POWER Offshore Summer School 2006

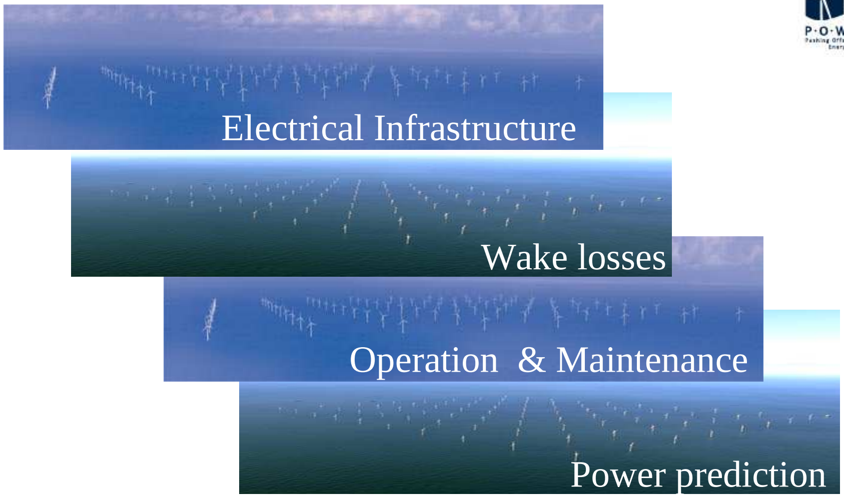
OFFSHORE WIND FARM Aspects

Gerard van Bussel

TU Delft

The Netherlands

Typical wind farm aspects



- Electrical Infrastructure
- Wake losses
- Operation & Maintenance
- Power prediction

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Contents

- **power production**
  of wind turbines in wind farm
- **power collection**
  inside wind farm
- **power transmission**
  from wind farm to shore

“The example”

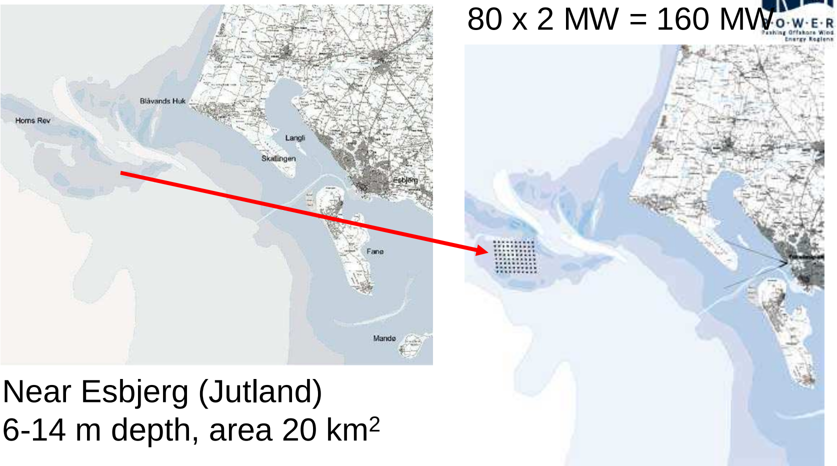
Horns Rev, an 80 unit offshore wind farm
in the North Sea

www.hornsrev.dk

Pushing Offshore Wind Energy Regions (POWER)

Horns Rev (DK)

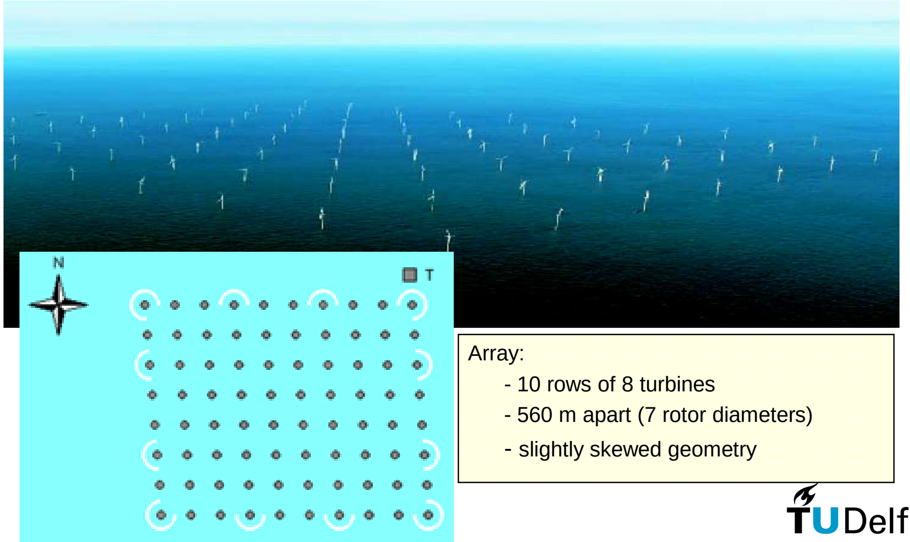
80 x 2 MW = 160 MW



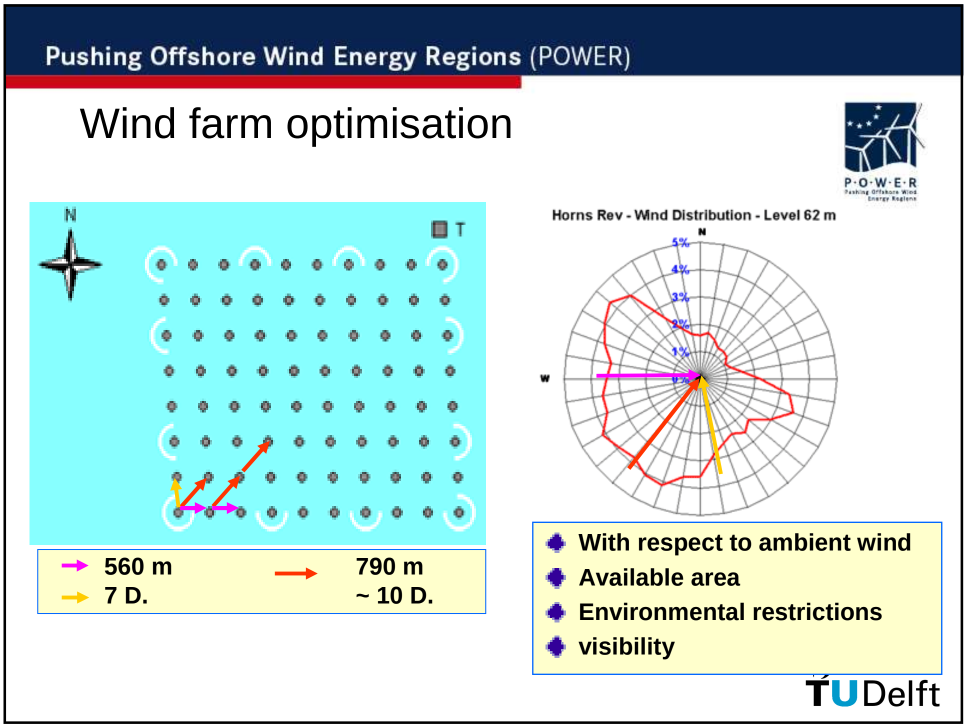
Near Esbjerg (Jutland)
6-14 m depth, area 20 km^2

Pushing Offshore Wind Energy Regions (POWER)

Horns Rev (DK)



Array:
- 10 rows of 8 turbines
- 560 m apart (7 rotor diameters)
- slightly skewed geometry



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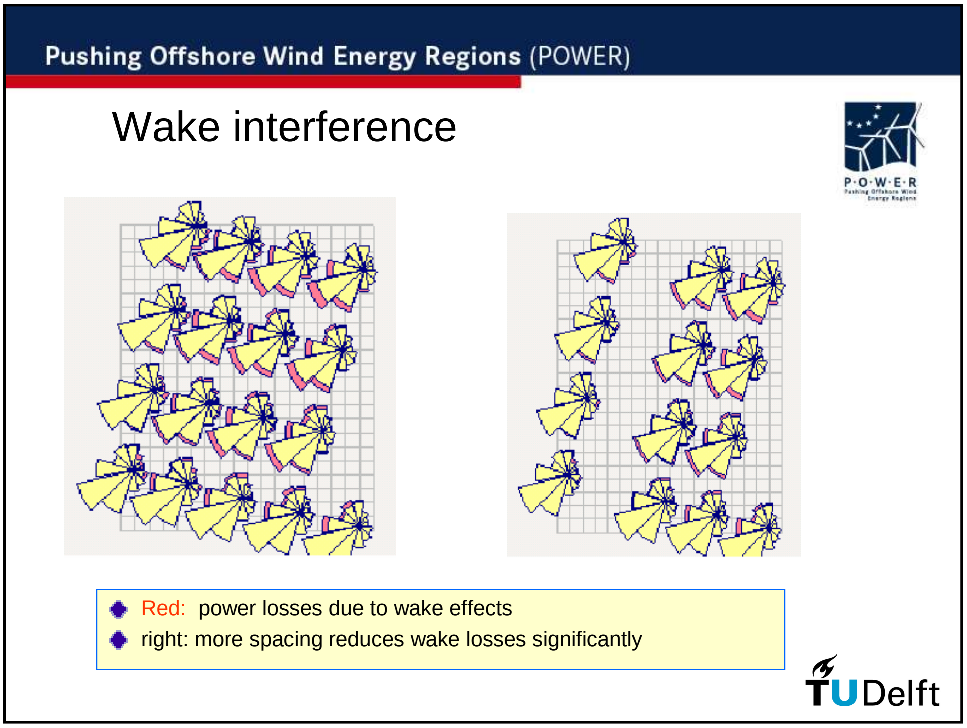
Wind farm optimisation

→ 560 m
→ 7 D.
→ 790 m
~ 10 D.

