Wakes in large wind farms

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Data from DONG, Vattenfall

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Funding from Flodesign /ARRA & NSF CBET

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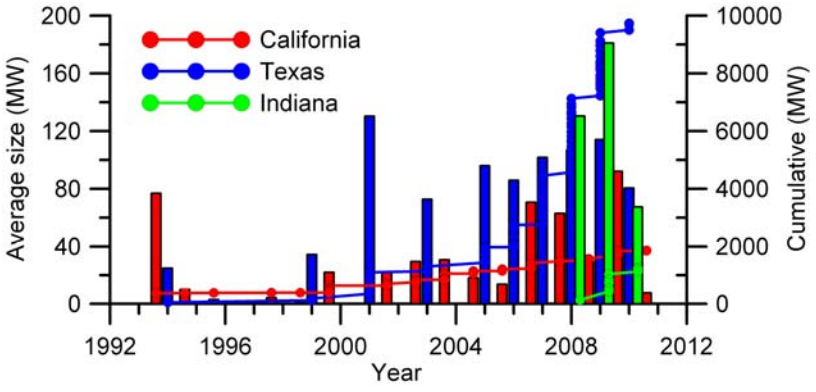
Wind farm issues

- Wind farm size increased to > 100 MW
- Cost - balancing power, loads and cabling



Data from www.awea.org/projects

Barthelmie et al. AWEA 2010

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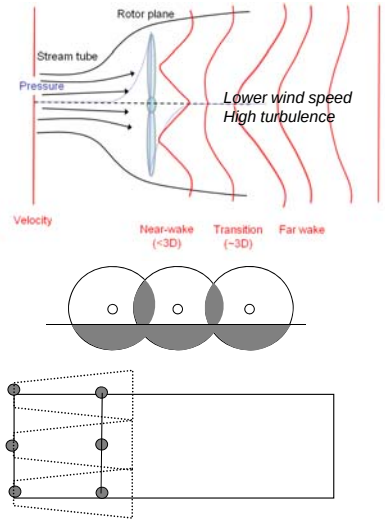
Wind-turbine interactions: wakes

- Wakes: volume of high turbulence, lower wind speed behind turbines
- Wake recovery depends on many factors:
  - Atmosphere - Wind speed, turbulence, stability
  - Turbine type – Pitch, stall, thrust coefficient, hub-height
- Multiple wakes
  - Wind farm size/layout
  - Continue to interact with each other and the environment



Frandsen et al. 2009 Wind Energy; 12, 445-458

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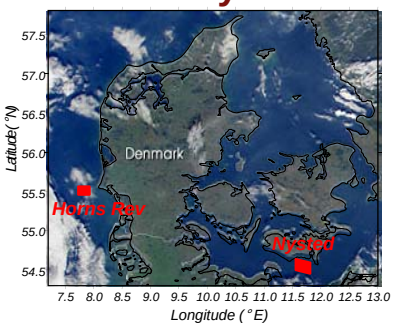
Observations from Horns Rev and Nysted

Wind farm	Nysted	Horns Rev
Owner	DONG Energy (80%) E.On Sweden (20%)	Vattenfall (60%) DONG Energy (40%)
Turbine number	72	80
Turbine	Siemens 2.3 MW	Vestas 2 MW
Turbine type	Active stall, 2-speed	Pitch, variable speed
Rotor diam (D)	82.4 m	80 m
Hub-height	69 m	70 m
Array	8 (E-W) x 9 (N-S)	10 (E-W) x 8 (N-S)
Dist. between turbines	10.3 D (E-W) & 5.8 D (N-S)	7 D (E-W & N-S)
Rated capacity	165.6 MW	160 MW
Annual prod.	595 GWh	600 GWh
Year comm.	2003	2002
Water depth	6-10 m	6-14 m
Distance land	10 km (closest)	14-20 km



http://earthobservatory.nasa.gov/IOTD/view.php?id=3389

Barthelmie et al. 2010 J. Atm. Oc. Tech. 27(8), 1302-1317

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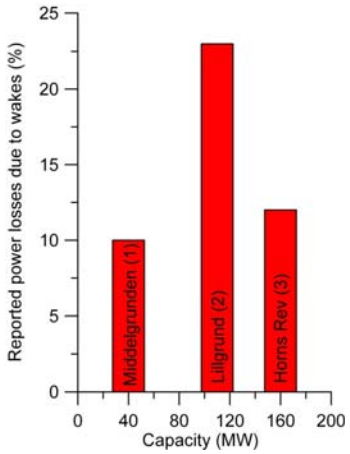
Power losses due to wakes



