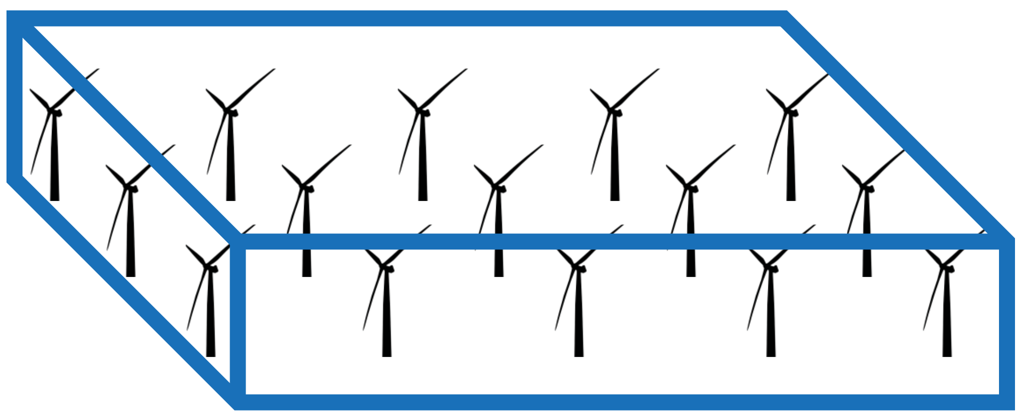
Our starting point: *wind resource utilization*



Evaluating Wind Energy Technologies

Our starting point: *wind resource utilization*

What fraction of wind energy flux into the wind farm volume is converted to electricity?



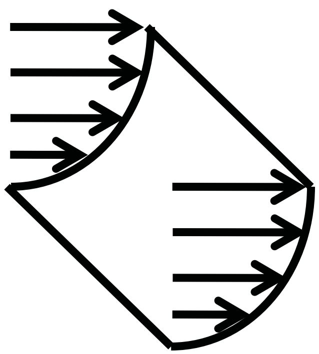
Evaluating Wind Energy Technologies

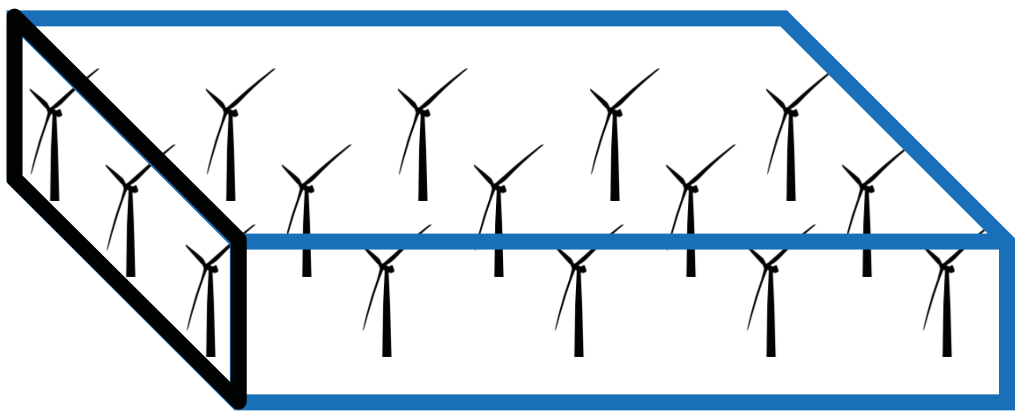
Our starting point: *wind resource utilization*

What fraction of wind energy flux into the wind farm volume is converted to electricity?

Frontal kinetic energy flux

$P_{horz} = ½\rho A_{frontal}U^3$





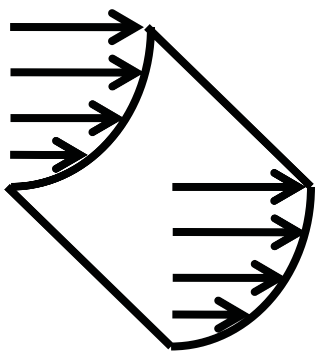
Evaluating Wind Energy Technologies

Our starting point: *wind resource utilization*

What fraction of wind energy flux into the wind farm volume is converted to electricity?

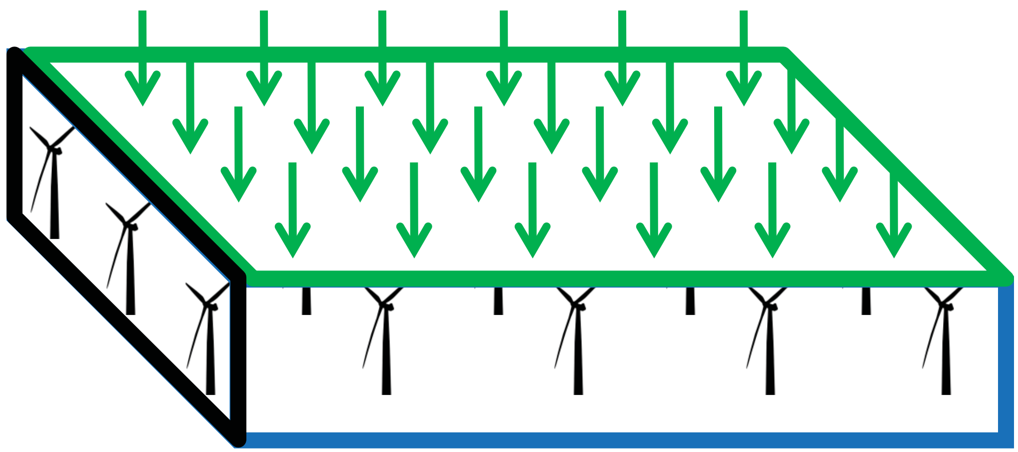
Frontal kinetic energy flux

$P_{horz} = \frac{1}{2}\rho A_{frontal} U^3$



Planform kinetic energy flux

$P_{vert} \approx -\rho A_{planform} U \langle u'w' \rangle$

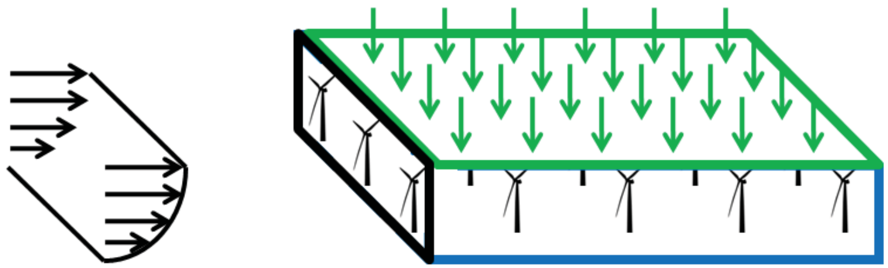


Turbulence velocity fluctuations u' (streamwise) and w' (wall-normal)

Ensemble average $\langle \bullet \rangle$

The planform kinetic energy flux ($\rho A_{planform} U \langle u'w' \rangle$)…

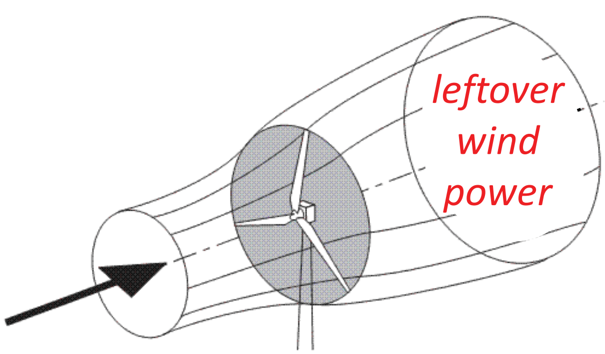
1. is the primary power source for most turbines in large-scale wind farms (Cal et. al. 2010)

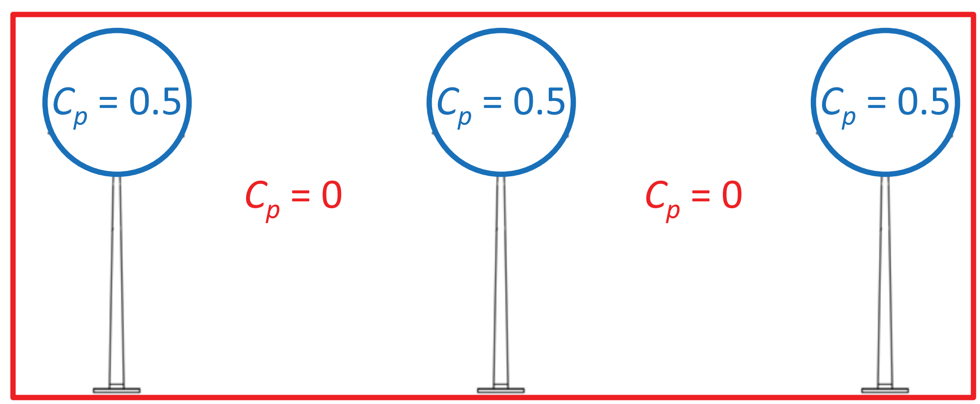


2. supersedes the Betz limit as the relevant constraint on wind farm performance

   WHY?

   - The Betz calculation does not account for wind power in the turbine wake that is extracted by neighboring turbines
   - The Betz calculation does not account for wind power that is not extracted in the region between turbines



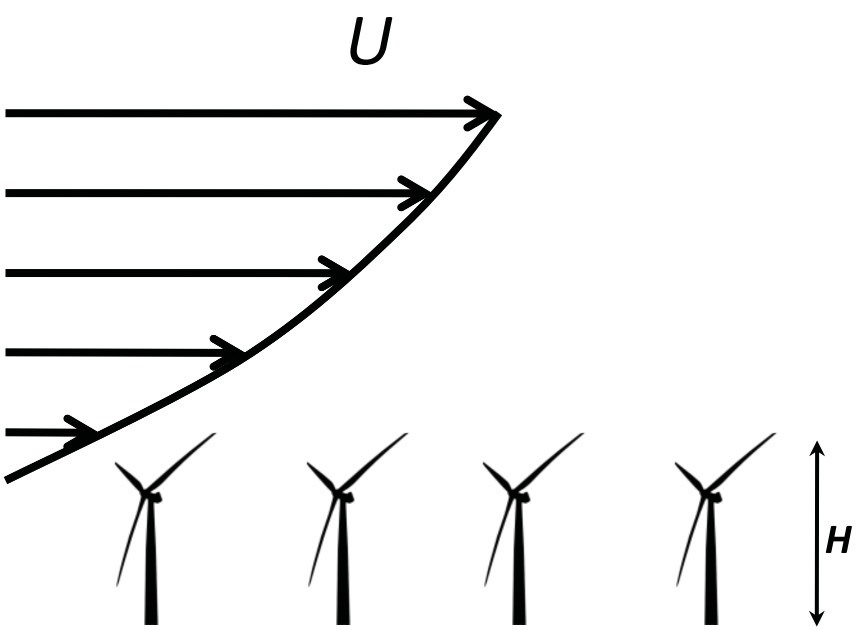


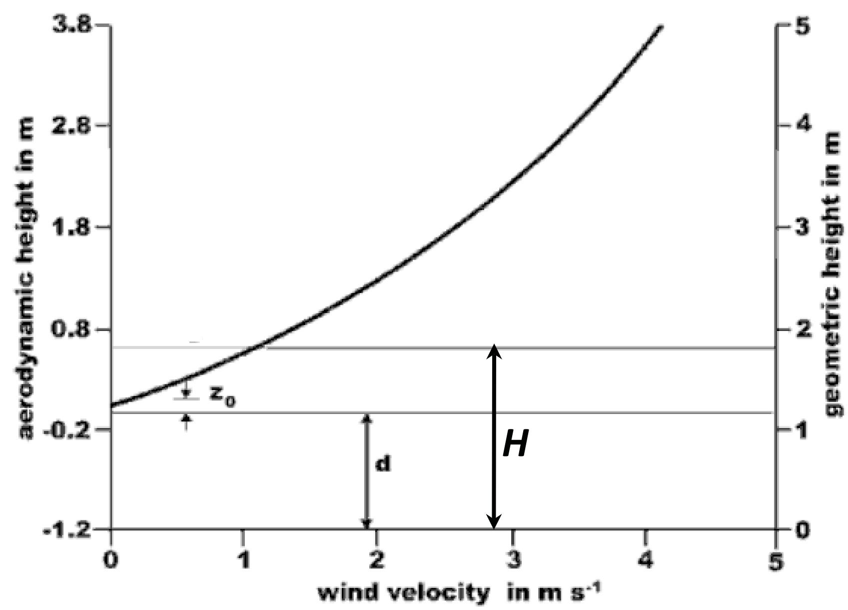
Modelling the planform flux limit

$$P_{vert} \approx -\rho A_{planform} U \langle u'w' \rangle$$

Assume log wind profile: $-\langle u'w' \rangle = u_*^2 = \left[\frac{U\kappa}{\ln[(z-d)/z_0]} \right]$

friction velocity, u_*
von Karman constant, $\kappa \approx 0.4$
zero plane displacement, $d \approx 2H/3$
roughness length, $z_0 \approx H/10$