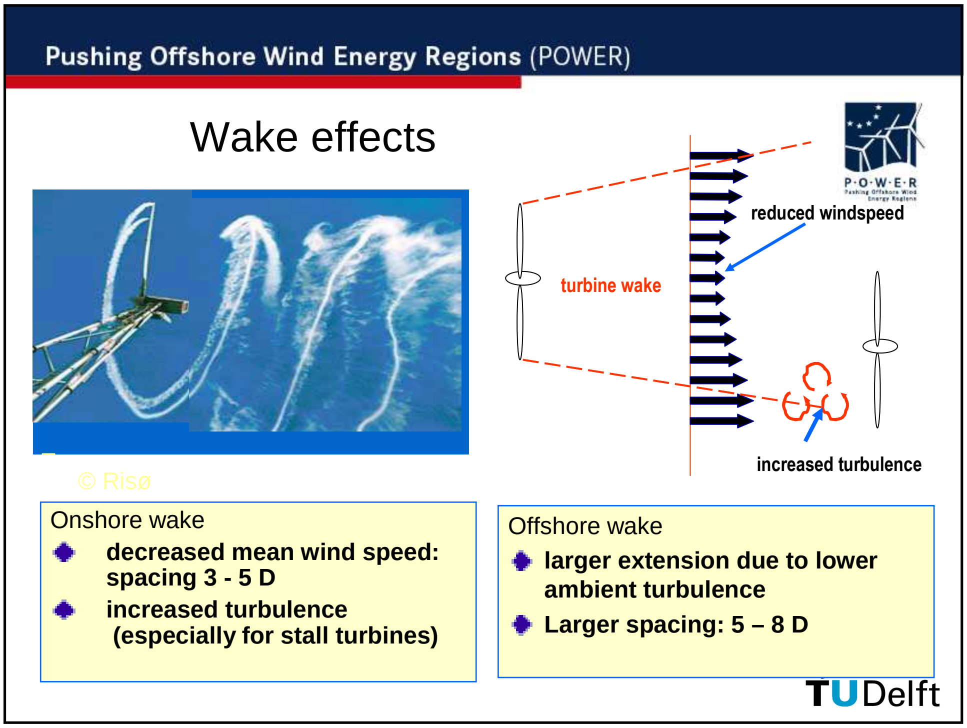
- With respect to ambient wind
- Available area
- Environmental restrictions
- visibility



Pushing Offshore Wind Energy Regions (POWER)

Wake interference

- Red: power losses due to wake effects
- right: more spacing reduces wake losses significantly



Pushing Offshore Wind Energy Regions (POWER)

Wake effects

© Risø

Onshore wake
- **decreased mean wind speed: spacing 3 - 5 D**
- **increased turbulence (especially for stall turbines)**

Offshore wake
- **larger extension due to lower ambient turbulence**
- **Larger spacing: 5 – 8 D**

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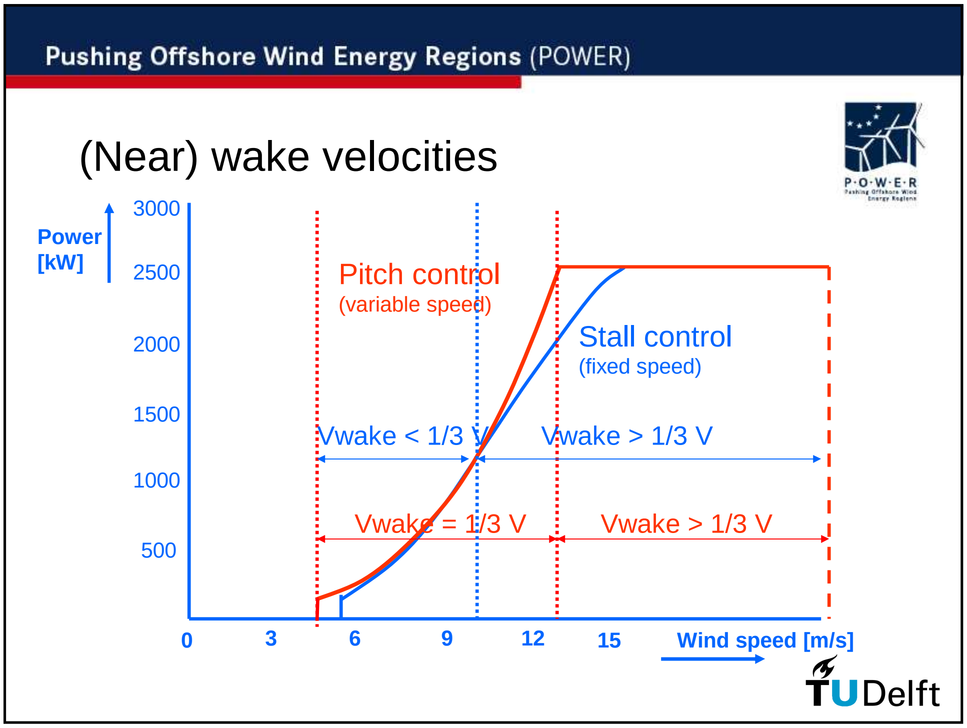

Pushing Offshore Wind Energy Regions (POWER)

(Near) wake velocities

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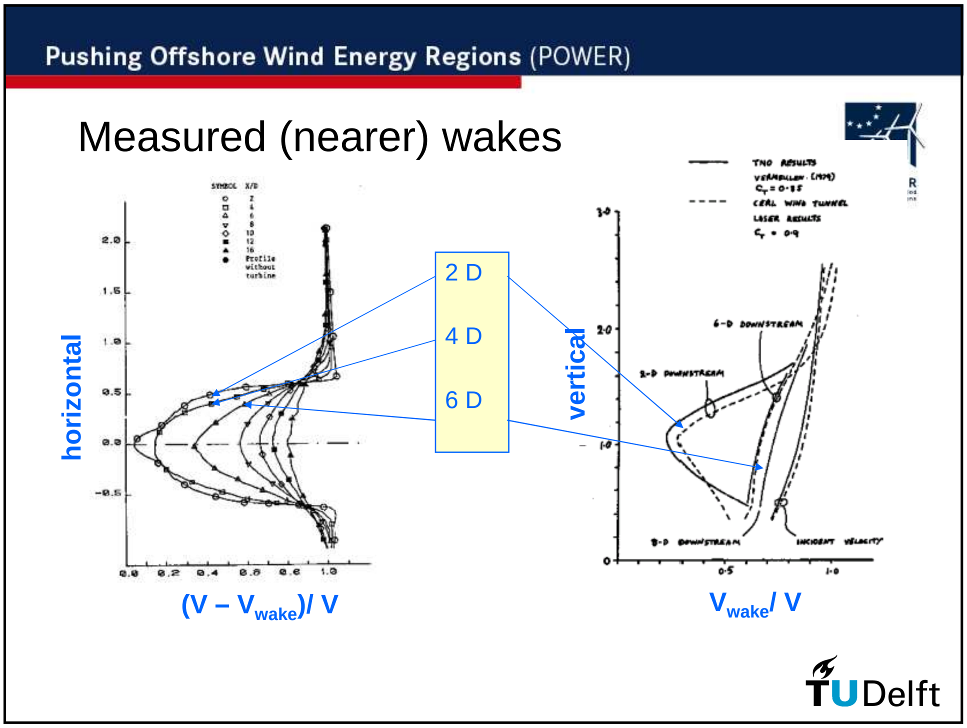
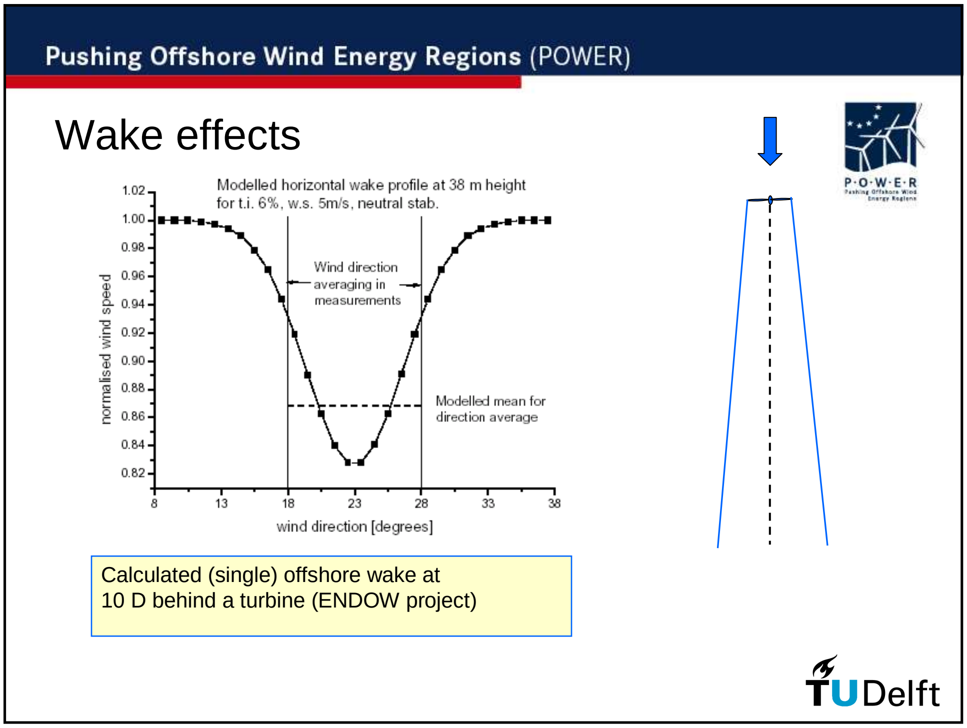


