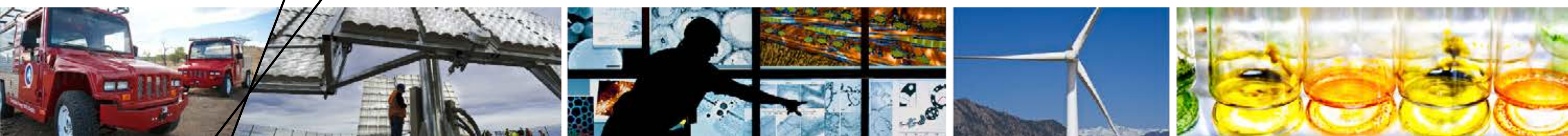
The Role of Wake Models in Wind Plant Design and Optimization



2nd NREL Wind Energy Systems Engineering Workshop

Matthew J. Churchfield

January 30, 2012

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

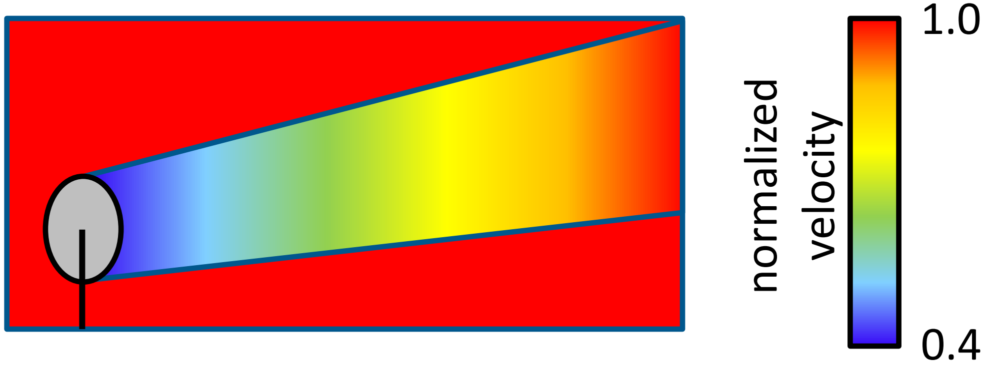
Motivation

- The focus has been to design/optimize turbine or plant
- Focus shifting to simultaneous turbine/plant optimization
- Wake models are important for this design/optimization
- Current computationally efficient wake models from ’80s-’90s
- Need for more accurate, more comprehensive wake models that are still computationally efficient

Current Computationally Efficient Models

- **Examples: Park, eddy viscosity, deep array**

- **Deficiencies**
  - Steady solution
  - Based on axisymmetric equations
  - Devised or tuned using observations