Foken 2008

Modelling the planform flux limit

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friction velocity, u_*
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zero plane displacement, $d \approx 2H/3$
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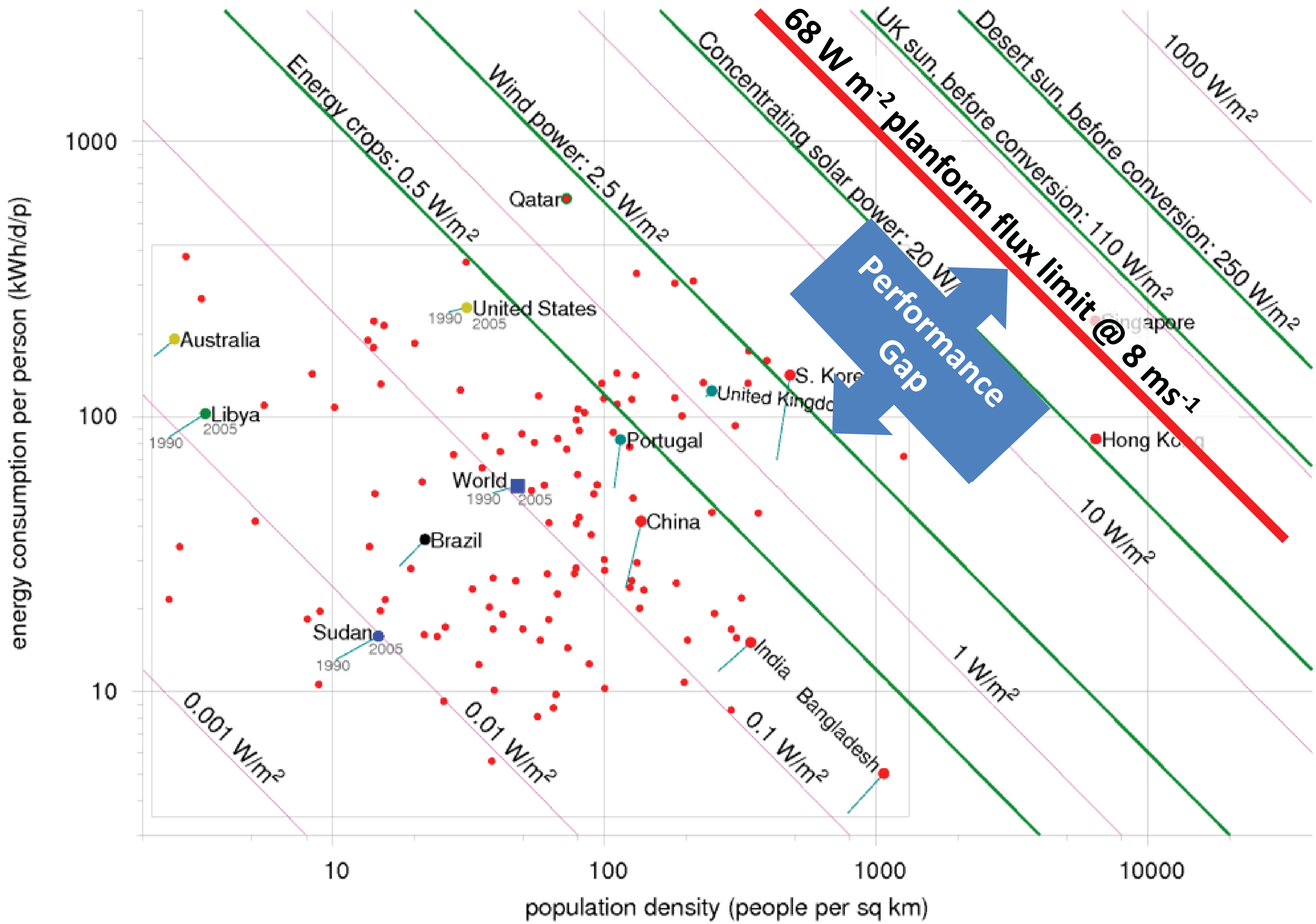
The energy flux through the top of a wind farm is
68 watts per square meter in **8 m/s** mean wind speed

How do existing wind farms compare to this upper limit? 2.5 versus 68 W m^{-2}

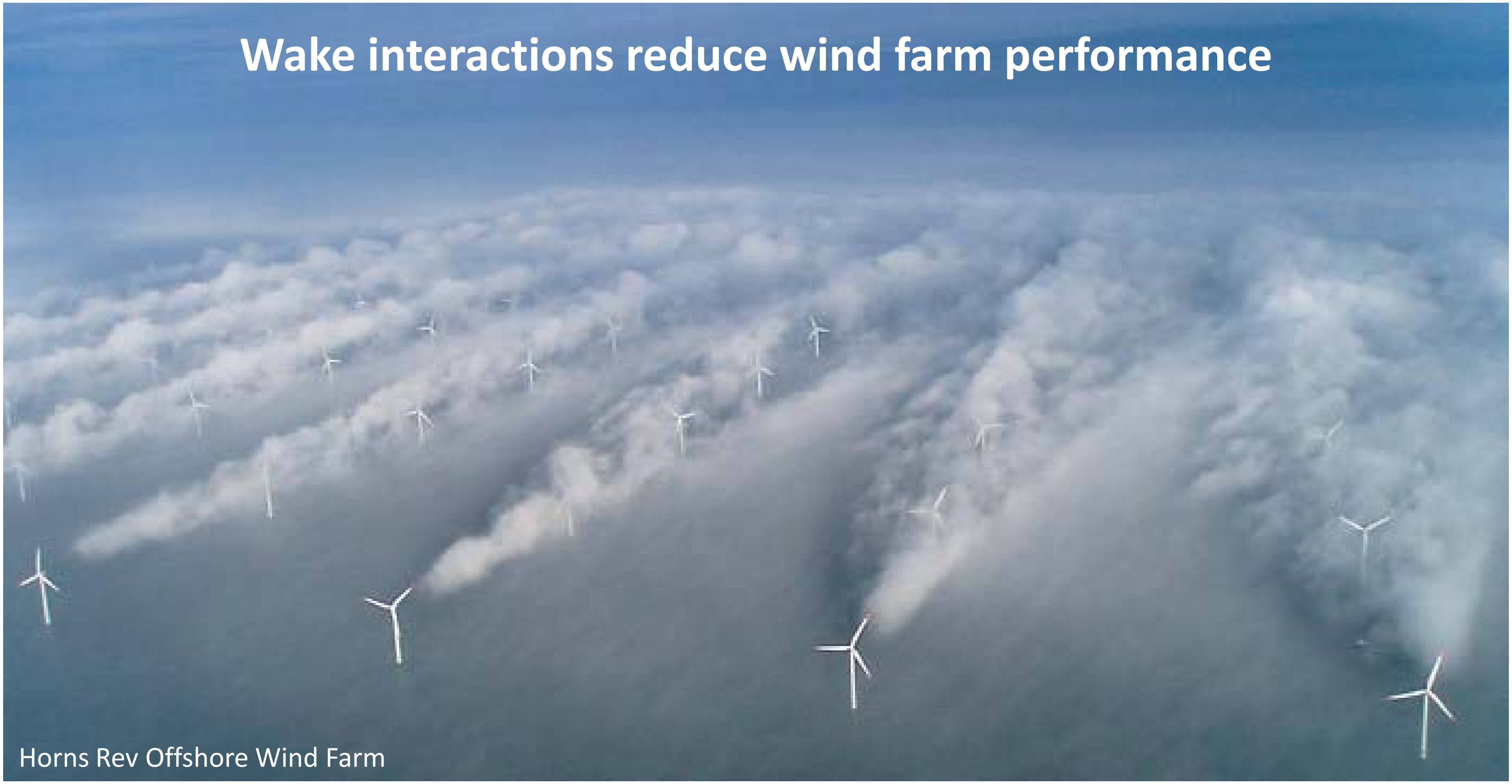


DJC Mackay 2010

2.5 versus 68 W m^{-2}

Whereas modern wind turbines achieve power coefficients that approach the theoretical maximum, ***existing <u>wind farm</u> performance remains far below the flux limit***

Why?



2.5 versus 68 W m^{-2}

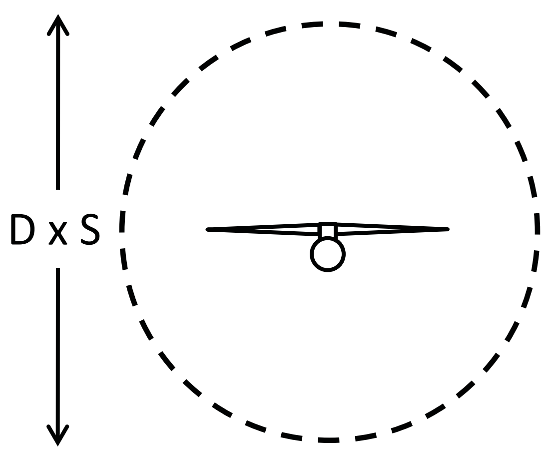
Whereas modern wind turbines achieve power coefficients that approach the theoretical maximum, ***existing wind farm performance remains far below the flux limit***

Why?