Pushing Offshore Wind Energy Regions (POWER)

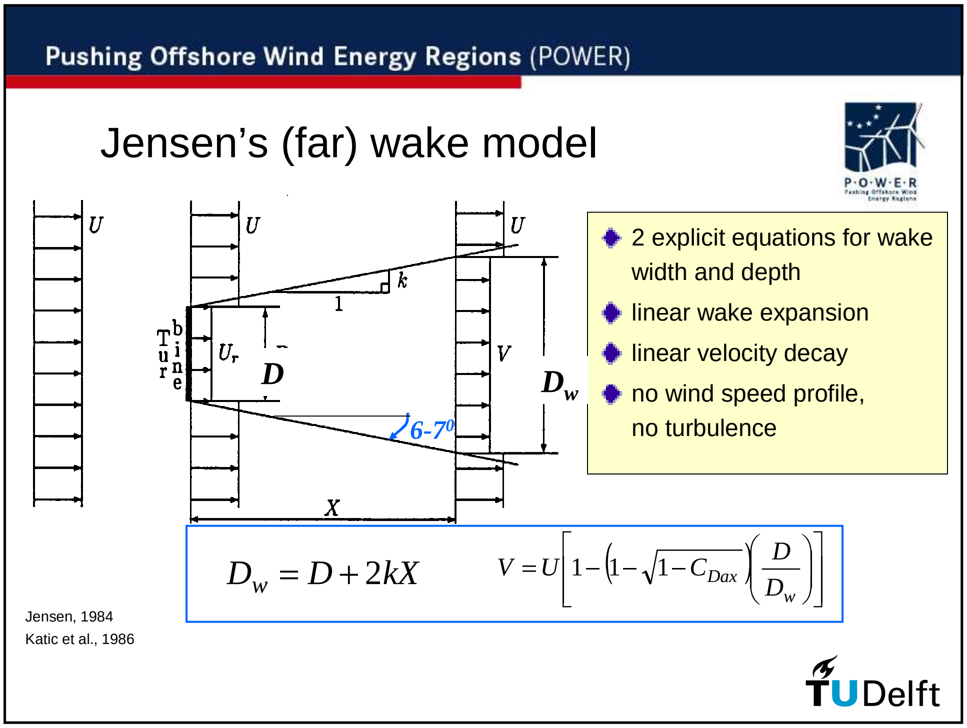
Measured (nearer) wakes



Pushing Offshore Wind Energy Regions (POWER)

Wake effects

Calculated (single) offshore wake at
10 D behind a turbine (ENDOW project)



Pushing Offshore Wind Energy Regions (POWER)

Jensen’s (far) wake model

- 2 explicit equations for wake width and depth
- linear wake expansion
- linear velocity decay
- no wind speed profile, no turbulence

$$D_w = D + 2kX \qquad V = U\left[1-\left(1-\sqrt{1-C_{Dax}}\right)\left(\frac{D}{D_w}\right)\right]$$

Jensen, 1984
Katic et al., 1986

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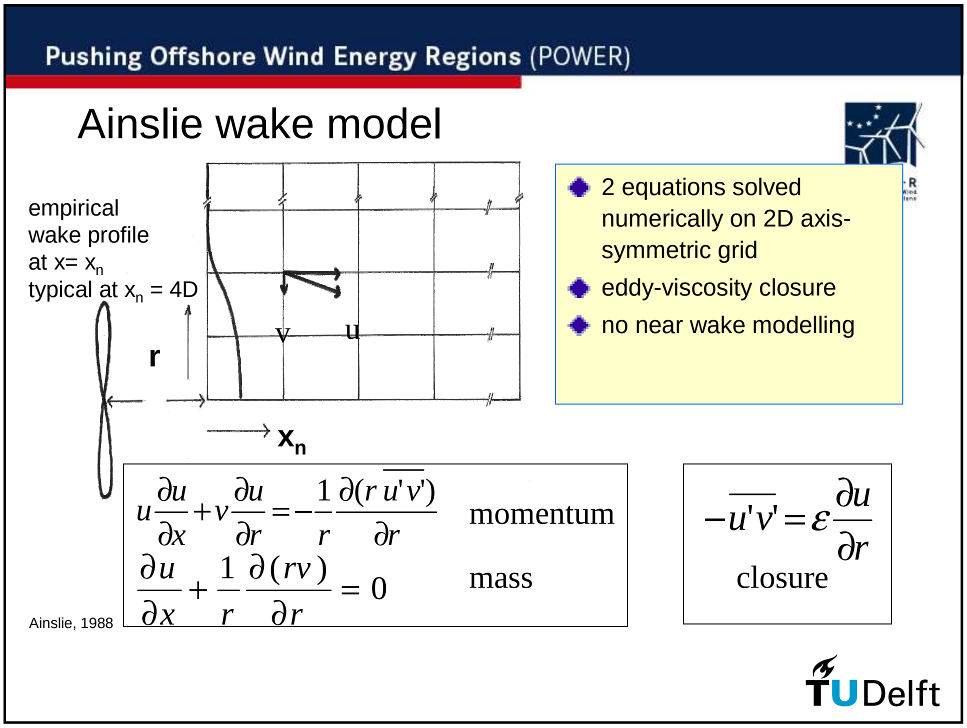

Pushing Offshore Wind Energy Regions (POWER)

Ainslie wake model

- 2 equations solved numerically on 2D axis-symmetric grid
- eddy-viscosity closure
- no near wake modelling

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}=-\frac{1}{r}\frac{\partial(r\overline{u'v'})}{\partial r} \quad \text{momentum}$$

$$\frac{\partial u}{\partial x}+\frac{1}{r}\frac{\partial(rv)}{\partial r}=0 \quad \text{mass}$$

$$-\overline{u'v'}=\varepsilon\frac{\partial u}{\partial r}$$

closure

Ainslie, 1988

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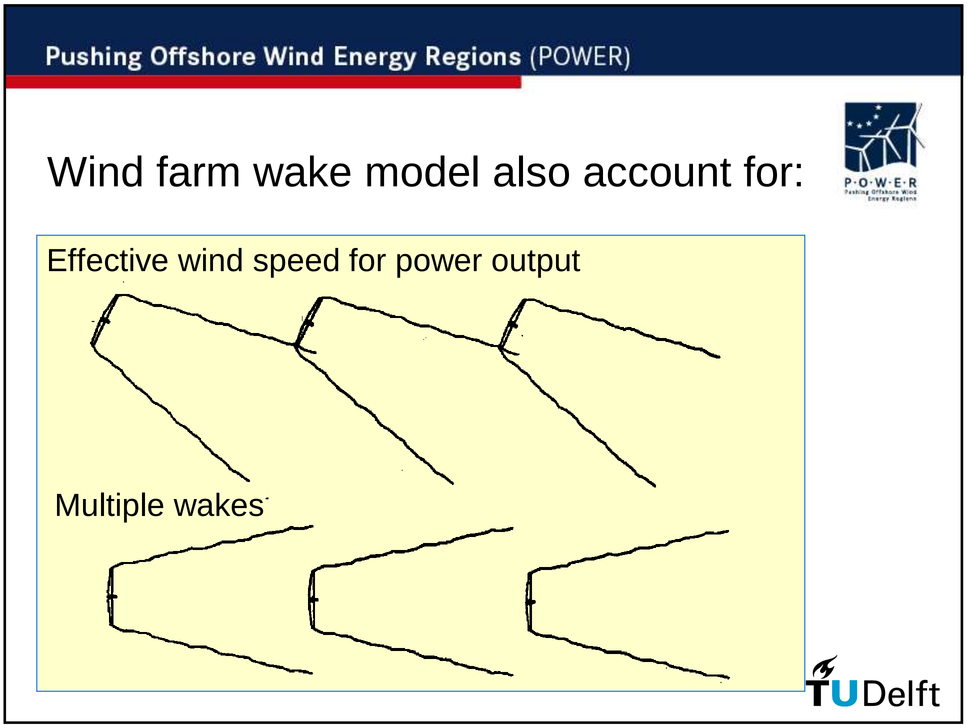