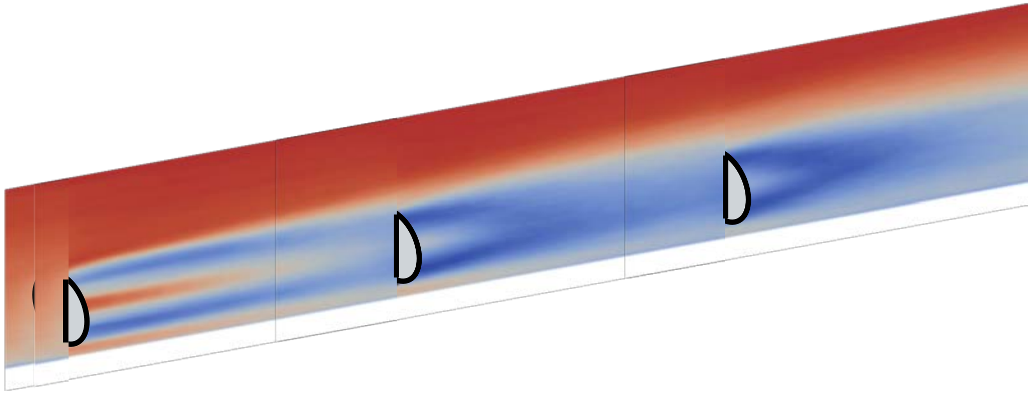


Current Computationally Efficient Models

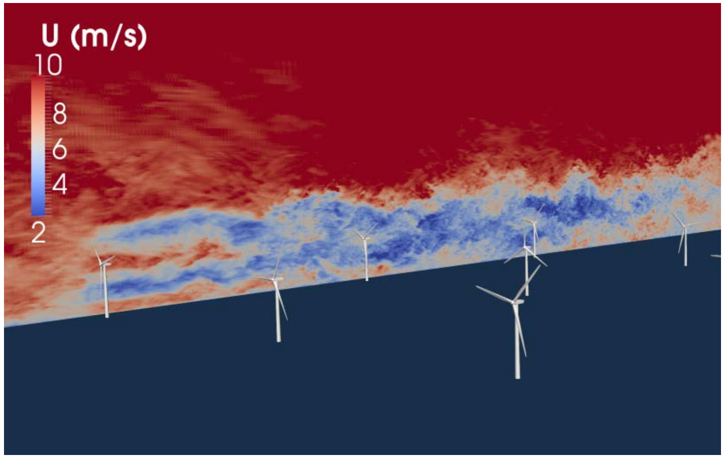
- **Mainly used to predict power**
- **But, loads are important, too…**
  - IEC 61400-1 standard says:
    - "Wake effects from neighboring wind turbines may be taken into account during normal operation for fatigue calculation by an effective turbulence intensity I_{eff}, Frandsen (2003)"
    - This does not consider wake deficit
  - Wake models should be part of loads analysis in wind plant design/optimization
- **Ideal for wind plant design/optimization**

Medium and High-Fidelity Wake Models

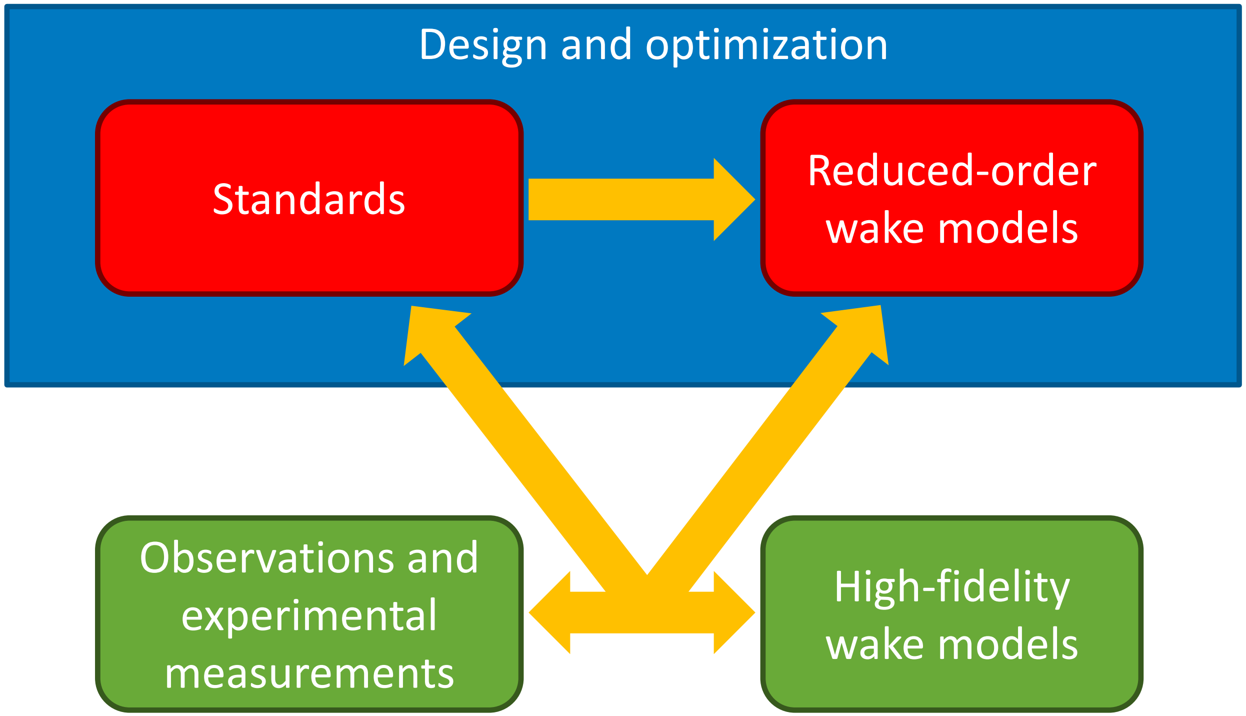
- **Reynolds-averaged Navier-Stokes (RANS)**
  - All turbulent scales modeled
  - Steady
  - Full 3D, terrain conforming (not axisymmetric)
  - Mid-level computational efficiency