Turbine spacing requirements directly affect wind farm power density

Power Density Calculation

$$PD = \frac{4 \times \text{rated power} \times \text{capacity factor}}{\pi\,(\text{turbine diameter} \times \text{turbine spacing})^2}$$



For ***six-diameter*** *average turbine spacing and 30% capacity factor…*

Turbine #1 (2.5 MW, 100 m dia.): **PD = 2.7 W/m^2**

Turbine #2 (3.0 MW, 112 m dia.): **PD =2.5 W/m^2**

If turbine spacing is reduced to ***four diameters****…*

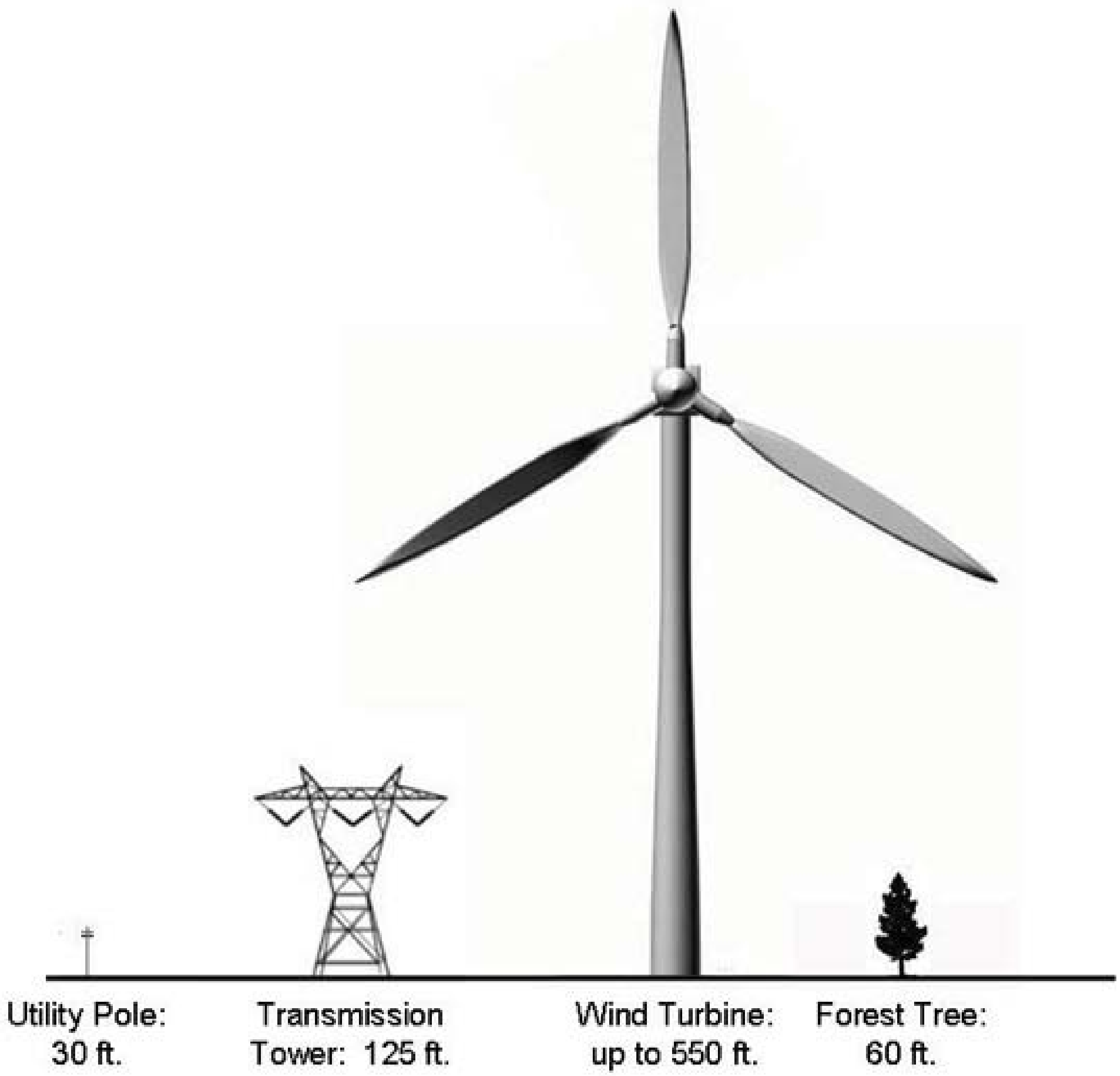
Turbine #1 (2.5 MW, 100 m dia.): **PD = 6.0 W/m^2**

Turbine #2 (3.0 MW, 112 m dia.): **PD =5.7 W/m^2**

i.e. power density is more than doubled.

Additional challenges for conventional wind energy

- Structure size, associated design requirements and materials costs



johnrsweet.com

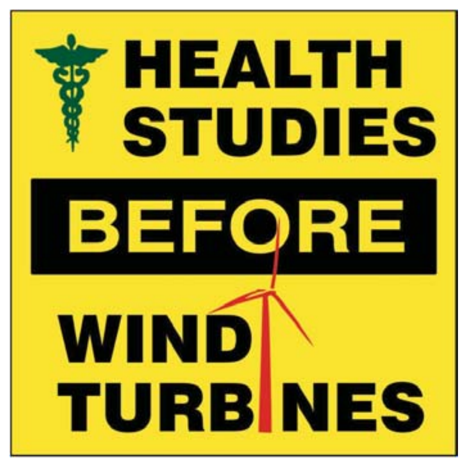
Additional challenges for conventional wind energy

- Structure size, associated design requirements and materials costs
- Logistics of installation and maintenance

Paul
Anderson

Additional challenges for conventional wind energy

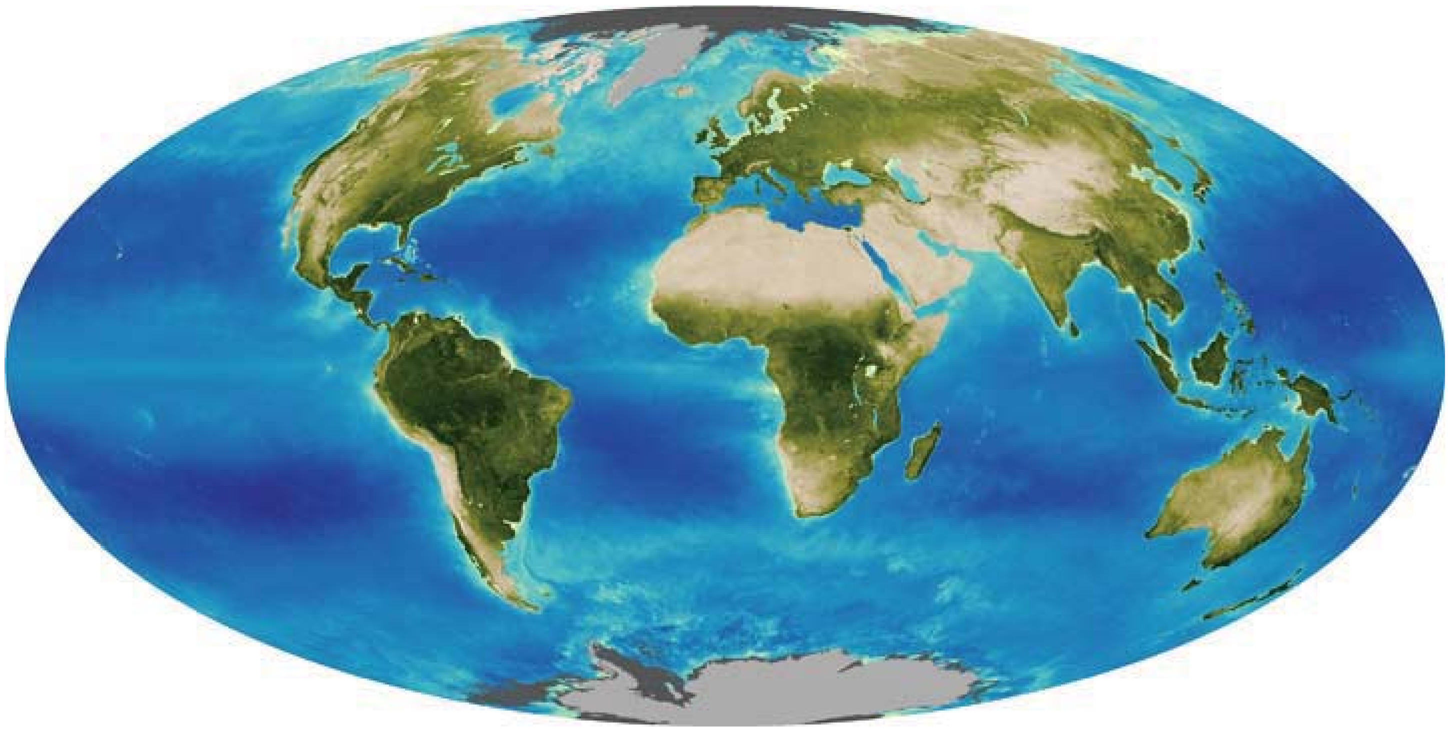
- Structure size, associated design requirements and materials costs
- Logistics of installation and maintenance
- Societal acceptance
  - impact on birds/bats
  - visual signature
  - acoustic signature
  - radar signature



Google Images

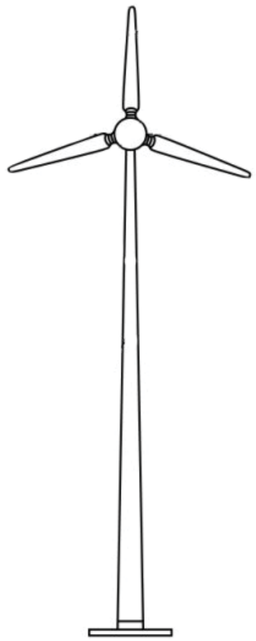
Additional challenges for conventional wind energy

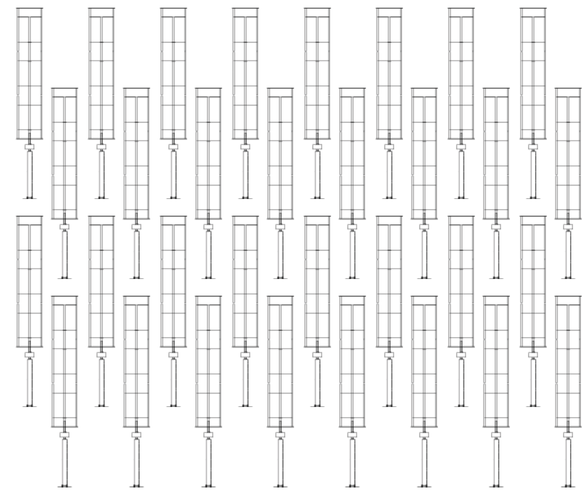
- Structure size, associated design requirements and materials costs
- Logistics of installation and maintenance
- Societal acceptance
- Access in the developing world → limited infrastructure



Google Images

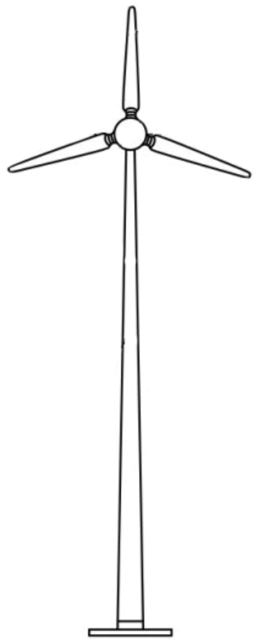
A new approach: Optimized arrays of smaller **vertical-axis** wind turbines

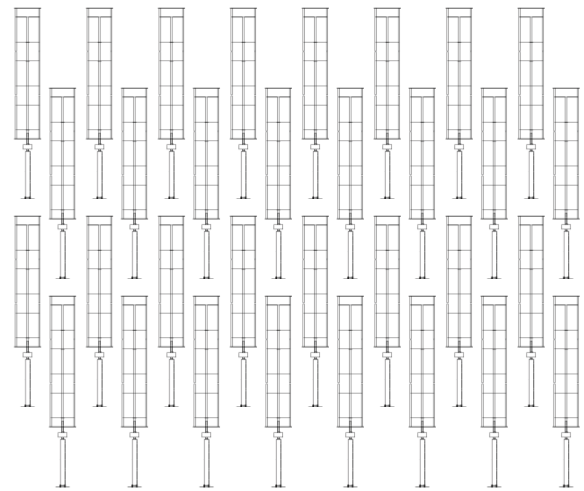




- **Smaller** structure size, materials costs, and wind farm signatures
- **Simpler** logistics of installation, operations, and maintenance
- **Scalable** from distributed to utility power
- **Safer** for birds and bats

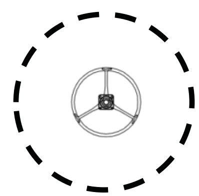
A new approach: Optimized arrays of smaller **vertical-axis** wind turbines





Power Density Calculation Revisited

$$PD = \frac{4 \times \text{rated power} \times \text{capacity factor}}{\pi\,(\text{turbine diameter} \times \text{turbine spacing})^2}$$