(1) Barthelmie Wind Energy 2007
(2) Dahlberg European Offshore 2009
(3) Sørensen AWEA 2008

- Difficult to calculate & generally not reported
- Offshore ~ 10-23% wind farm power
- Wake magnitude f:
  - Freestream wind speed (wind speed distribution, C_T)
  - Turbine number & layout
  - Turbulence/atmospheric stability
  - Turbine characteristics

Barthelmie et al. 2009 Wind Energy; 12:431–444

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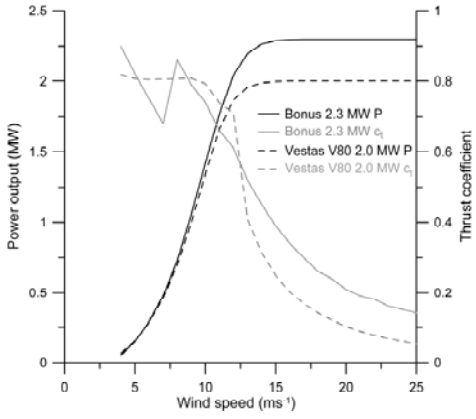
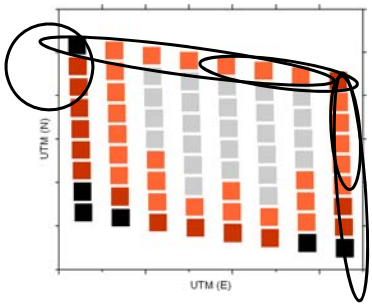
Wind speed/C_t and freestream



Freestream wind speed/power

1. Met Mast (distance/height)
2. Highest power output } Power curve
3. Mean of row



Choice of freestream e.g. -4→+12% change in efficiency

Barthelmie and Jensen 2010 Wind Energy; 13:573–586

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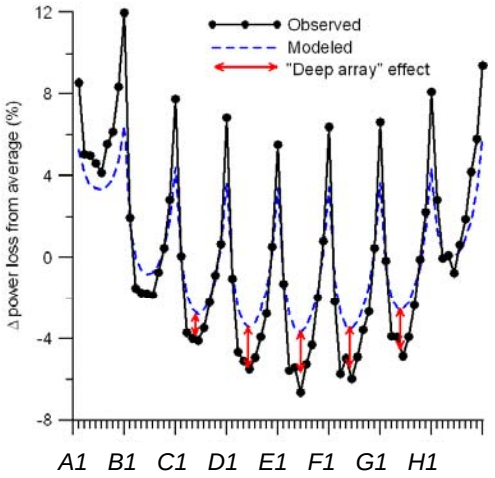
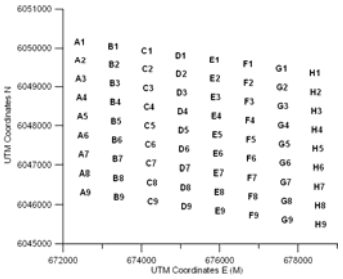
Turbine number/spacing





Nysted: 'Deep array effect'