- **Unsteady RANS (URANS)**
- **Large-eddy simulation (LES)**
  - Larger turbulent scales directly resolved
  - Unsteady
  - If well validated, complementary to field data/measurements
    - Use to inform reduced-order wake models

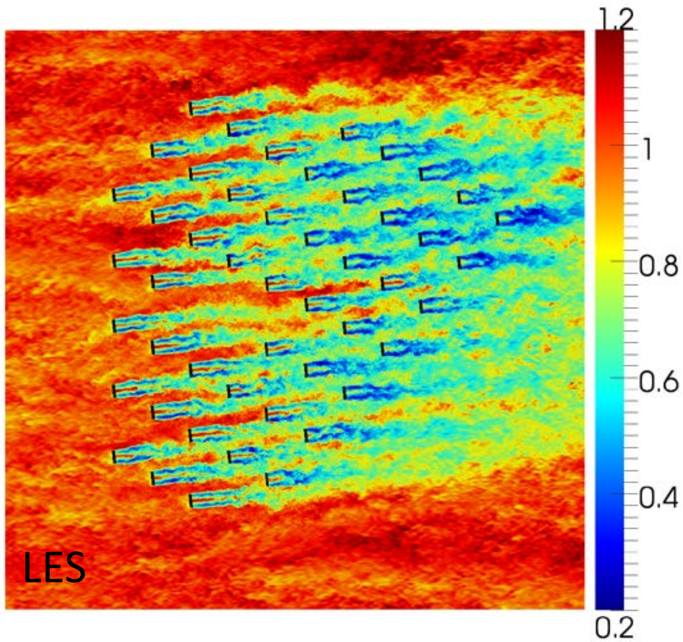


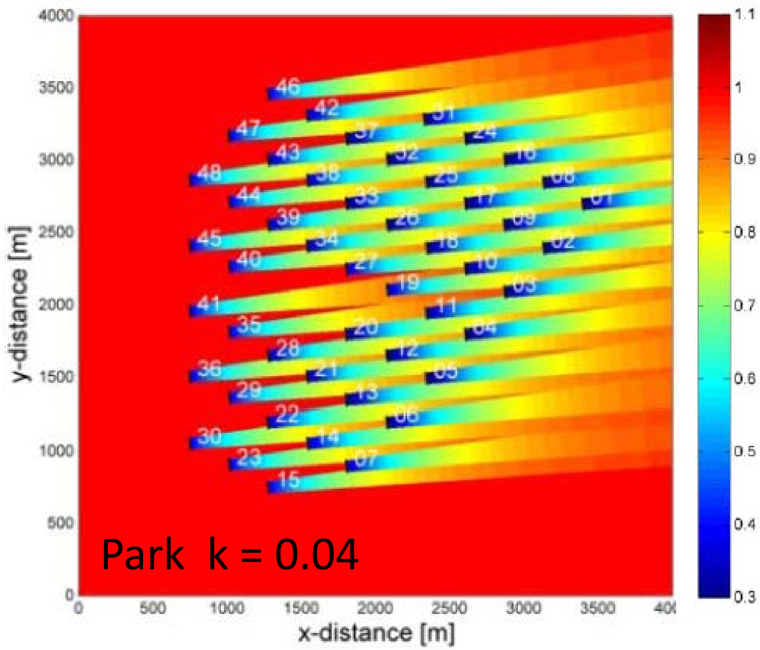