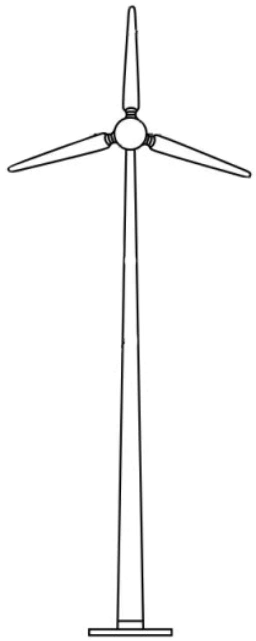


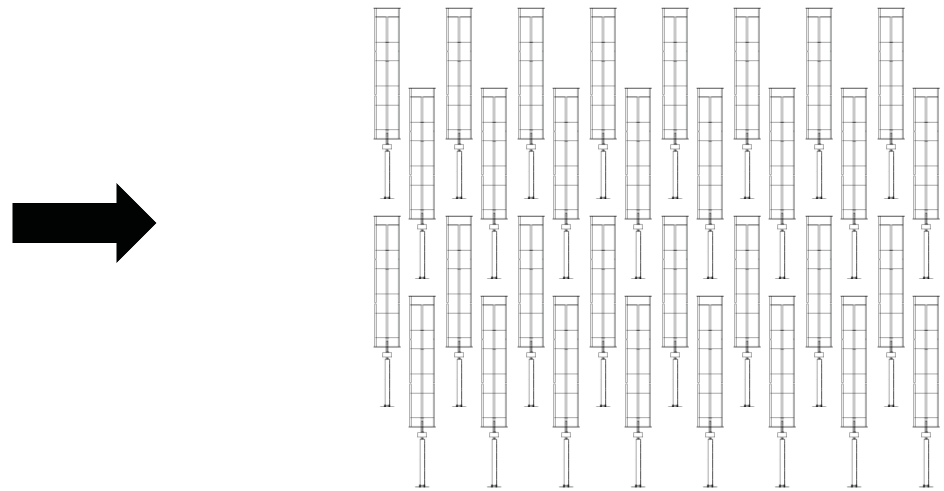
For six-diameter average turbine spacing and 30% capacity factor…

Windspire Energy VAWT
0.0012 MW, 1.2 m dia.
PD = 8.8 W/m²

3X power density at 1/10 HAWT height!

A new approach: Optimized arrays of smaller **vertical-axis** wind turbines

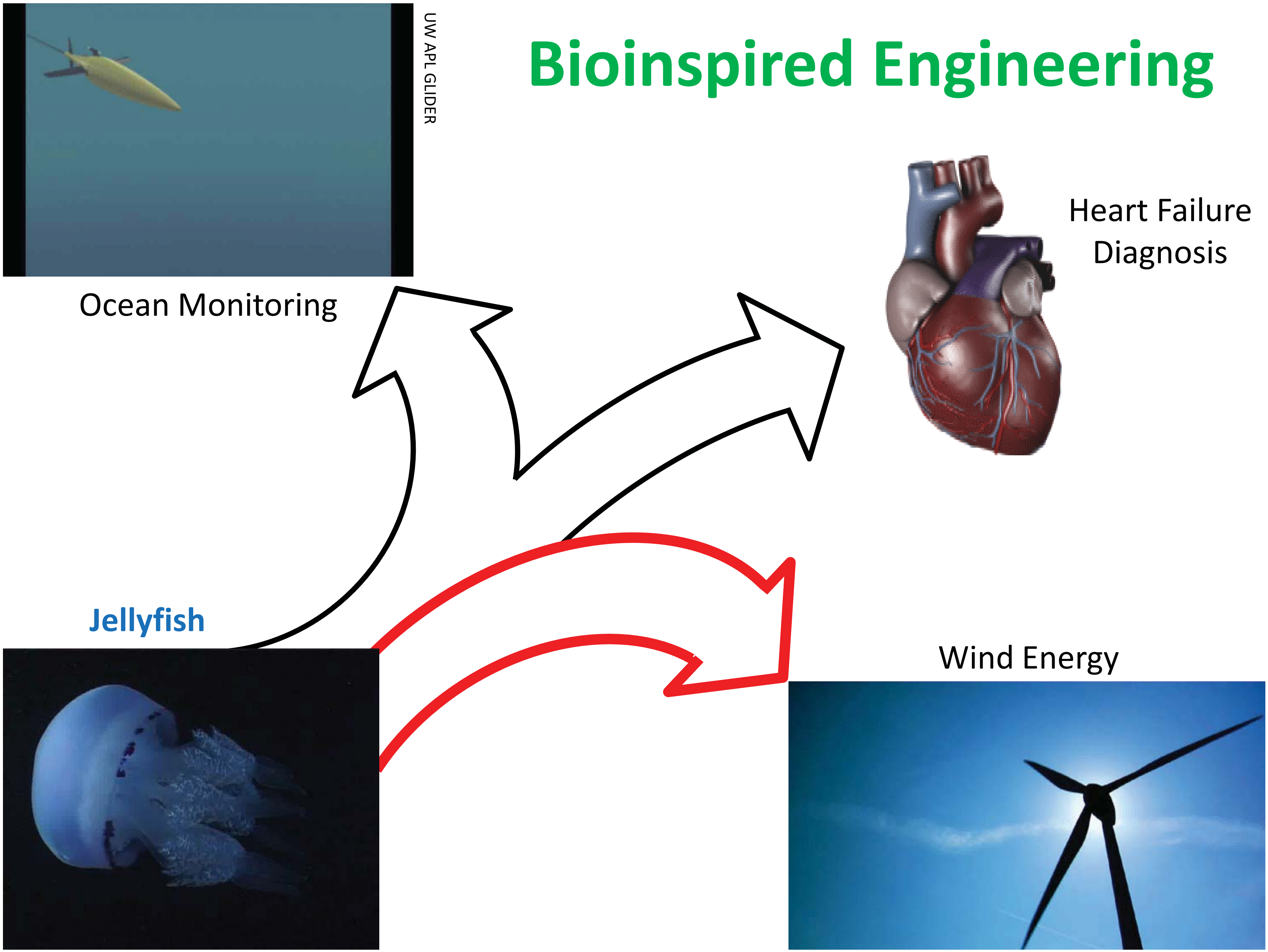




150 Megawatt Wind Farm Comparison

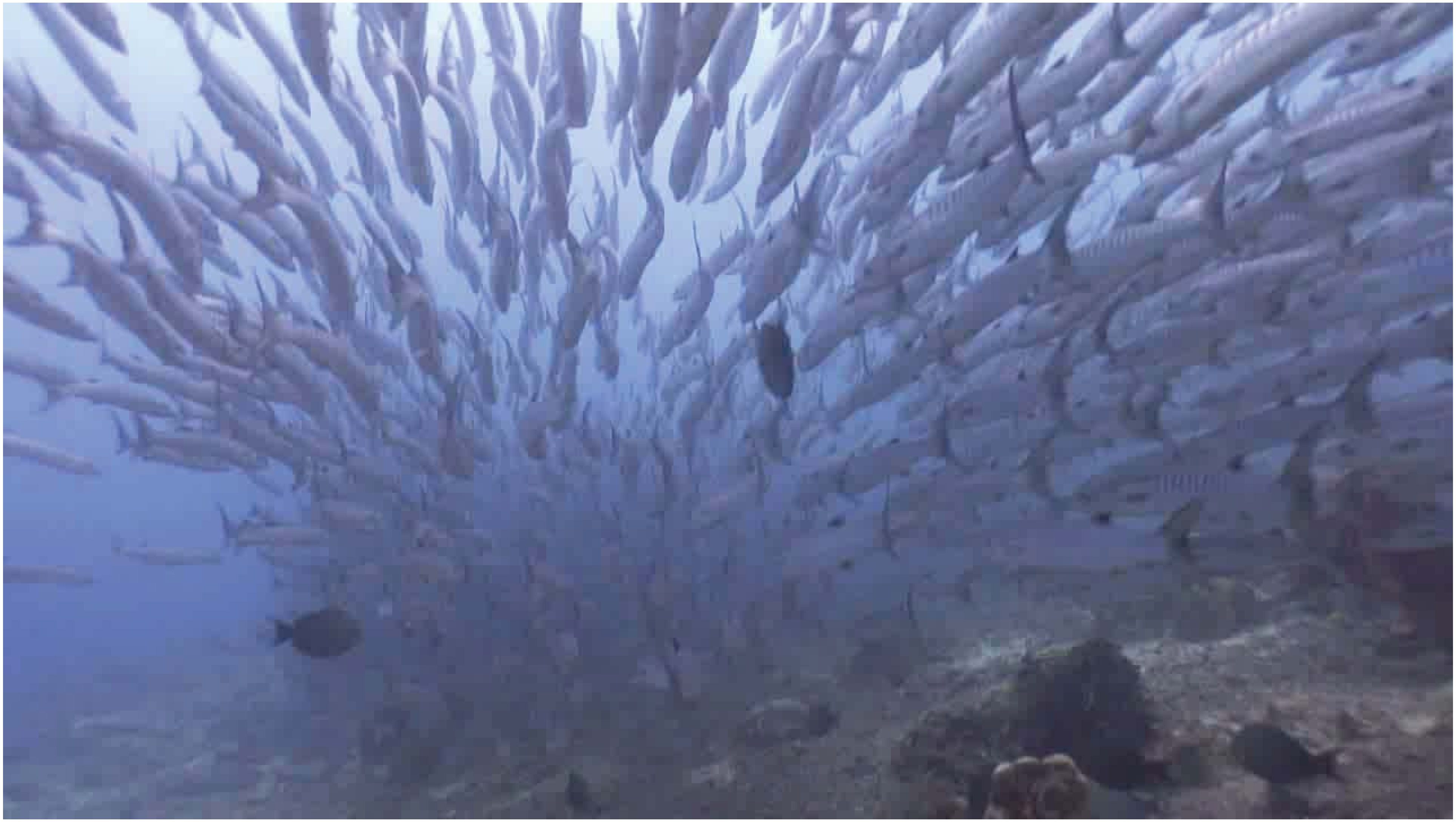
	HAWT	VAWT
Turbine capacity	1.5 MW	3.0 kW
Number of turbines	100	50,000
Wind farm footprint (6D spacing)	77 square km	18 square km
Wind farm footprint (4D spacing)	N/A	**8 square km**

What is the optimal arrangement of VAWTs in a wind farm?


Bioinspired Engineering
UW APL GLIDER
Ocean Monitoring
Heart Failure Diagnosis
Jellyfish
Wind Energy

What is the optimal arrangement of VAWTs in a wind farm?