Barthelmie and Jensen 2010 Wind Energy; 13:573–586

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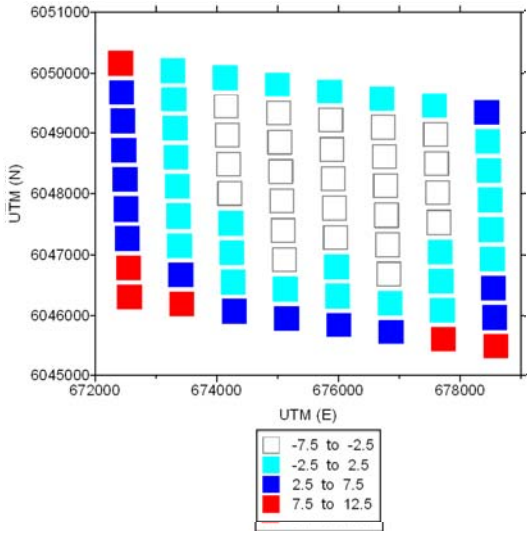
Deep array effect: Nysted

- Nysted
  - Wake decay coefficient =0.03
- Losses shown as % difference from average



Barthelmie and Jensen 2010 Wind Energy; 13:573–586

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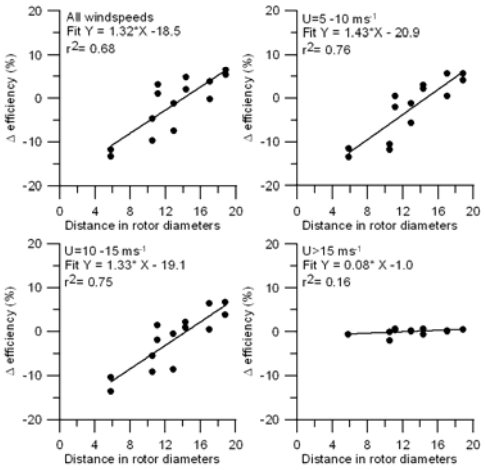
Quantifying impact of spacing

- Empirical analysis of Nysted
  - •Δ incident angle → Δ spacing
  - •Highly wind speed dependent
- Average power Δ 1.3% per 1D spacing change



Barthelmie and Jensen 2010 Wind Energy; 13:573–586

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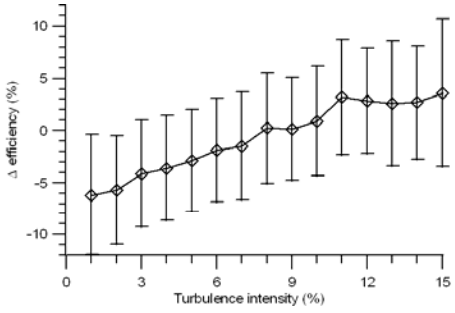
Turbulence/stability effects on wakes

- Efficiency improves (wake losses smaller) as turbulence intensity increases (independent of wind speed)



Barthelmie and Jensen 2010 Wind Energy; 13:573–586

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Stability

- Atmospheric stability impacts wake recovery
- In stable conditions, efficiency is 5-8% lower than neutral conditions
- Differences in unstable conditions are small (+1-3%)

	5-6 ms^{-1}	6-7 ms^{-1}	7-8 ms^{-1}	8-9 ms^{-1}	9-10 ms^{-1}
Stable	-6.1	-5.7	-4.7	-7.2	-8.1
0<L<1000 m	(34.7)	(38.7)	(37.4)	(39.0)	(38.7)
Neutral	0.0	0.0	0.0	0.0	0.0
|L|>1000 m	(21.3)	(18.7)	(19.8)	(23.1)	(26.4)
Unstable	3.0	1.3	0.7	1.0	0.8
-1000<L<0 m	(44.0)	(42.6)	(42.8)	(37.9)	(34.9)

Barthelmie et al. AWEA 2010

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Remote sensing of wakes

- In addition to SCADA data and met.masts
- Lidar give wind speed and turbulence profiles to 200 m (+?)
  - More freestream information
  - Better vertical resolution
  - 'Mobile' measurements inside wind farm

Lidar wind speed/turbulence measurements to heights of ~200 m

Pryor et al. 2011 Atmospheric Chemistry & Physics 11 1641-1657

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Wake models

- E.g. EU funded UpWind project
- Model development/ evaluation
- Nysted and Horns Rev cases in Virtual Wakes Laboratory