Pushing Offshore Wind Energy Regions (POWER)

Wind farm wake model also account for:

Effective wind speed for power output

Multiple wakes

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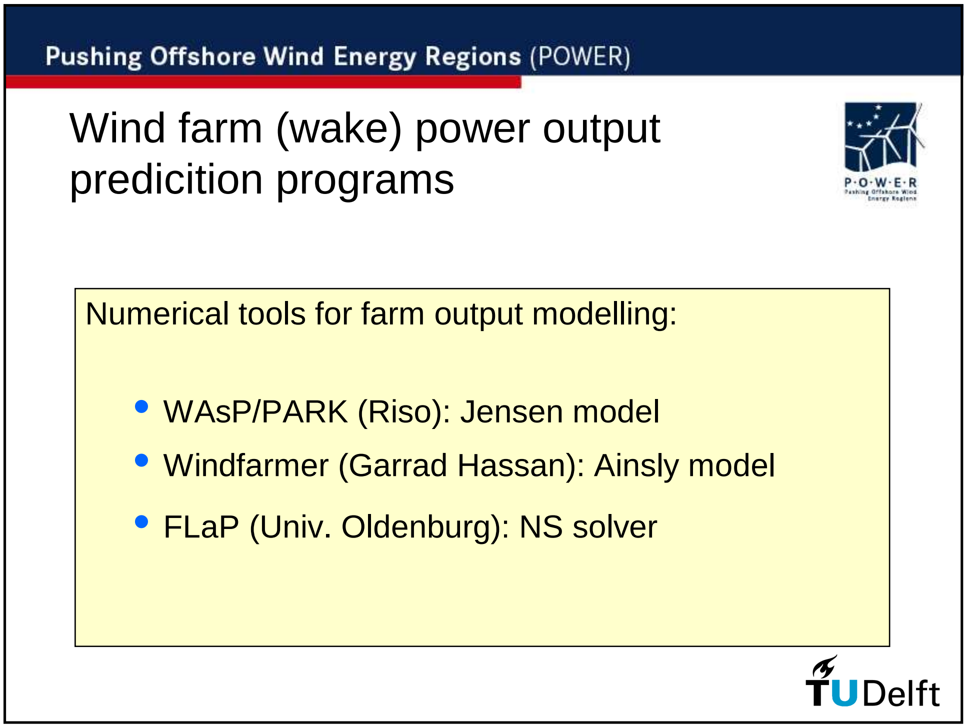

Pushing Offshore Wind Energy Regions (POWER)

Wind farm (wake) power output predicition programs

Numerical tools for farm output modelling:

- WAsP/PARK (Riso): Jensen model
- Windfarmer (Garrad Hassan): Ainsly model
- FLaP (Univ. Oldenburg): NS solver

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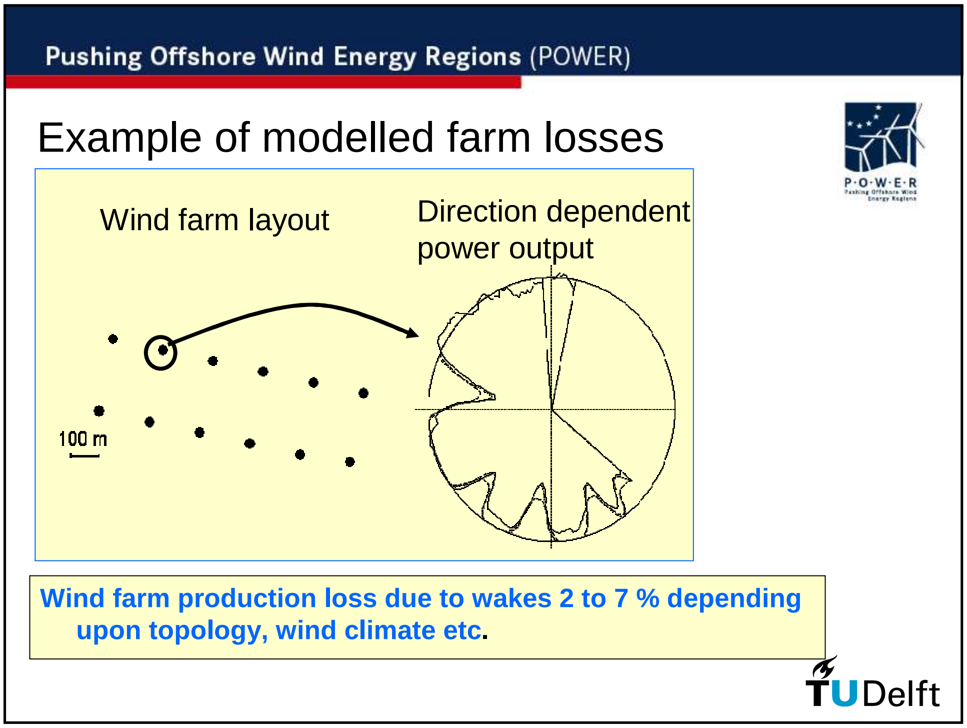

Pushing Offshore Wind Energy Regions (POWER)

Example of modelled farm losses

Wind farm layout

Direction dependent power output

Wind farm production loss due to wakes 2 to 7 % depending upon topology, wind climate etc.

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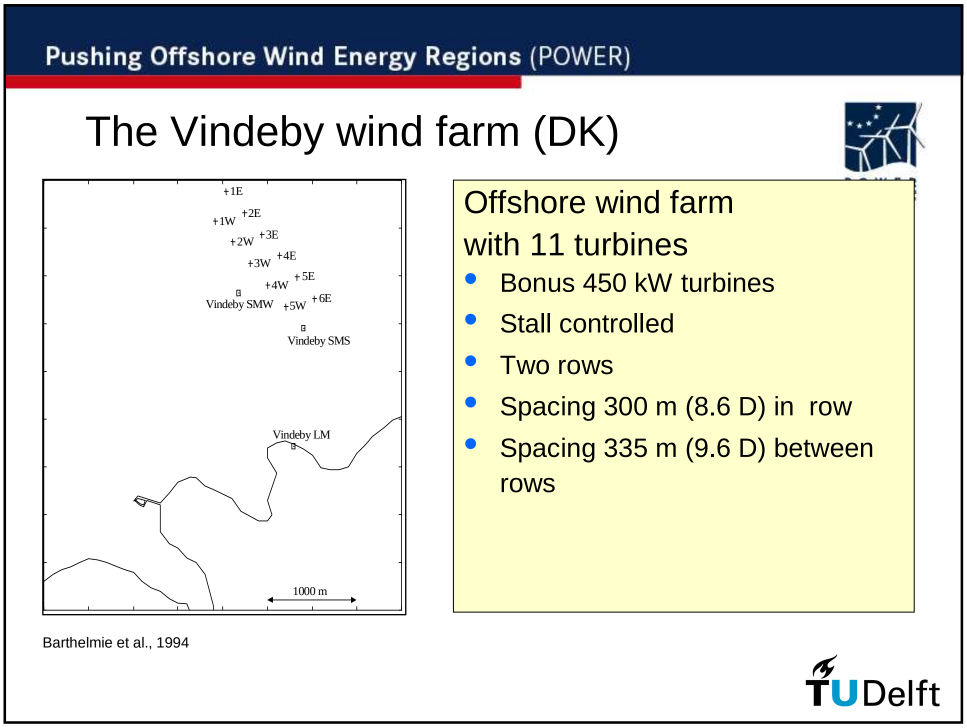

Pushing Offshore Wind Energy Regions (POWER)

The Vindeby wind farm (DK)

Barthelmie et al., 1994

Offshore wind farm with 11 turbines

- Bonus 450 kW turbines
- Stall controlled
- Two rows
- Spacing 300 m (8.6 D) in row
- Spacing 335 m (9.6 D) between rows