Biological inspiration: ***Fish Schooling***



Triantafyllou et al. (1995)

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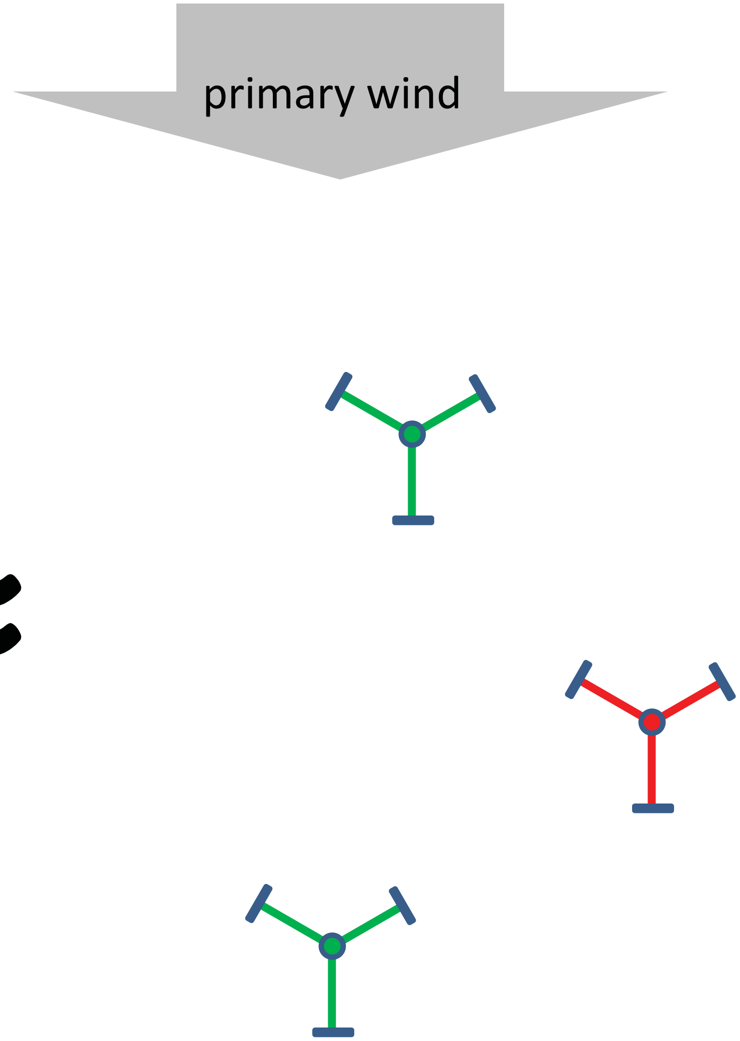
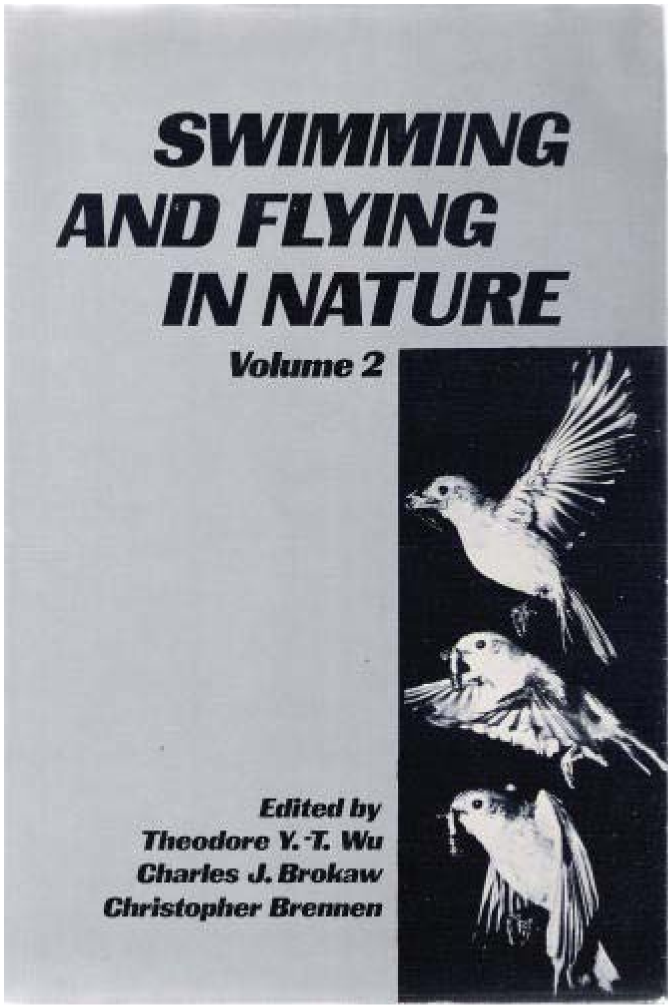
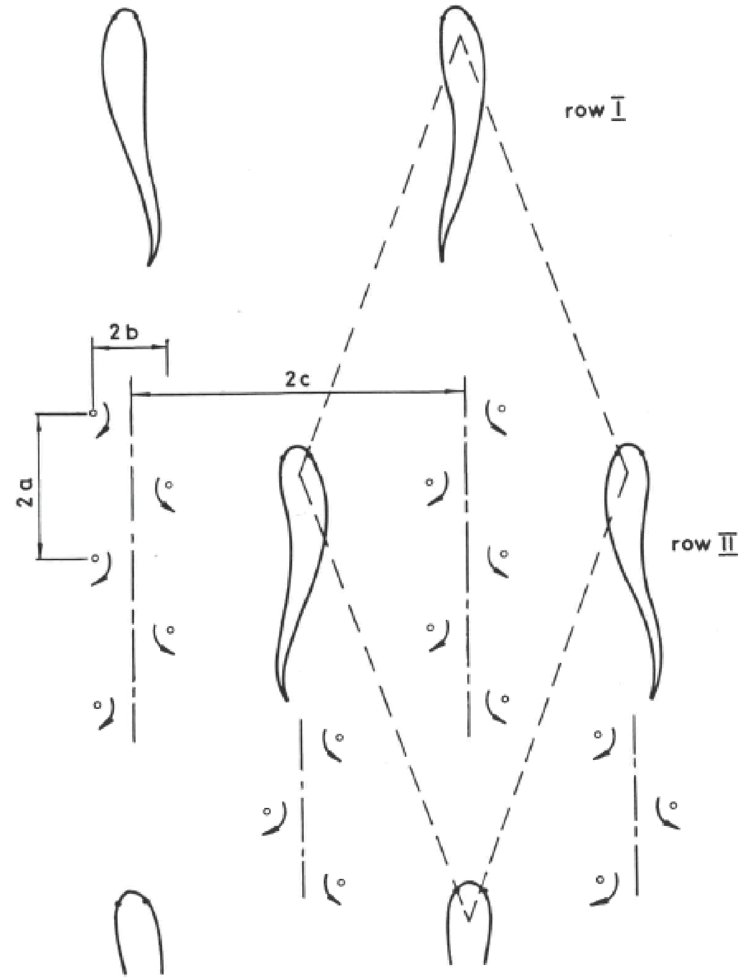


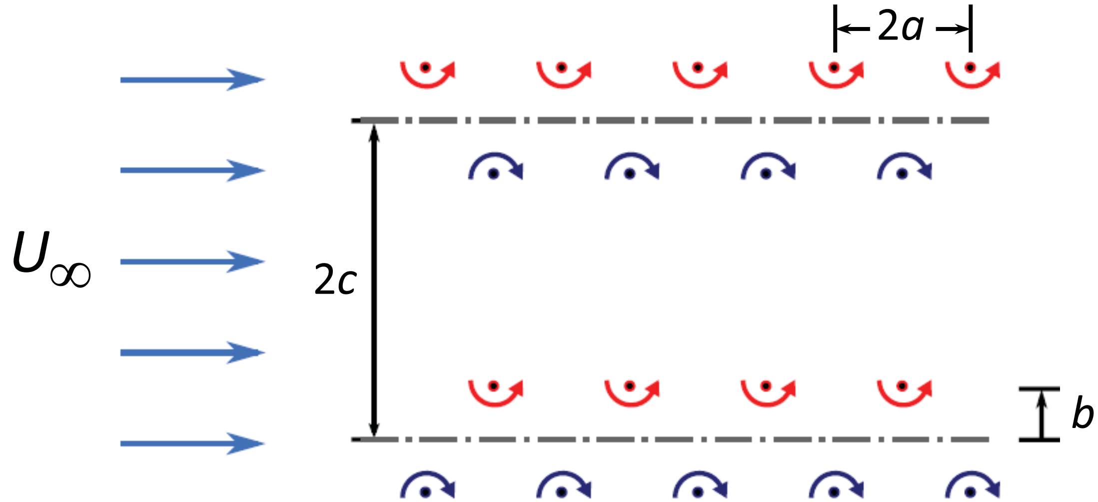
'Optimal' fish schooling provides our starting point…



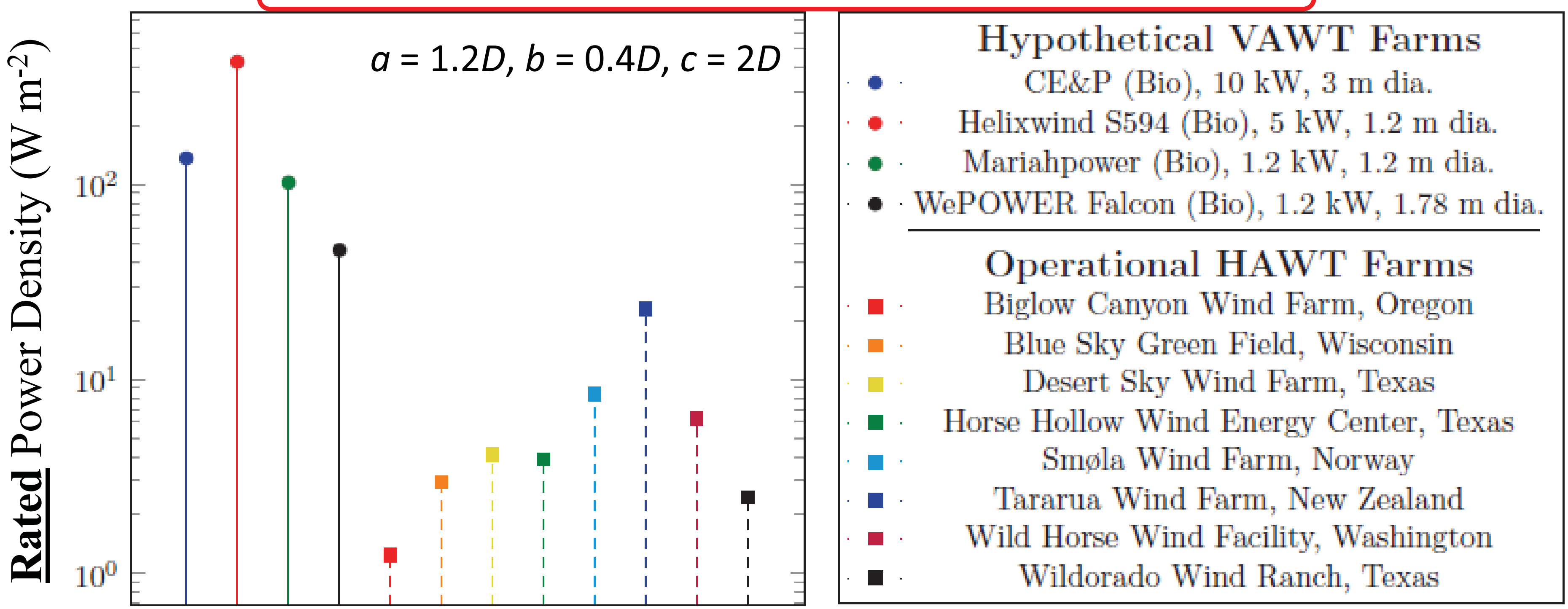


Weihs (1975)

2D potential flow VAWT farm model



Model predicts order-of-magnitude increase in power density



Whittlesey, Liska, Dabiri (*Bioinspiration and Biomimetics*, 2010)

“Clever idea, but does it work for real turbines?”

Challenges:

- computer modeling requires empirical data inputs
- wind tunnel testing requires assumptions to scale-up measurements
- neither can replicate natural wind conditions

…end of story?