Name	Company	Type	Commercial/ Research
WAsP	Risø DTU	Engineering	C
FLaP	Oldenburg	Ainslie	R
Windfarmer	GH	Ainslie	C
"Canopy"	Risø DTU	Under development	R
Wakefarm	ECN	Parabolised CFD	C/R
CENER Fluent	CENER	CFD	R
NS FLow	CRES	CFD	R
NTUA	NTUA	CFD	R

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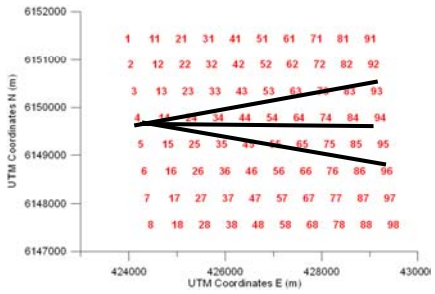
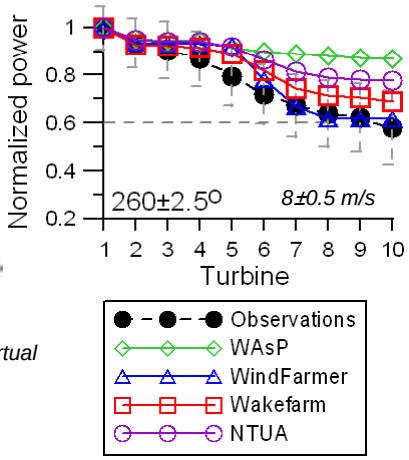
Horns Rev case studies (7D by 7D)



Nysted and Horns Rev cases available in Virtual Wakes Laboratory



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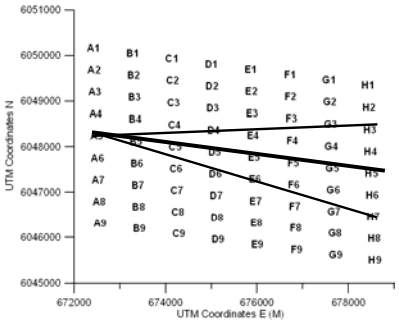
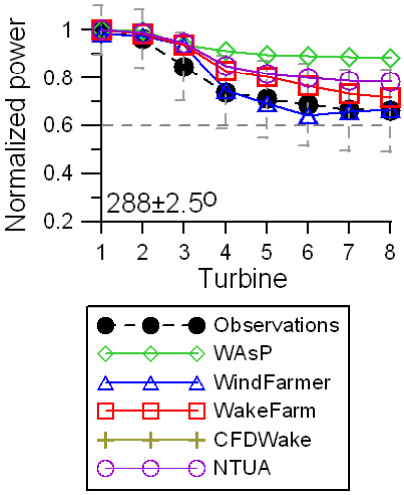
Nysted case studies 10.5D by 5.8D





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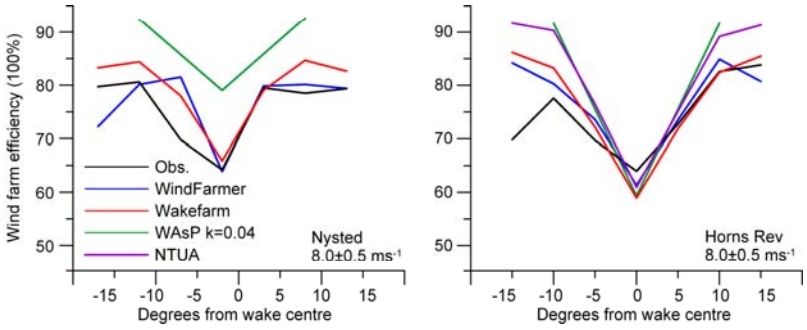
Metrics



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Summary/Future work

- Recent improvement in wake understanding & wind farm power predictions
- Clusters of wind farms & larger wind farms being developed ⇒ urgent need for improved understanding & modeling of wake effects
- Needs:
  - Accessible wind farm data sets
  - High resolution measurements (particularly in complex terrain and offshore)
  - Improved models (& model evaluation tools)