Wake Model Organization



High-Fidelity Versus Current Models

Lillgrund wind plant example

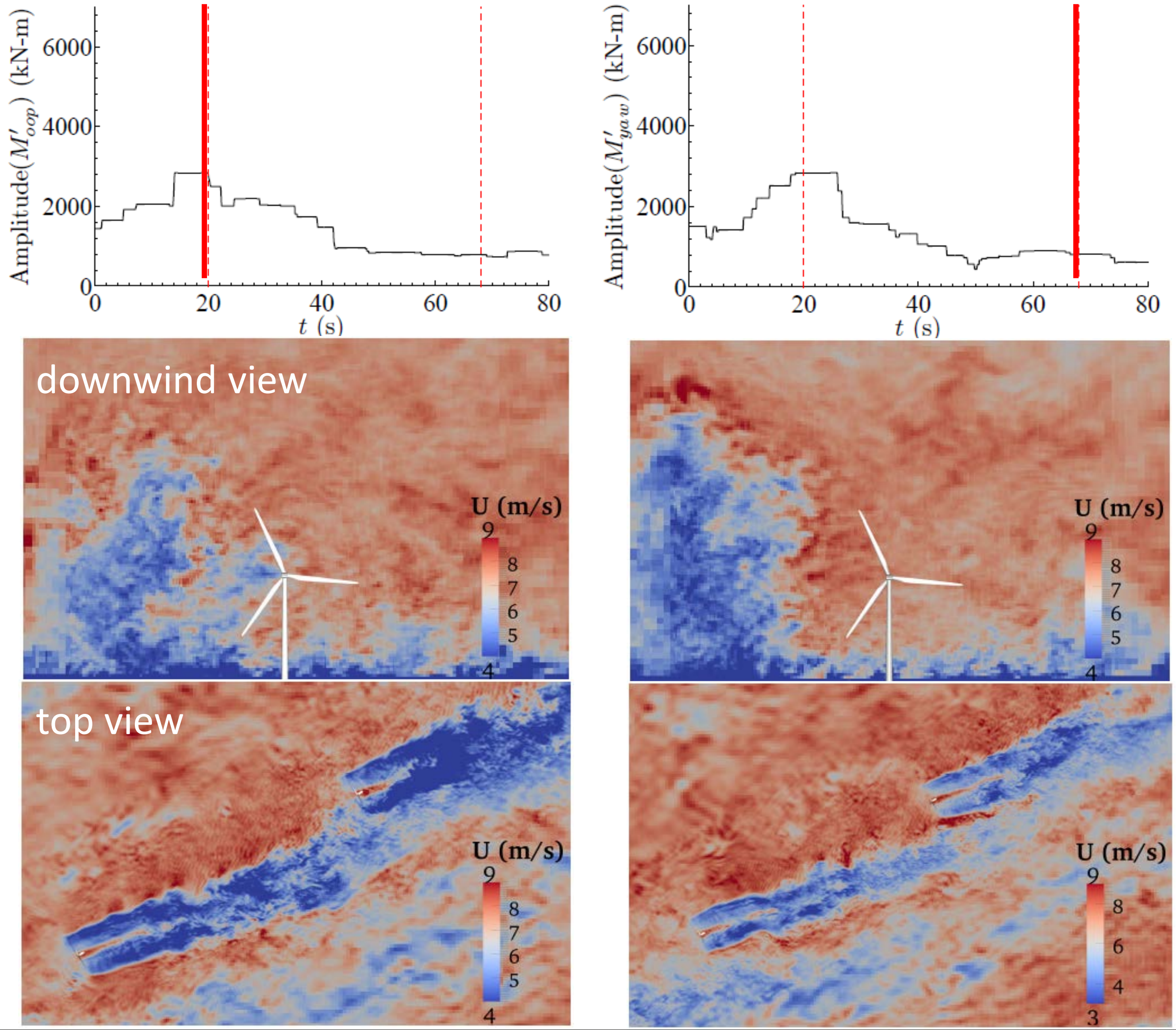




High-Fidelity Versus Current Models

- Two NREL 5MW turbines separated by 7D, subject to an unstable atmospheric boundary layer, computed with LES