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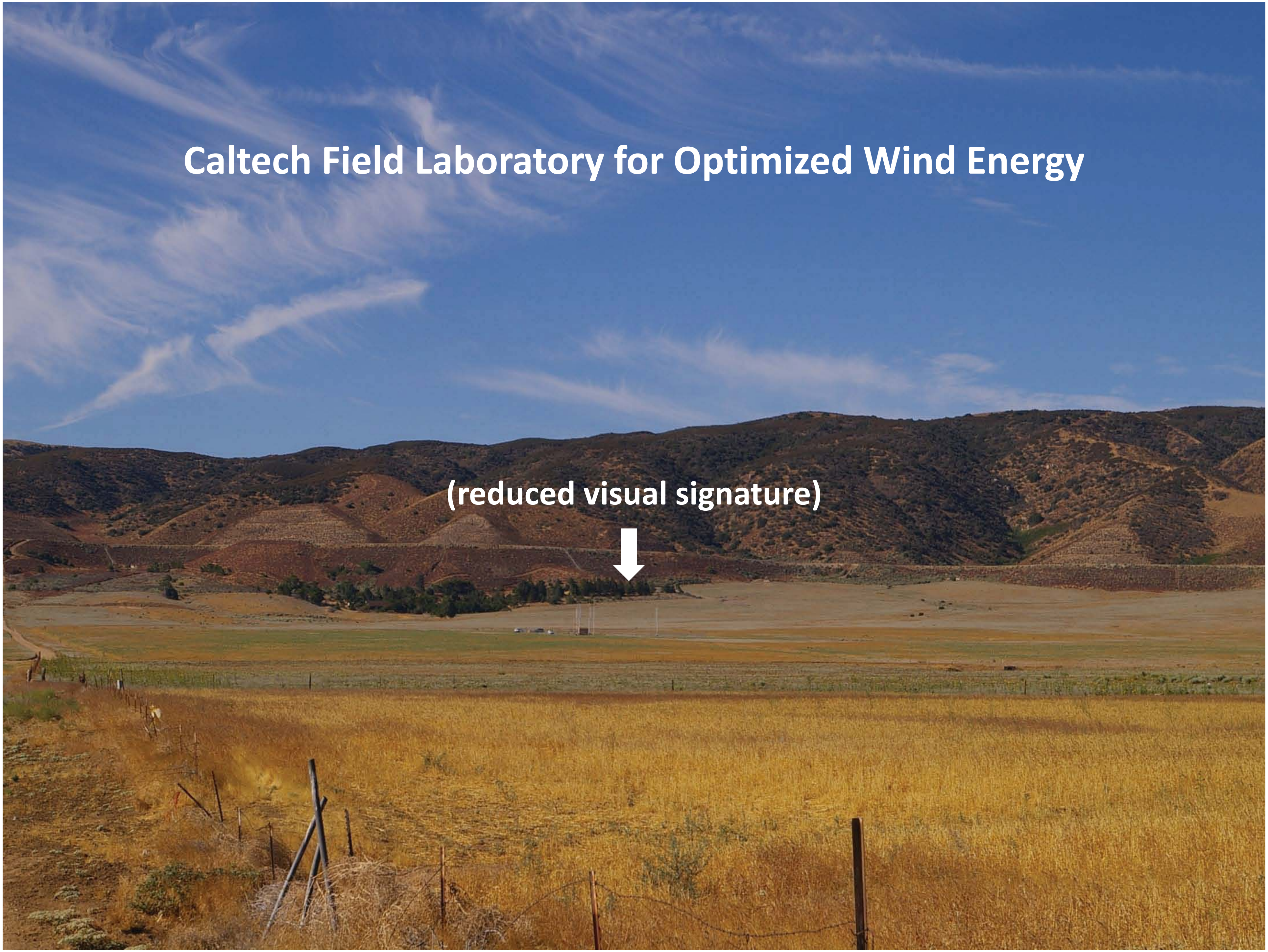
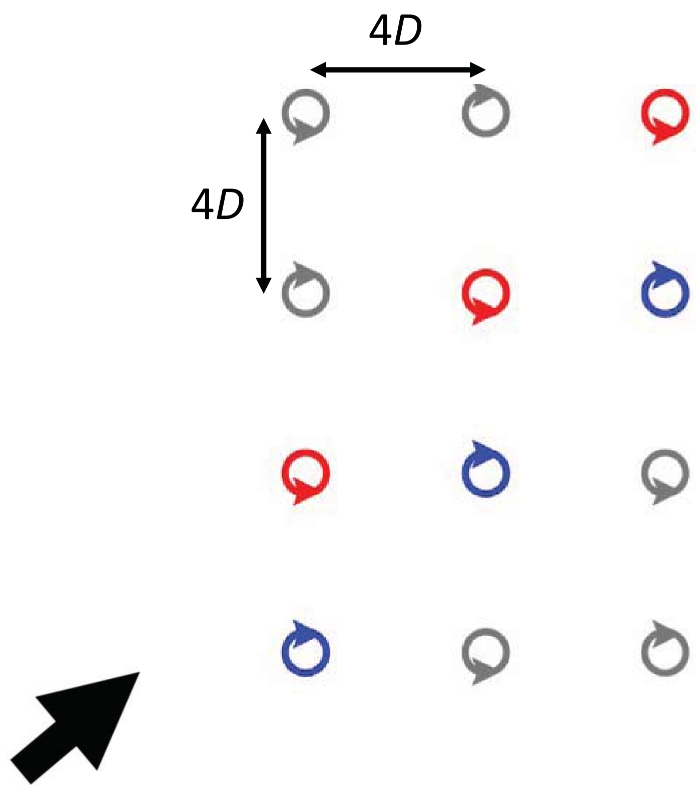
~~***…end of story?***~~

GORDON AND BETTY MOORE FOUNDATION


Caltech Field Laboratory for Optimized Wind Energy
(reduced visual signature)

Field Study Results

6-VAWT array measured over 250 continuous hours



Field Study Results

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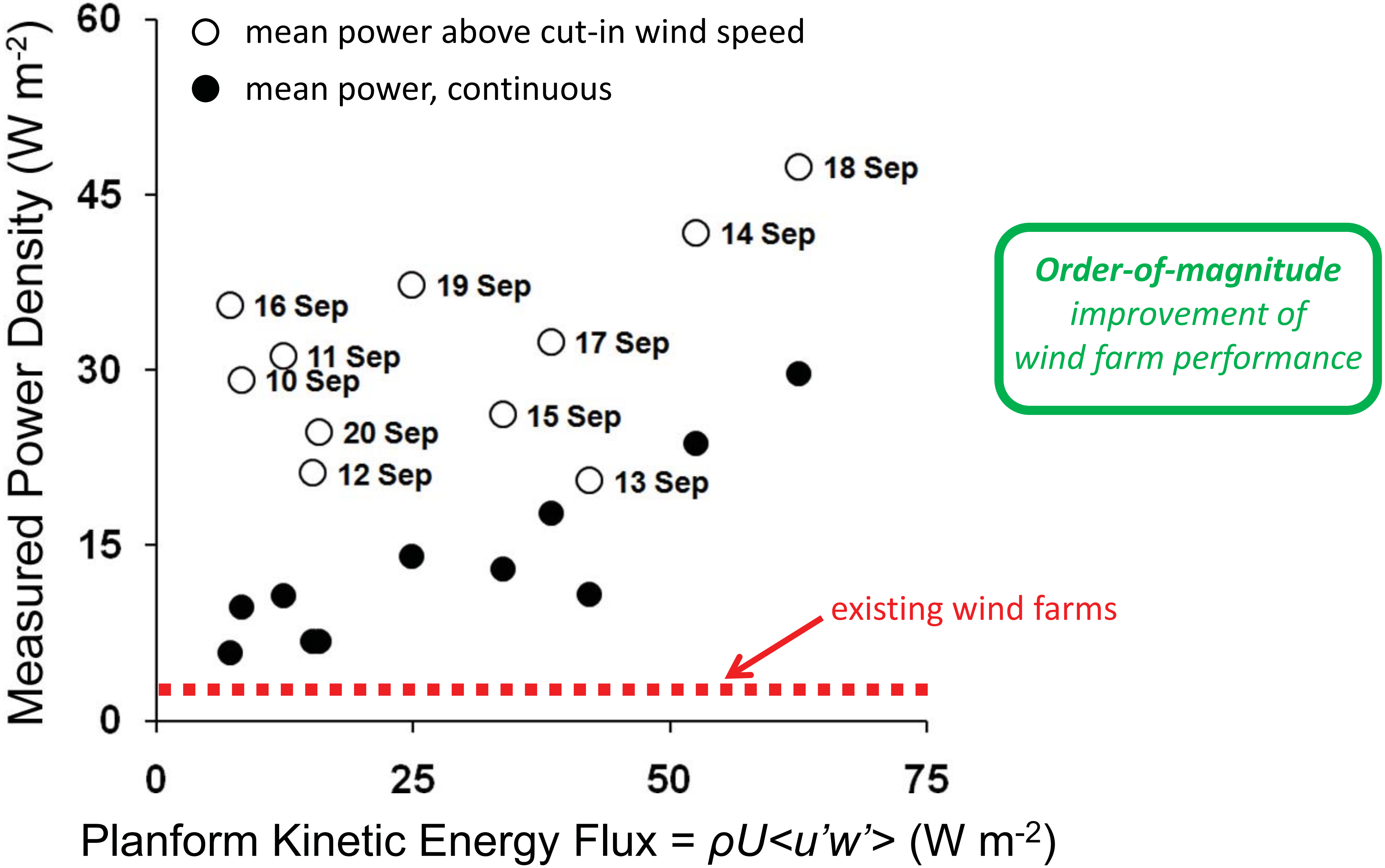


AIP | Journal of Renewable and Sustainable Energy

"Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays"
Volume 3, July 2011

Los Angeles Times

BBC NEWS

SCIENTIFIC AMERICAN

Discovery CHANNEL

FAST COMPANY

MSNBC

cnet

U.S.News & WORLD REPORT

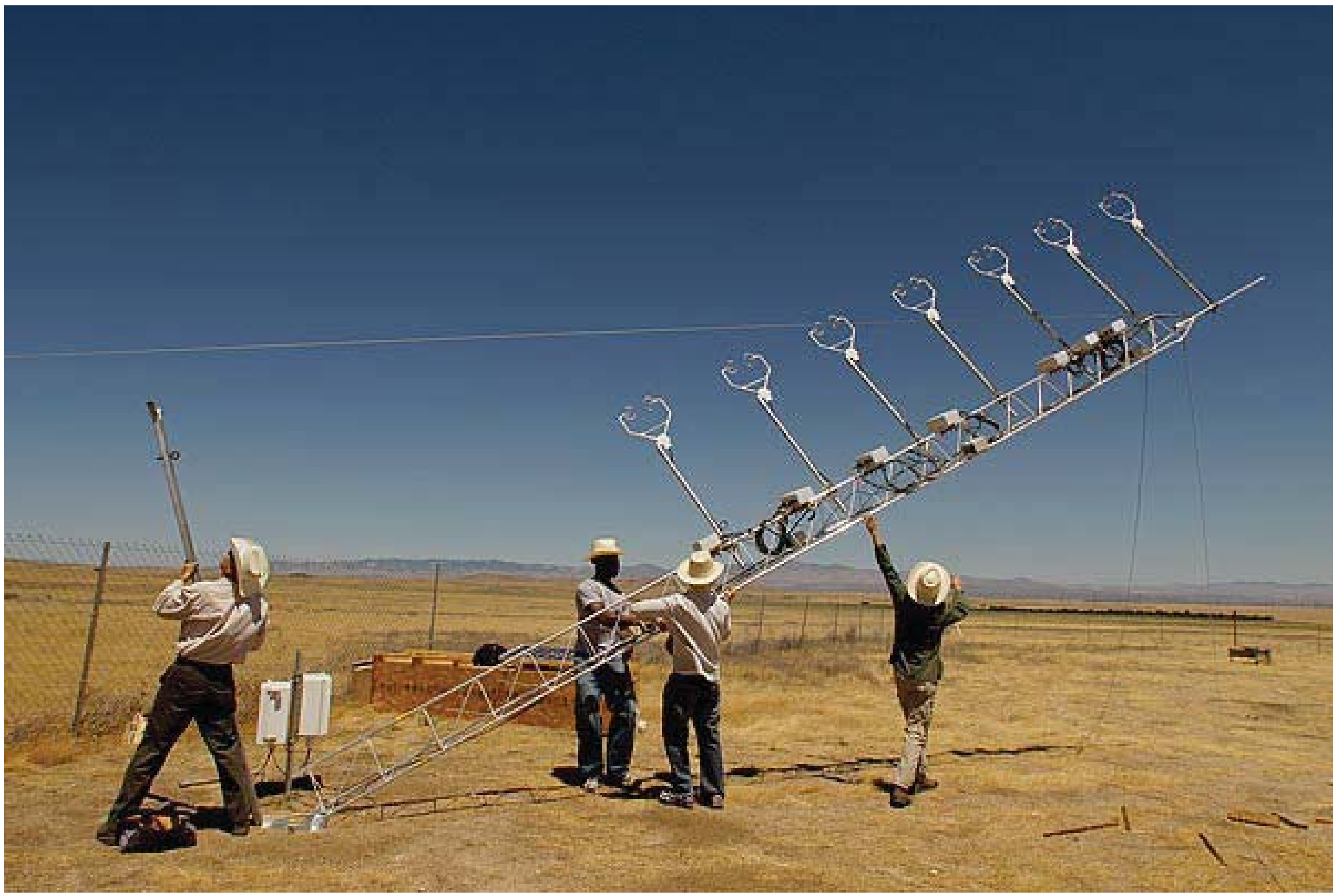
WIRED

NewScientist

Common questions ("Yeah, but…")

Can these results be achieved in a ***larger*** array?
Will wind pass ***around*** a larger array instead of through it?