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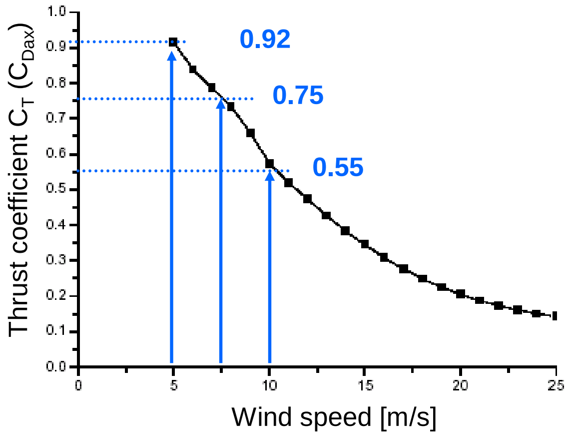
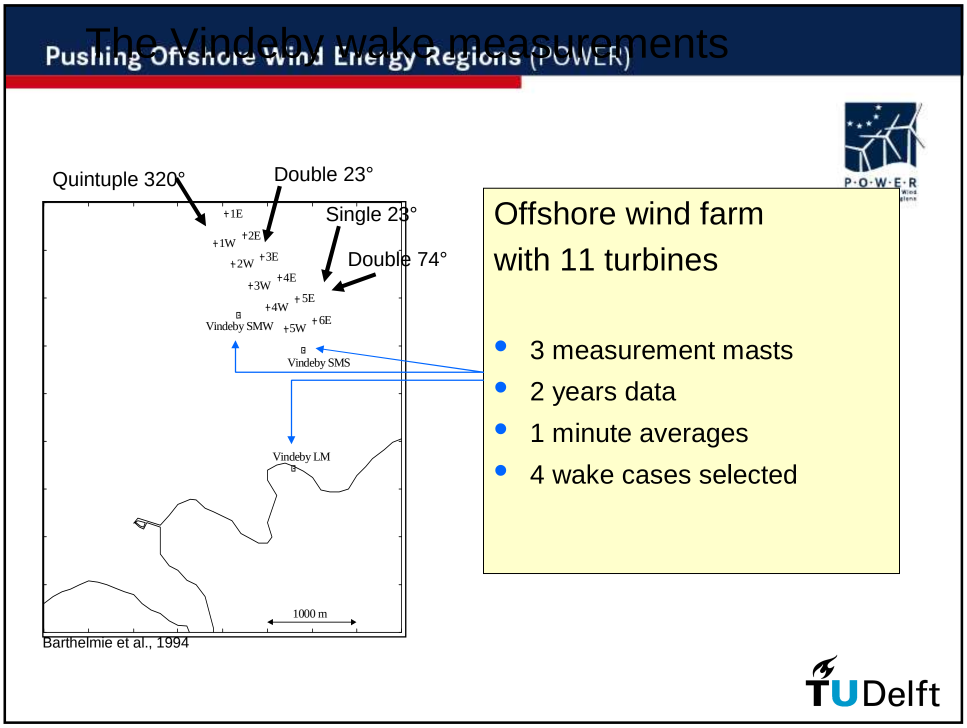
Thrust coefficient of Bonus 450 kW



The Vindeby windfarm

Near shore wind farm
with 11 BONUS windturbines



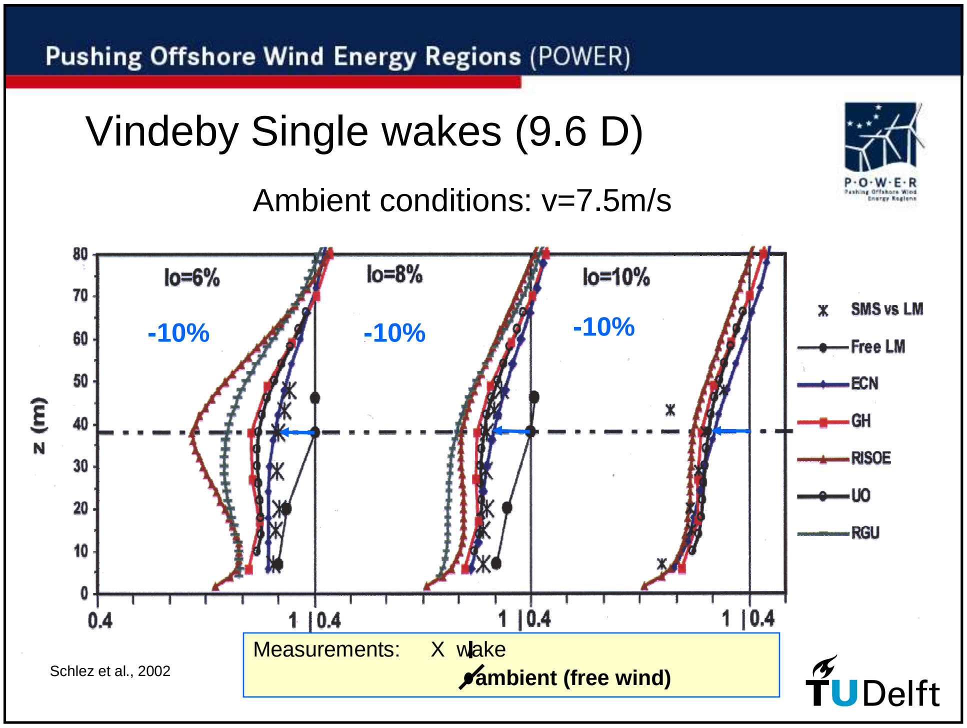
Pushing Offshore Wind Energy Regions (POWER)

The Vindeby wake measurements

Barthelmie et al., 1994

Offshore wind farm with 11 turbines

- 3 measurement masts
- 2 years data
- 1 minute averages
- 4 wake cases selected



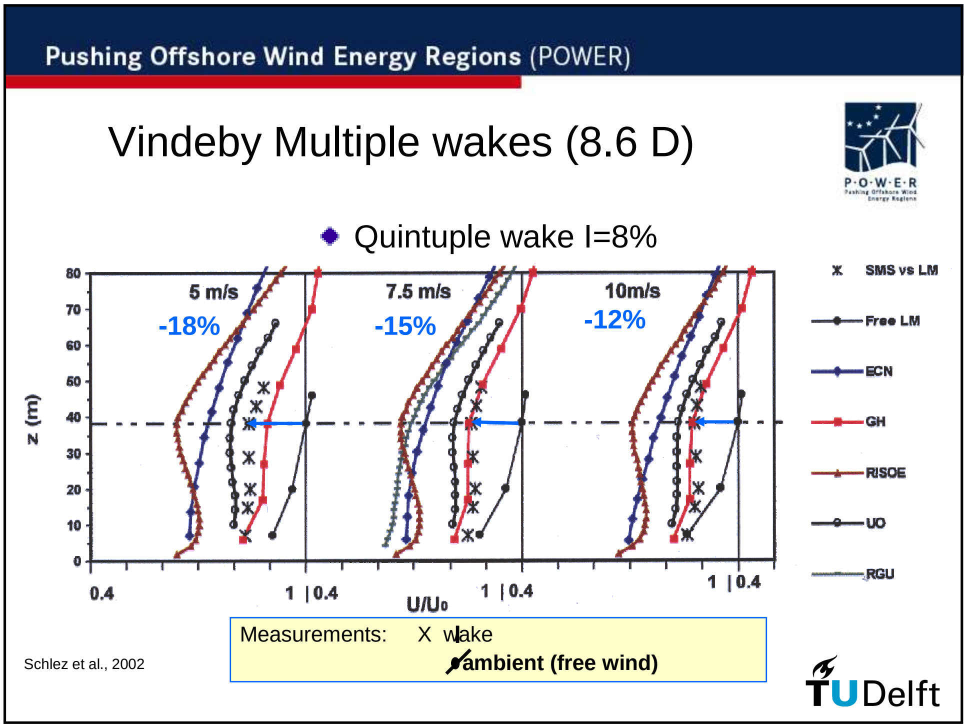
Pushing Offshore Wind Energy Regions (POWER)

Vindeby Single wakes (9.6 D)

Ambient conditions: v=7.5m/s

Measurements: X wake
ambient (free wind)

Schlez et al., 2002



Pushing Offshore Wind Energy Regions (POWER)

Vindeby Multiple wakes (8.6 D)

- Quintuple wake I=8%

Measurements: X wake
● ambient (free wind)

Schlez et al., 2002

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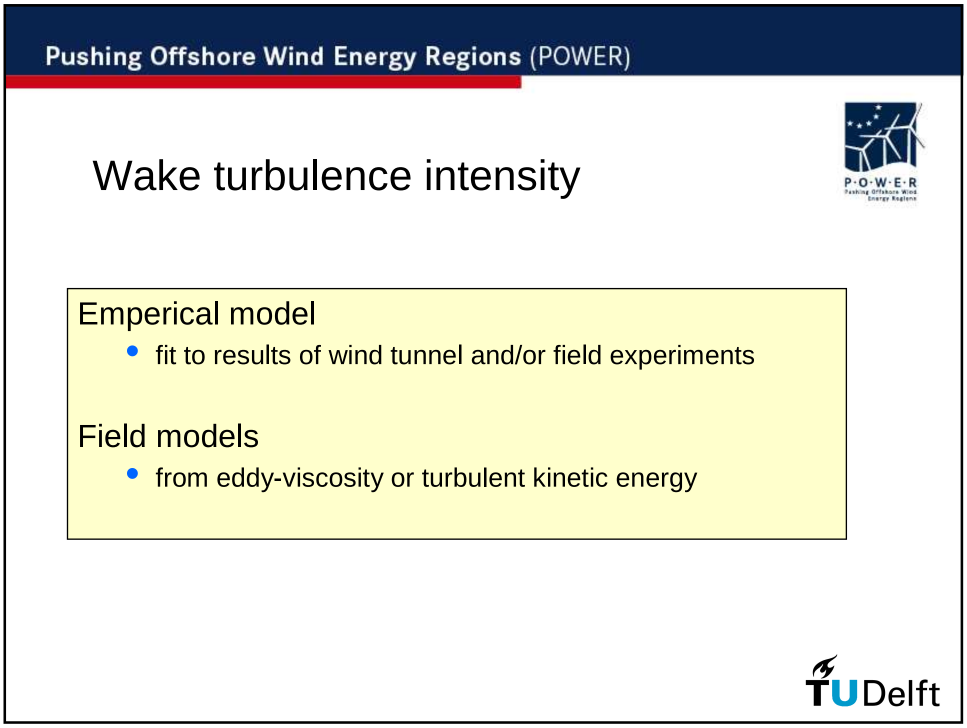