fluctuating loads



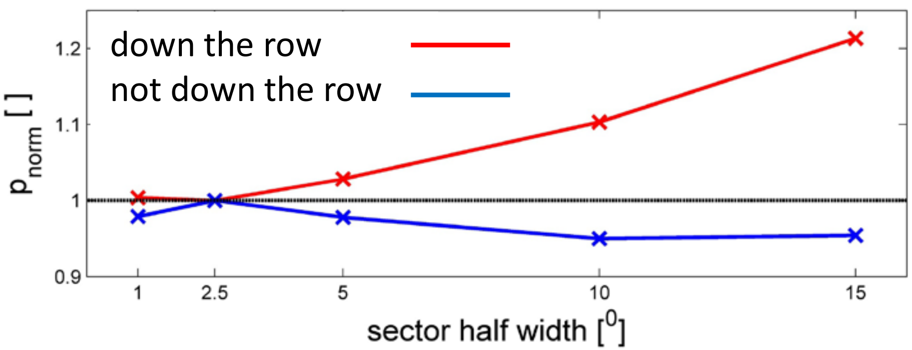
Is High Fidelity Better?

Lillgrund wind plant example

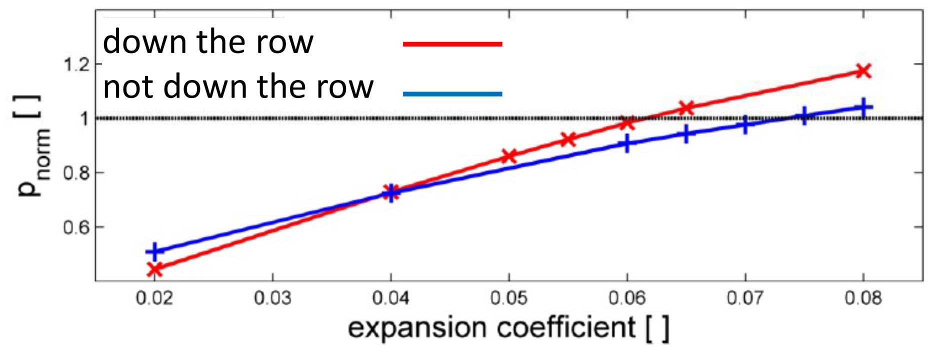
	down-the-row	Not down-the-row
	$\theta = 222^0$	$\theta = 264^0$
Obs (+/- 5^0)	1.00	1.00
Park (k = 0.06/0.07)	0.98	0.98
LES (TI = 6%)	1.08	1.25
WAsP (k = 0.04)	0.92	0.96

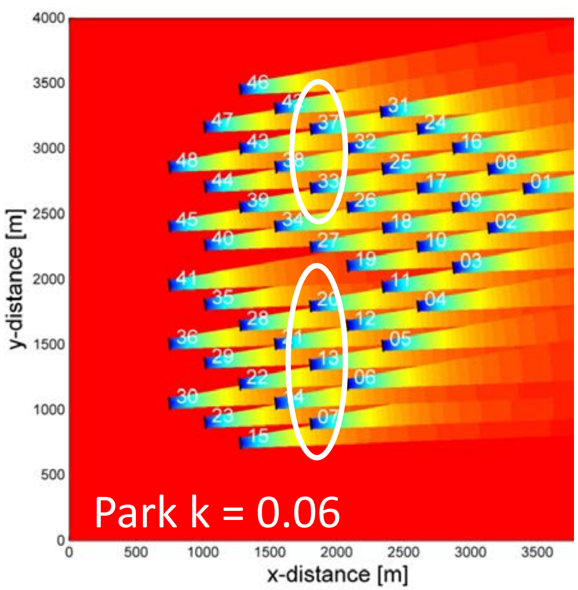
Is High Fidelity Better?