Wind profile measurements using 7 three-component sonic anemometers



Anne Cusack, Los Angeles Times

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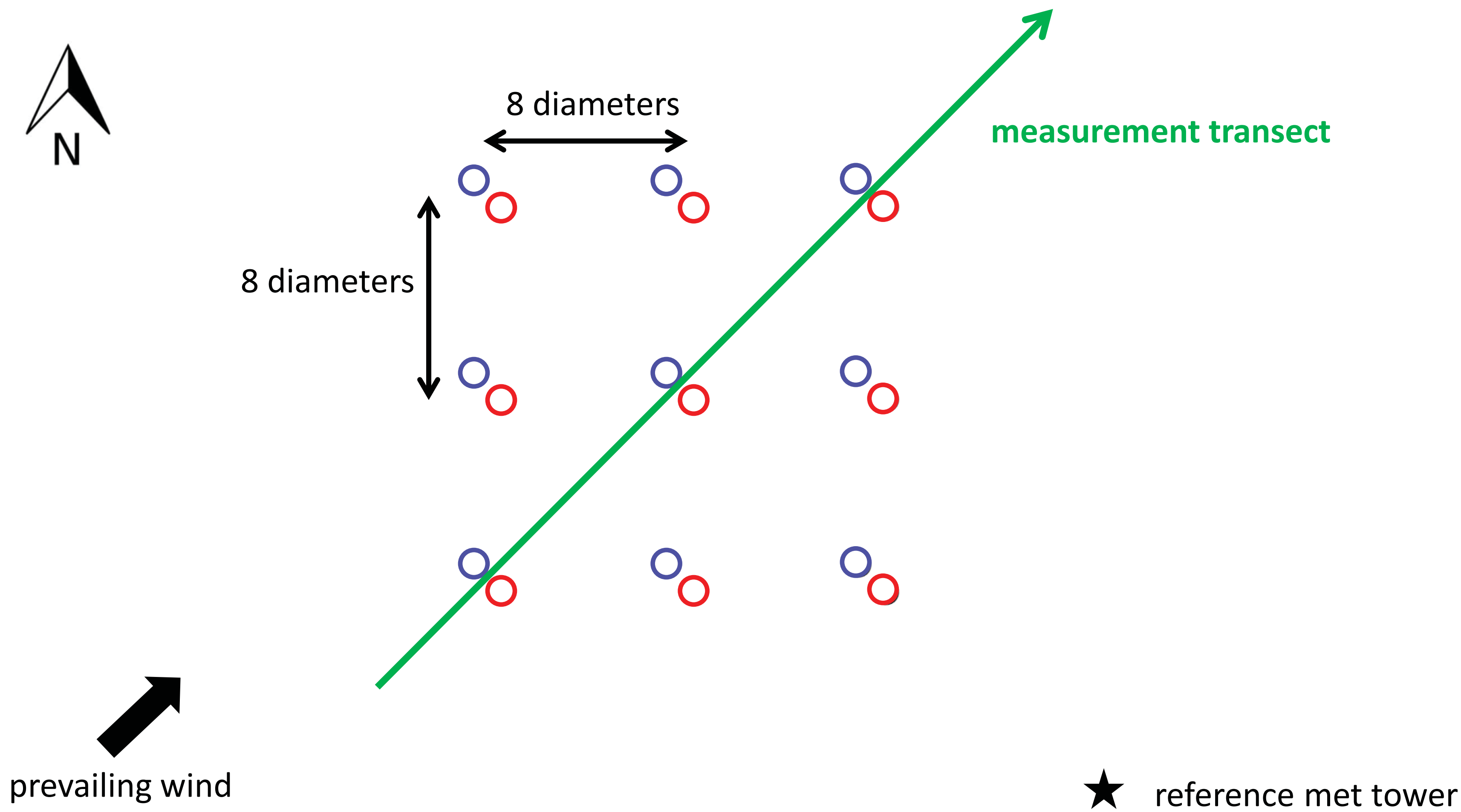

Common questions ("Yeah, but…")

Can these results be achieved in a ***larger*** array?
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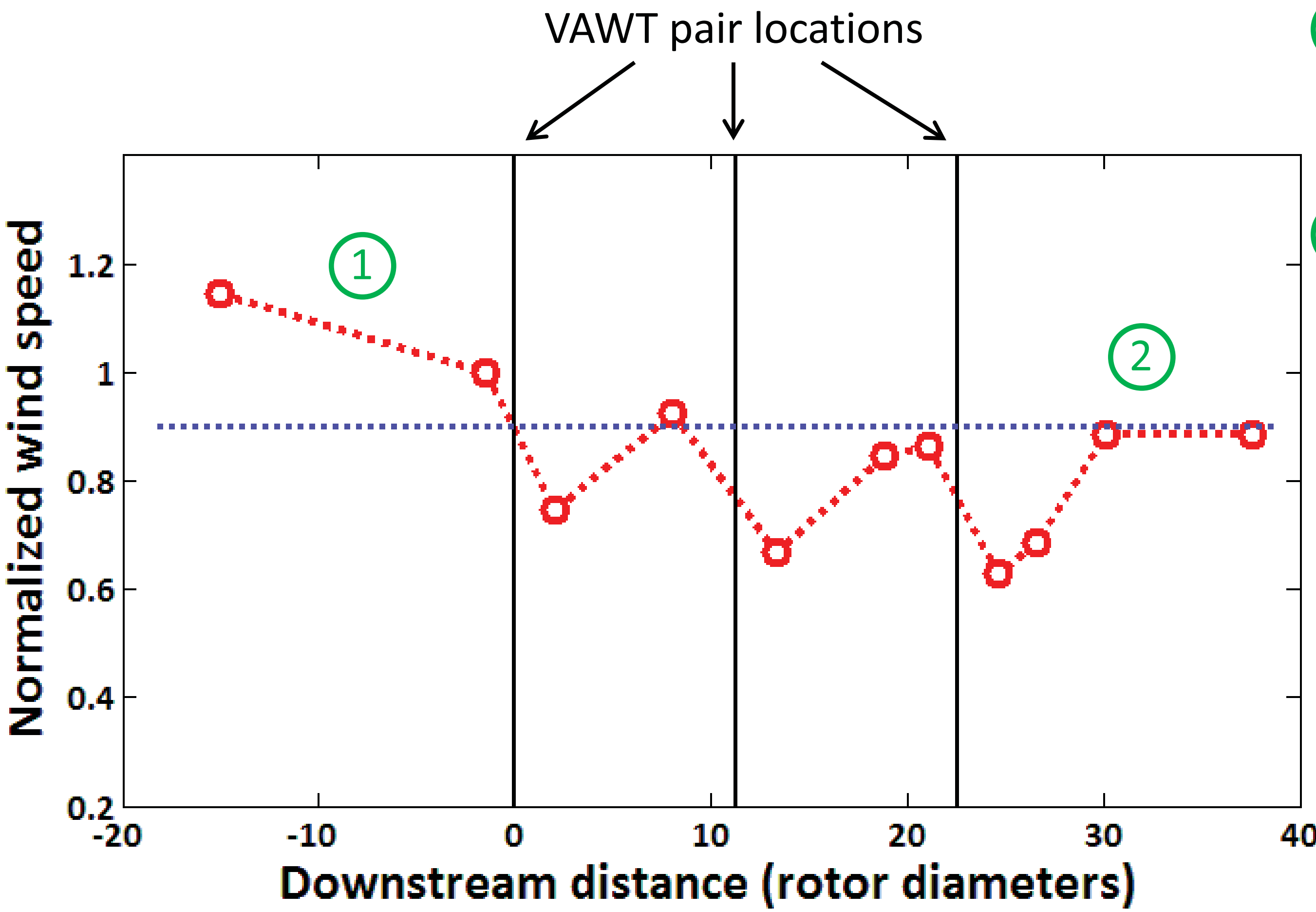
Wind speed at rotor mid-span



1. Wind speed decreases upstream of the VAWT array i.e. "**blockage effect**"
2. However, wind speed achieves **asympotic flow** (blue line) after **third row** (consistent with HAWT arrays)

Power density based on third row VAWTs is ***11 W/m²***

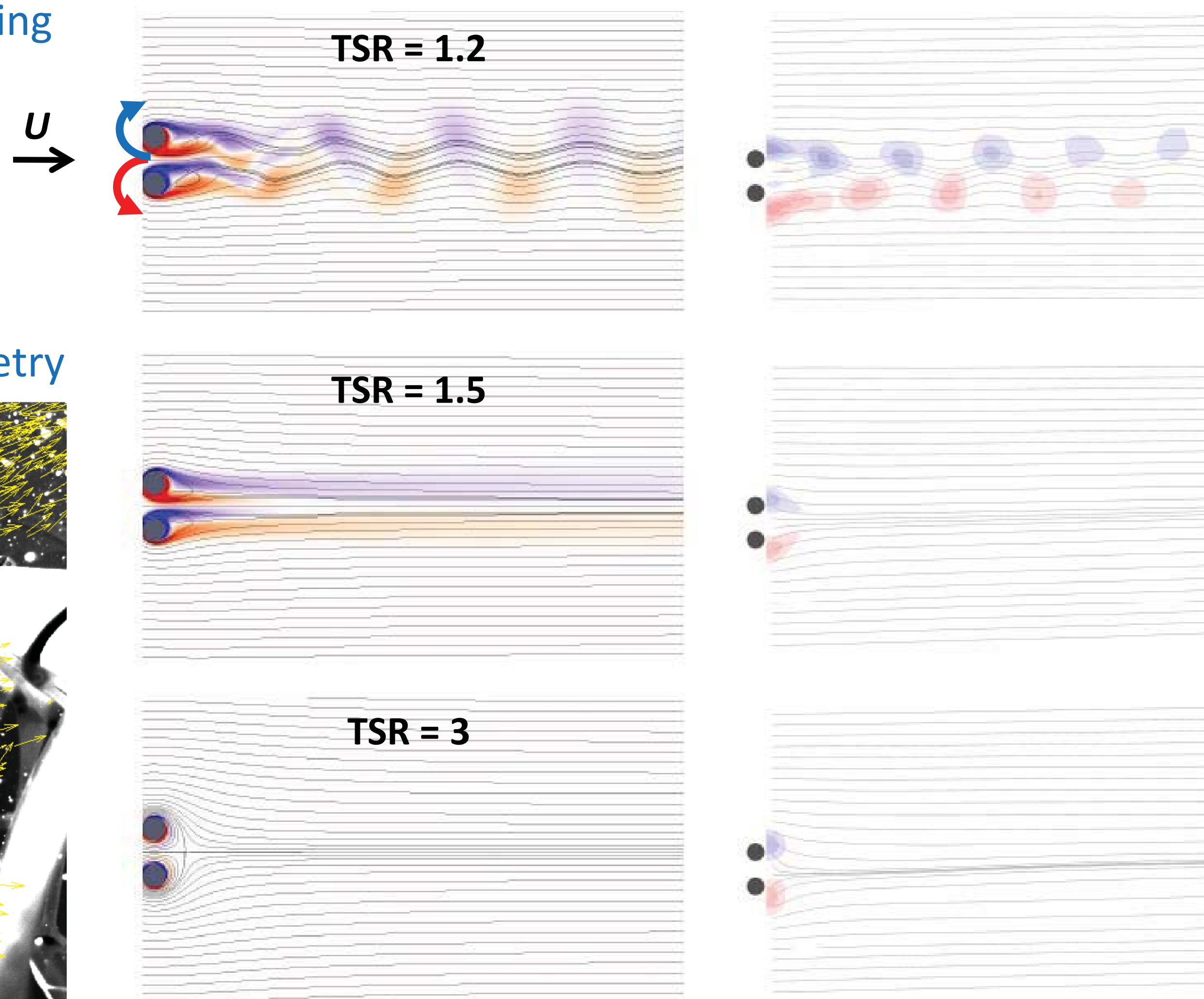
4X HAWT farms with <u>no</u> VAWT array optimization

Unanswered questions

How do aerodynamic interactions within the VAWT farm determine the overall performance?