Pushing Offshore Wind Energy Regions (POWER)

Wake turbulence intensity

Emperical model

- fit to results of wind tunnel and/or field experiments

Field models

- from eddy-viscosity or turbulent kinetic energy

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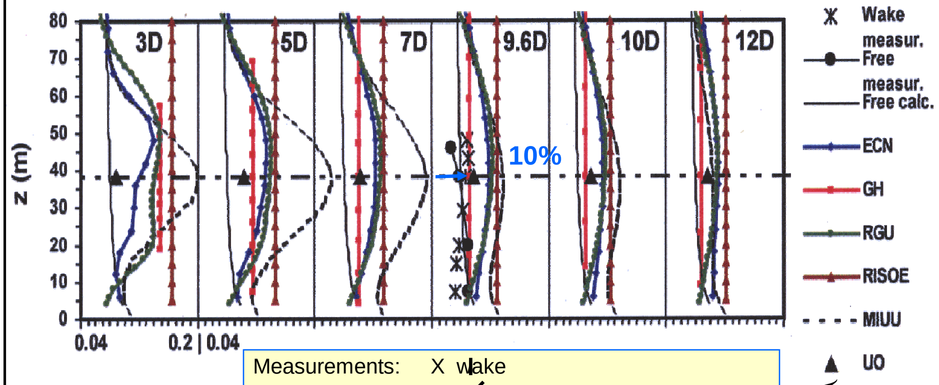
Turbulence in a wake

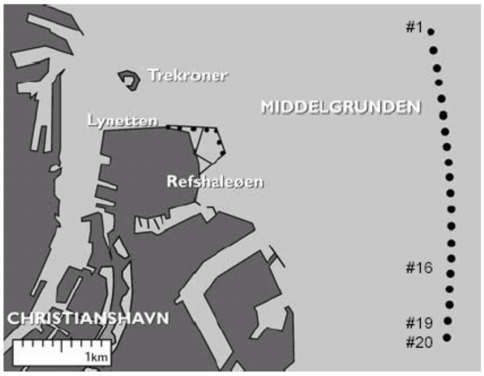
Ambient conditions: v=7.5m/s I=8%



Measurements: X wake
● **ambient (free wind)**

Rados et al., 2002

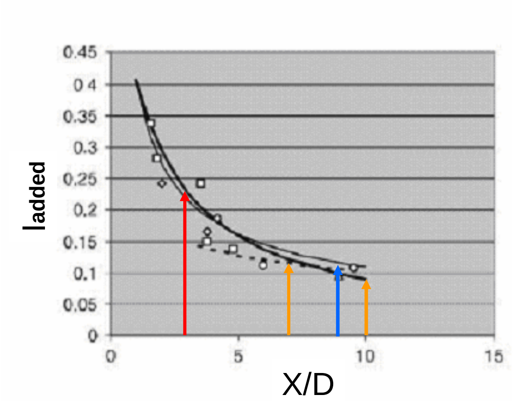
Middelgrunden wind farm



- 20 turbines
- Bonus 2000 kW
- (active) stall controlled
- one “row”
- Spacing 183 m (2.4 D)!!
- Production on line visible !!

www.middelgrund.com

Added turbulence in (single) wake



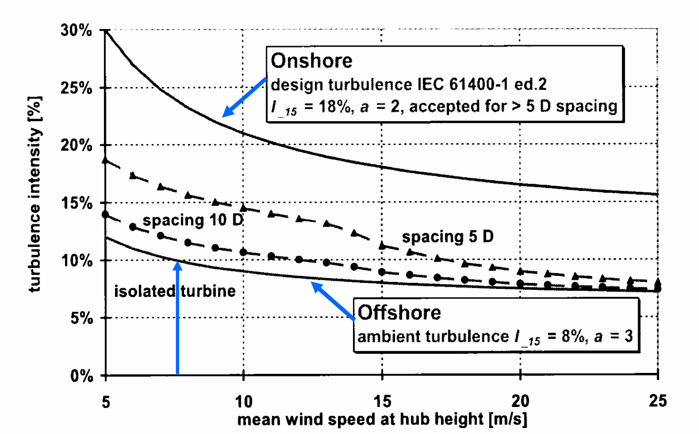
Added turbulence at hub height

$$\Delta I = \sqrt{I^2 + I_\infty^2}$$

- Vindeby
- Horns Rev
- Middelgrunden

Various sources compiled by Ghaie (1997)

Turbulence in offshore wind farms

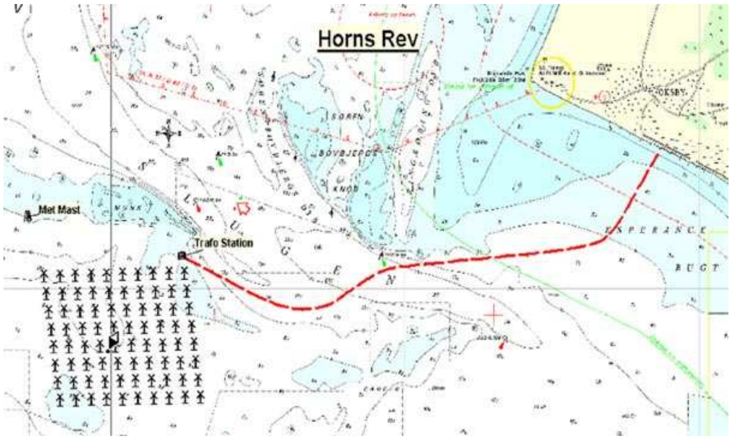


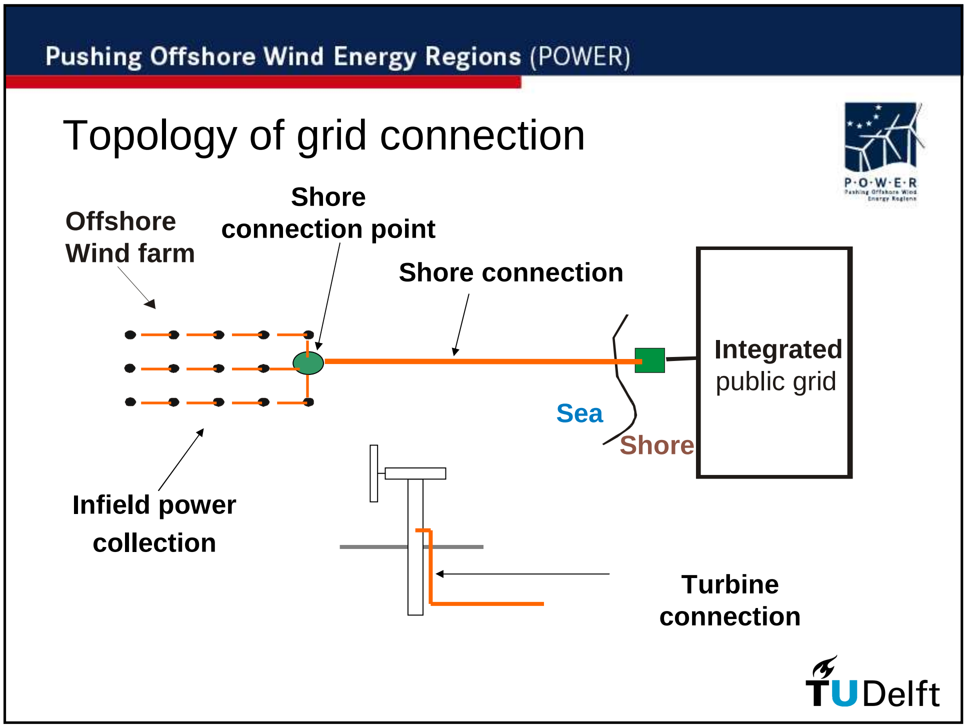
Vindeby

Summary wakes and wake losses

- spacing offshore >7 D with some (extreme) exceptions
- velocity reduction in wakes 10 – 20%
- production loss due to wakes 2 – 7%
- turbulence increase 8 – 10%
- with 8% ambient turbulence:
  => total wake turbulence 10 – 13% (> 7 D)

Electrical transmission (Horns Rev)





Pushing Offshore Wind Energy Regions (POWER)