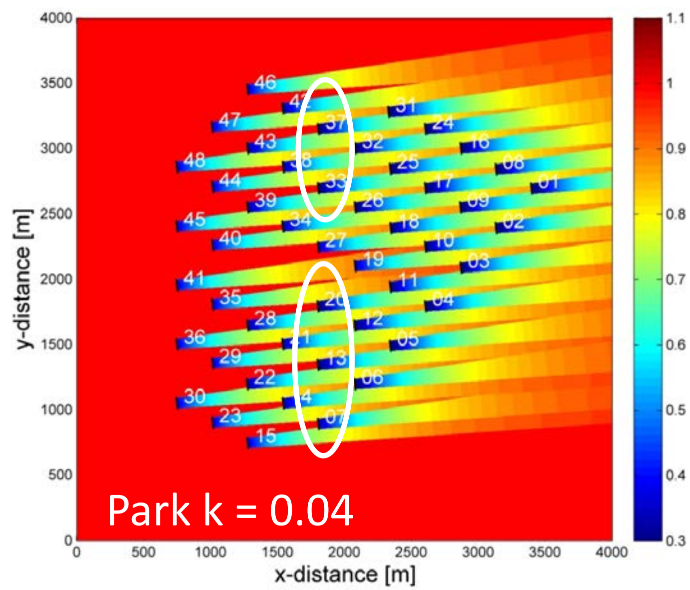
Effect of bin width

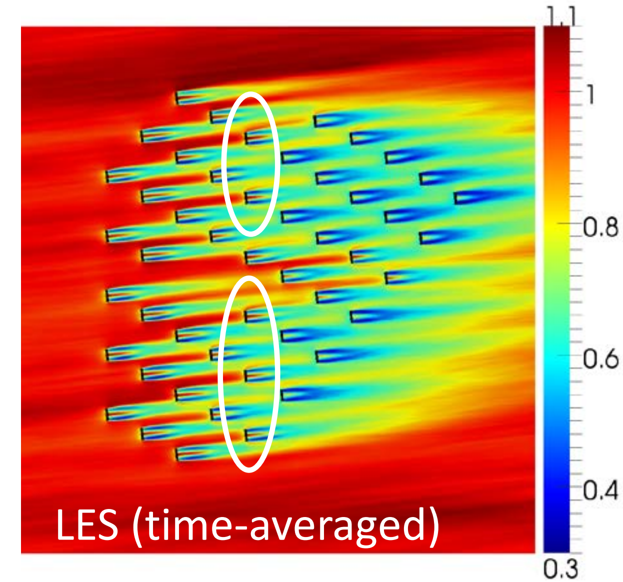


Effect of tunable parameters





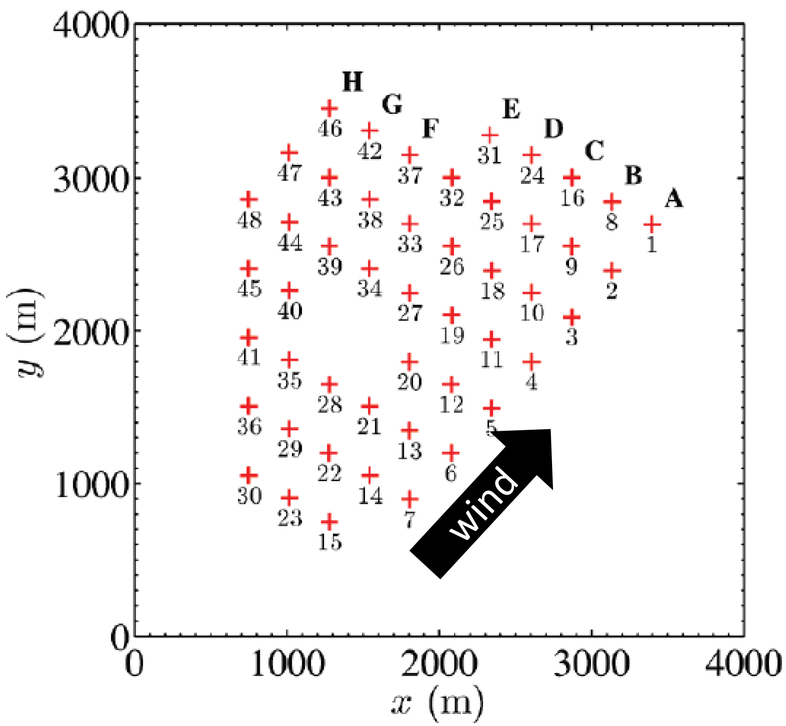


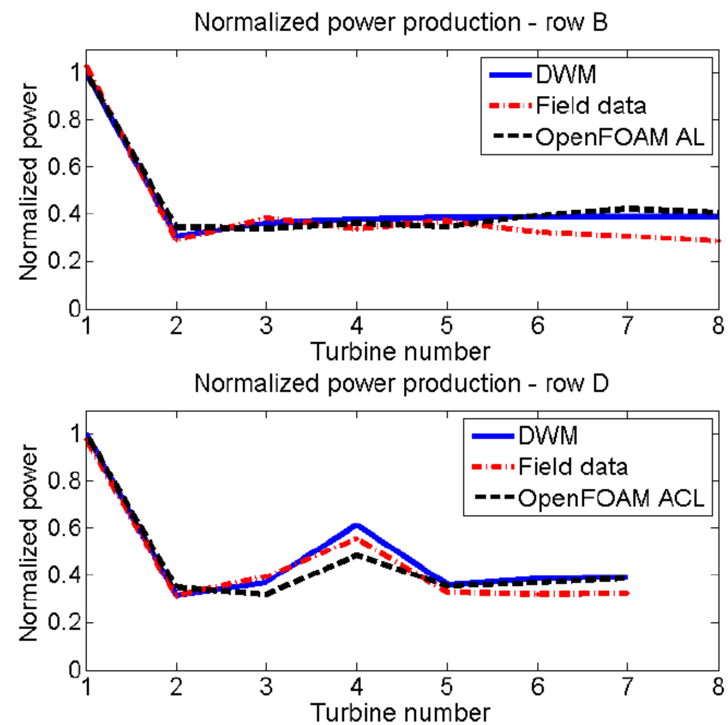


New Idea: Dynamic Wake Meandering

- **"Poor man's LES"**
  - Eddy-viscosity model "base" steady wake
  - Pre-generated atmospheric turbulence meanders base wake as passive tracer

- **Made a steady wake model unsteady, and we can now study loads**
- **Proposed for next version of IEC standards**





Uncertainty that Hinders Wake Modeling

- **All models have multiple sources of uncertainty**
  - Boundary/initial conditions (stability, etc.)
  - Duration of simulation versus measurement
  - Binning size of observations
- **Models tunable to particular dataset (down-the-row), but tuning not universal**
- **Adding physics may reduce need for tuning and bound uncertainty**

Conclusions

- **Current reduced-order wake models**
  - Lack physics, computationally efficient, ideal for design/optimization
- **High-fidelity wake models**
  - Have lots of physics, expensive, not design/optimization tool
- **High-fidelity models are not proven to be more accurate**
  - Limited knowledge of boundary conditions (“garbage in-garbage out”)
- **Need improved field measurements to provide input and validate high-fidelity models**
- **Not a question of “Is high-fidelity better?”**
  - Measurements and high-fidelity models inform reduced-order models and standards—THEY NEED TO WORK TOGETHER
- **Future reduced-order models**
  - Need to account for unsteadiness, non-axisymmetry, atmospheric stability
  - Used to design/optimize for **power** and **loads**
  - Designed with uncertainty quantification in mind