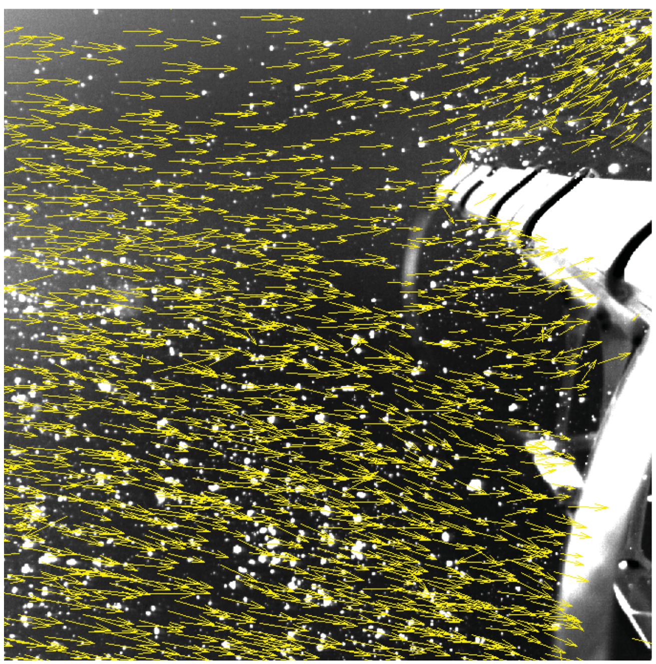
Suppression of vortex shedding by turbine rotation?

CFD | Experiment



Chan et al. 2011

Snow particle image velocimetry



Unanswered questions

How do aerodynamic interactions within the VAWT farm determine the overall performance?

How can canopy flow analogies be applied to understand turbulent transport in VAWT farms?

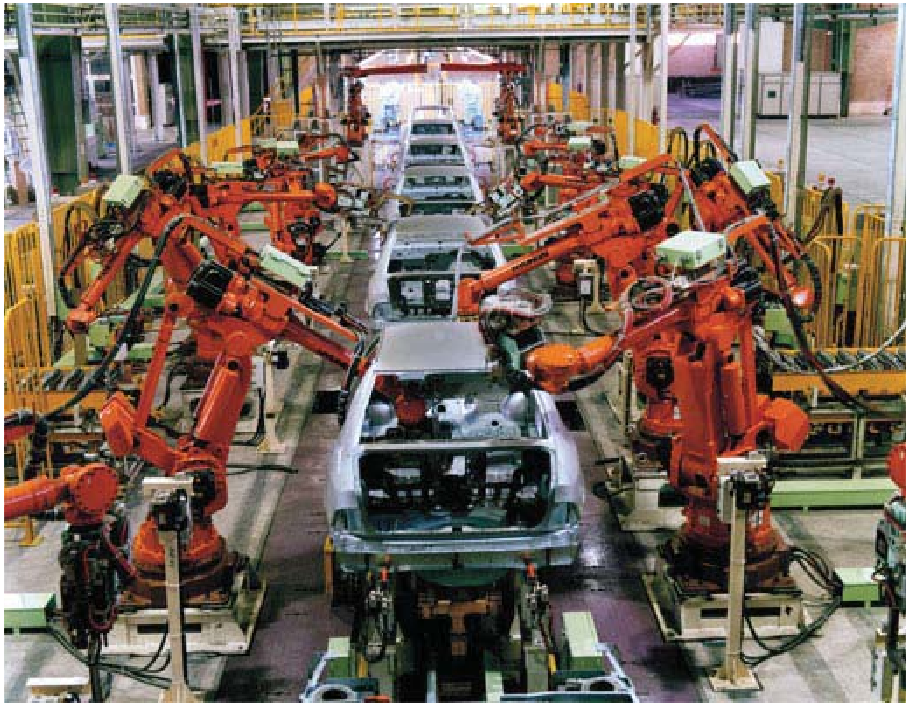
≈

Unanswered questions

How do aerodynamic interactions within the VAWT farm determine the overall performance?

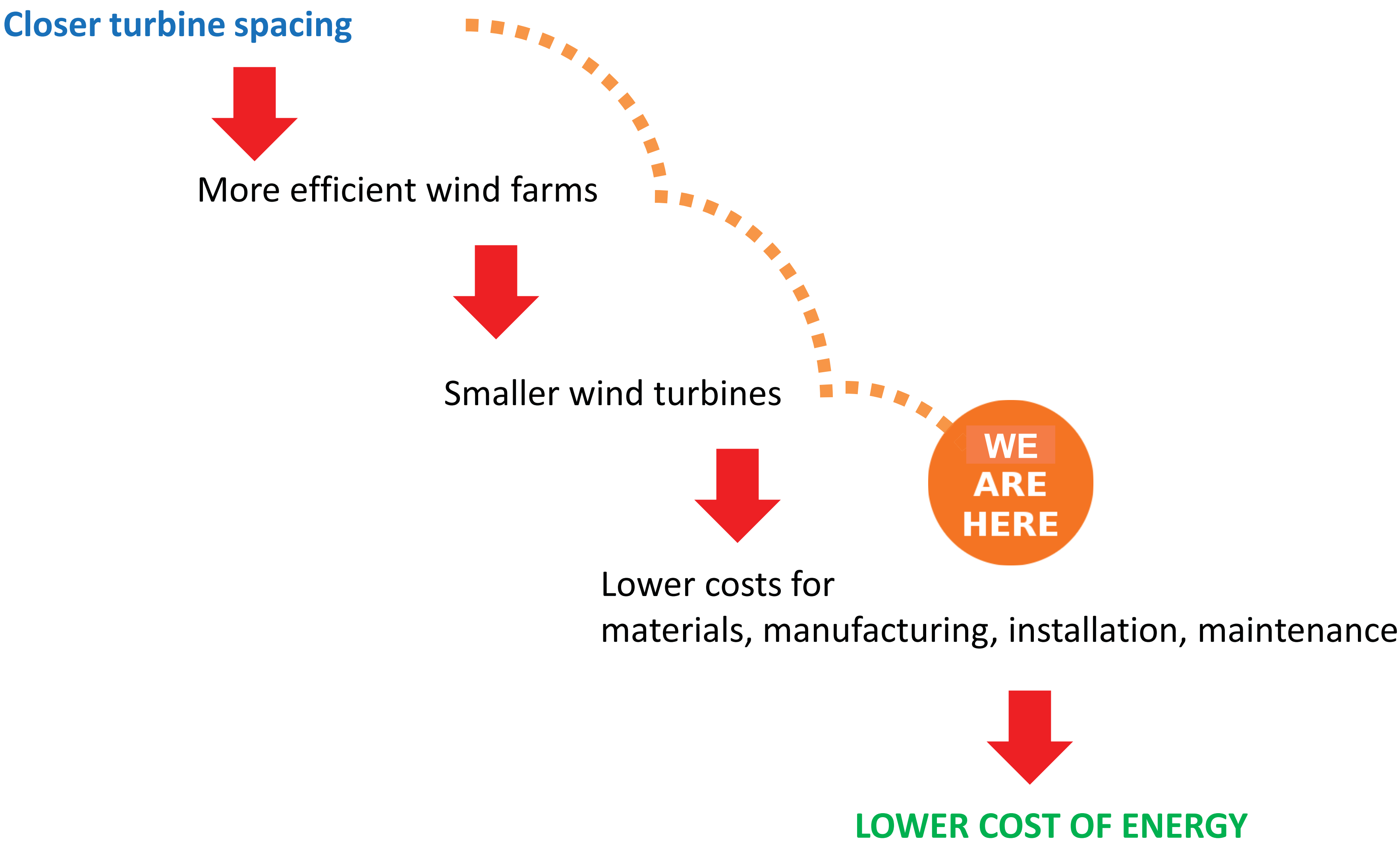
How can canopy flow analogies be applied to understand turbulent transport in VAWT farms?

How can we leverage the smaller VAWT size to improve materials costs, O&M, environmental impact, storage, LCOE?



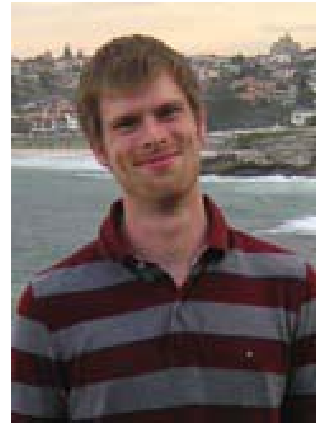
autoanything.com

From closer spacing…to lower cost



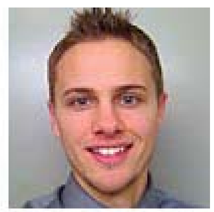
Acknowledgments

Robert Whittlesey
Aeronautics Grad Student
(array modeling)



Matthias Kinzel
Aeronautics Postdoc
(field measurements)

Anna Craig
Applied Physics Undergrad
(array modeling)



Quinn Mulligan
Visiting Undergrad
(field measurements)

Brad Saund
Mechanical Engineering Undergrad
(wind turbine testing)

GORDON AND BETTY MOORE FOUNDATION

National Science Foundation
WHERE DISCOVERIES BEGIN

CALIFORNIA INSTITUTE OF TECHNOLOGY

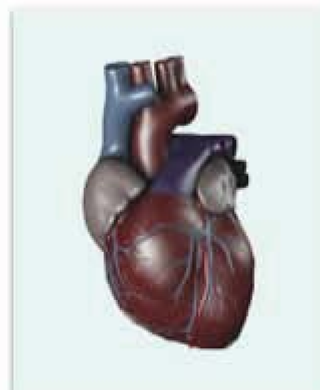
Center for Bioinspired Engineering

Home About Team Research Areas Facilities Positions Contact


Wind Energy


Flow Control


Propulsion


Biomedical Devices

http://bioinspired.caltech.edu

Caltech Program in Bio-inspired Wind Energy

Field Laboratory (Dabiri)
Wind Tunnel Research (Gharib, McKeon)
Computational Design (Colonius)
Materials and Manufacturing (Greer, Grubbs)

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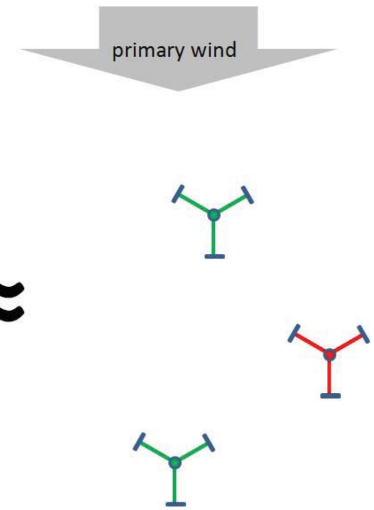

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Questions & Comments?

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