Topology of grid connection

Offshore Wind farm

Shore connection point

Shore connection

Integrated public grid

Sea

Shore

Infield power collection

Turbine connection

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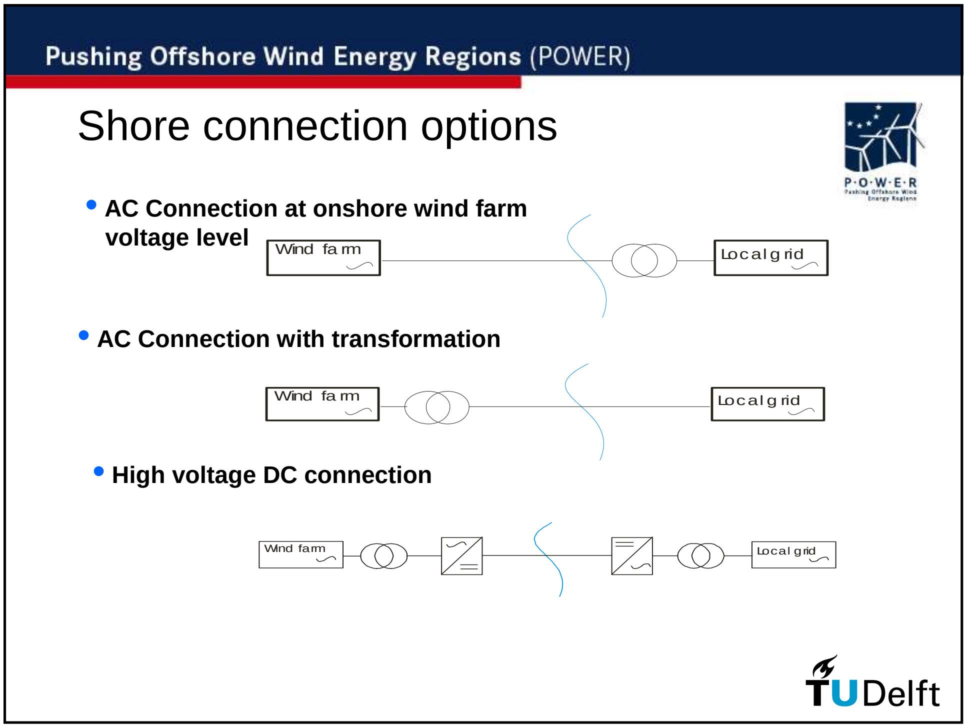

Pushing Offshore Wind Energy Regions (POWER)

Shore connection options

- AC Connection at onshore wind farm voltage level

- AC Connection with transformation

- High voltage DC connection

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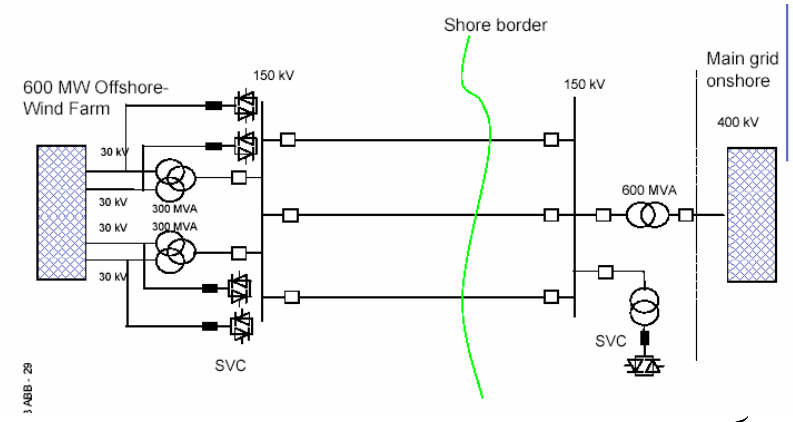
600 MW AC connection



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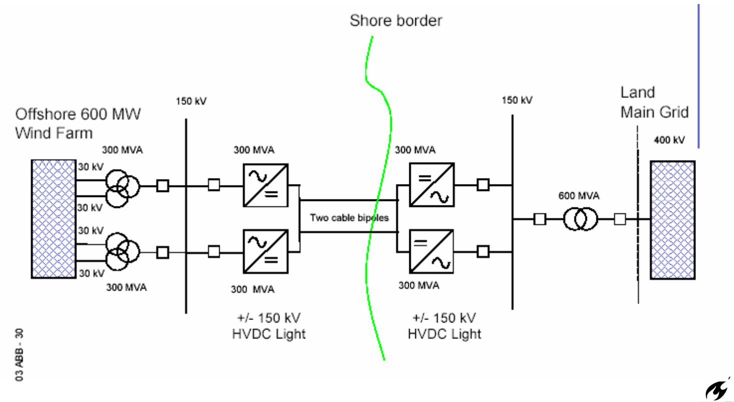
600 MW DC connection



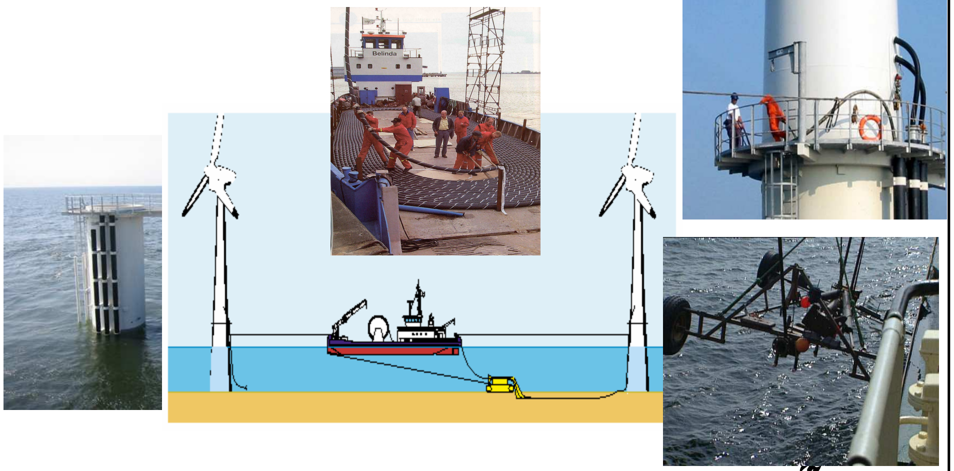
Components for power collection and transmission

- cables
- transformers for voltage adaptations
- switch gears for protection and redundancy
- offshore connection platform (larger wind farms)
- onshore connection point
- (HVDC) power electronic converters (if present)
- VAR compensators for AC voltage (if required)

Power cable installation

Specialised installation with existing equipment

Power cable installation and turbine connection



Offshore wind farm electrical systems

Wind farm name	Power	Collection voltage	Transm. Voltage	Distance to shore	
Utgrunden (S)	7 x 1.4 MW	20 kV	20 kV	8 km	AC
Middelgrunden (Dk)	20 x 2 MW	30 kV	30 kV	3 km	AC
Horns Rev (Dk)	80 x 2 MW	36 kV	150 kV	15 km	AC
Nysted Rodsand (Dk)	158 MW	33 kV	132 kV	10 km	AC
Egmond (NL)	100 MW	~33 kV	~ 33 kV	8 km	AC

- no DC connections yet
- larger farms at 110-150 kV level

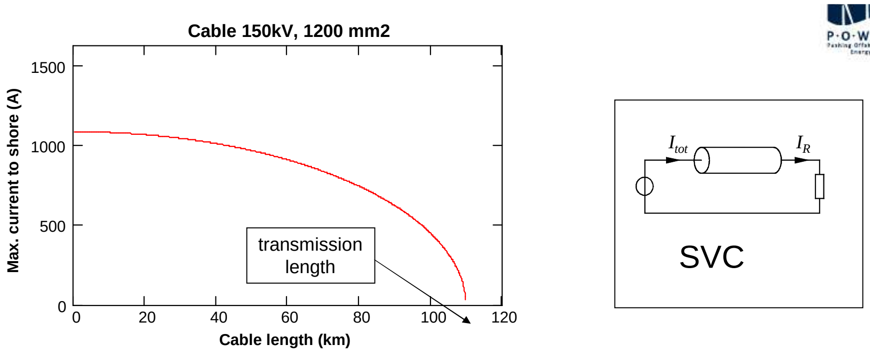
Pushing Offshore Wind Energy Regions (POWER)

Limiting factors for AC transmission

- cable current limited to 1000 - 1500 A (ampacity) with 150 kV → 150 – 200 MW
- cable losses increase with i^2
  → high voltage to reduce losses in long cables
- availability of space for placement of equipment
- reactive-power consumption of long AC cables
- high initial costs of high-voltage equipment
- failure risk of components
- distance to shore

Pushing Offshore Wind Energy Regions (POWER)

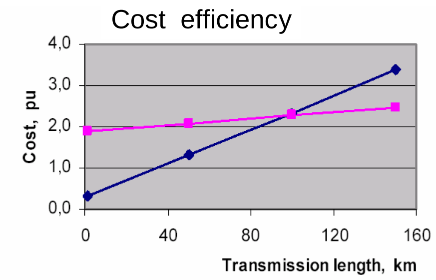
Allowable load current AC cables

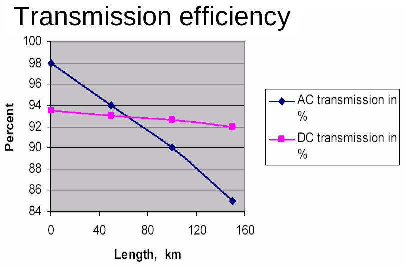


- compensation of capacitive current required for medium length cables using SVC’s (Static VAR Compensators)
-

Pushing Offshore Wind Energy Regions (POWER)

AC versus DC connection





w ith 1 pu cost = DC investment 0 km

Losses evaluated with 9,1 €C/kWh, 20 years 7 %

- compensation of capacitive current required for medium length cables using SVC's (Static VAR Compensators)
- DC feasible for cable connections longer than 60 km (!?)

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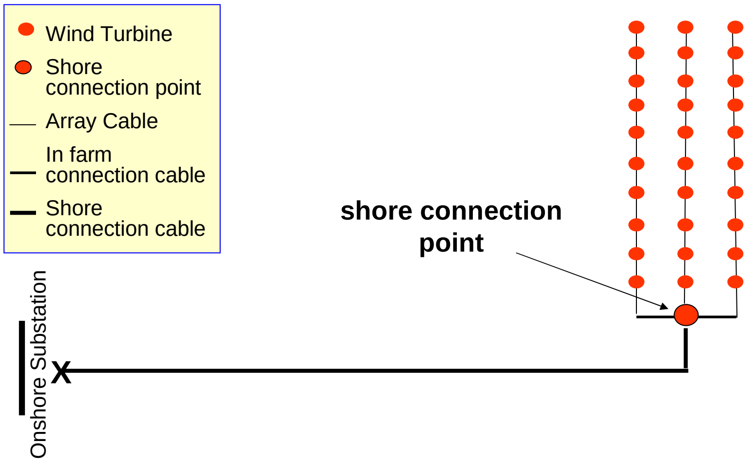
Pushing Offshore Wind Energy Regions (POWER)

Network Topologies
String or Radial Network



e.g. Horns Rev

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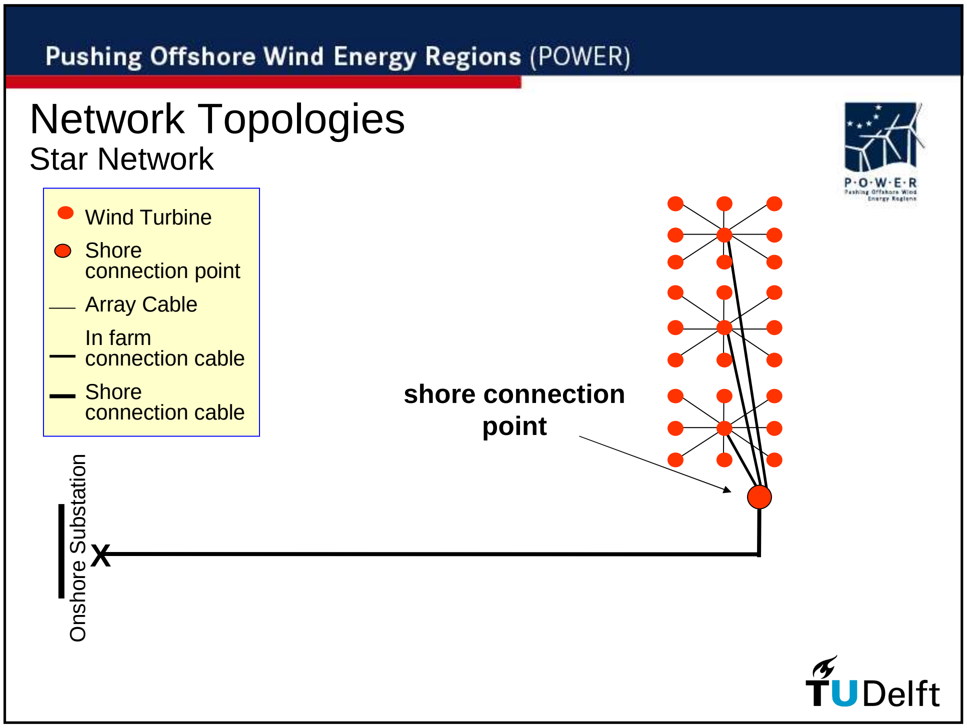

Pushing Offshore Wind Energy Regions (POWER)

Network Topologies

Star Network

- ● Wind Turbine
- ● Shore connection point
- — Array Cable
- — In farm connection cable
- — Shore connection cable

shore connection point

Onshore Substation

X

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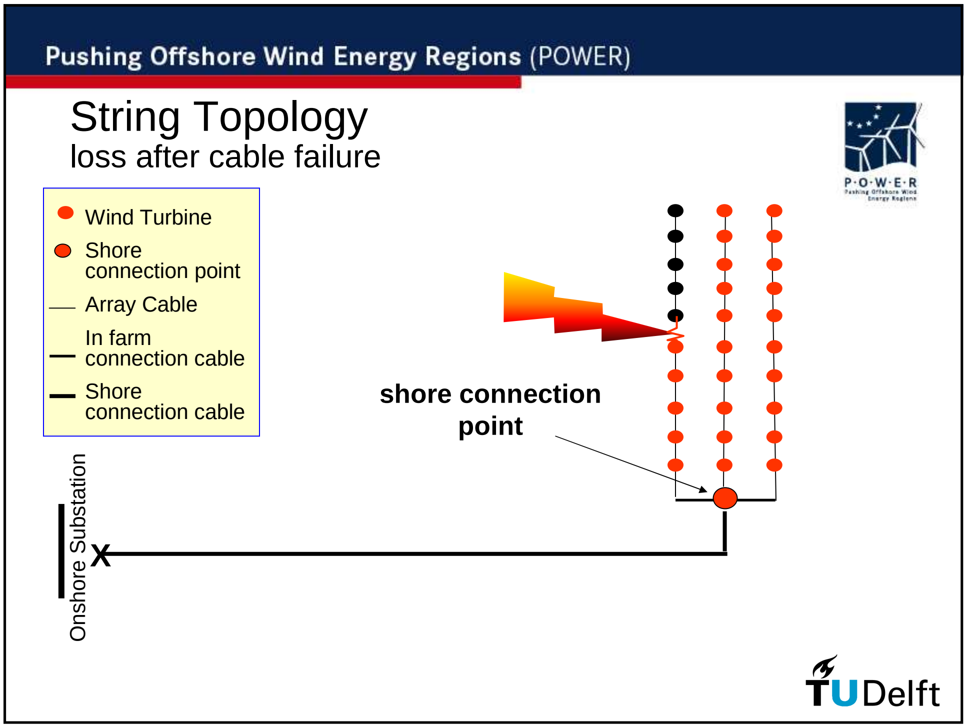


Pushing Offshore Wind Energy Regions (POWER)

String Topology

loss after cable failure

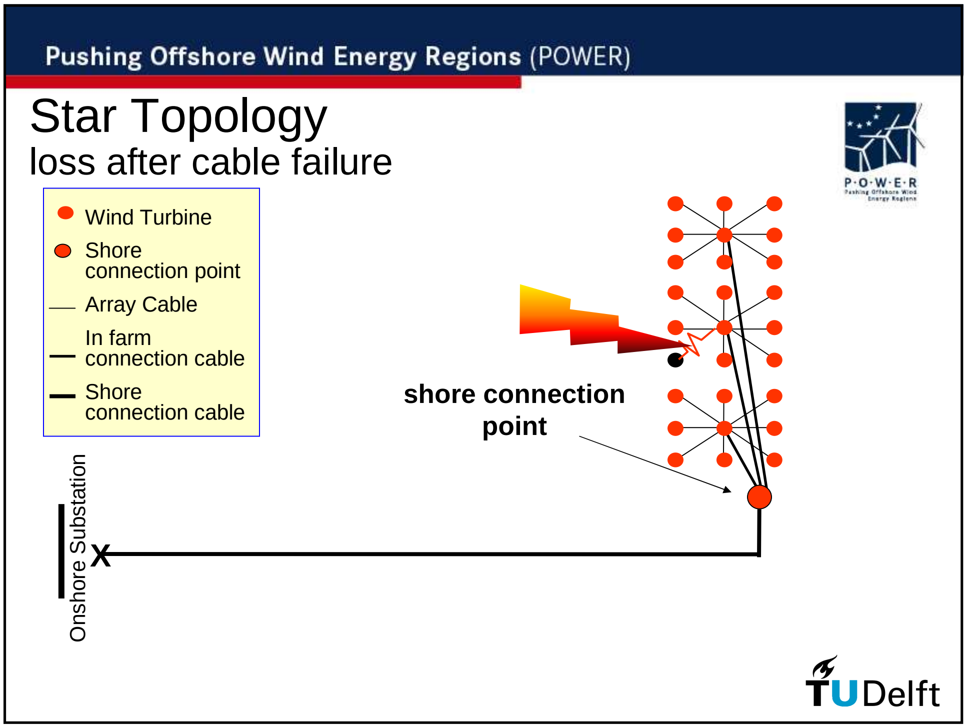
- ● Wind Turbine
- ● Shore connection point
- — Array Cable
- — In farm connection cable
- — Shore connection cable

shore connection point

Onshore Substation

X

TUDelft



Pushing Offshore Wind Energy Regions (POWER)

Star Topology

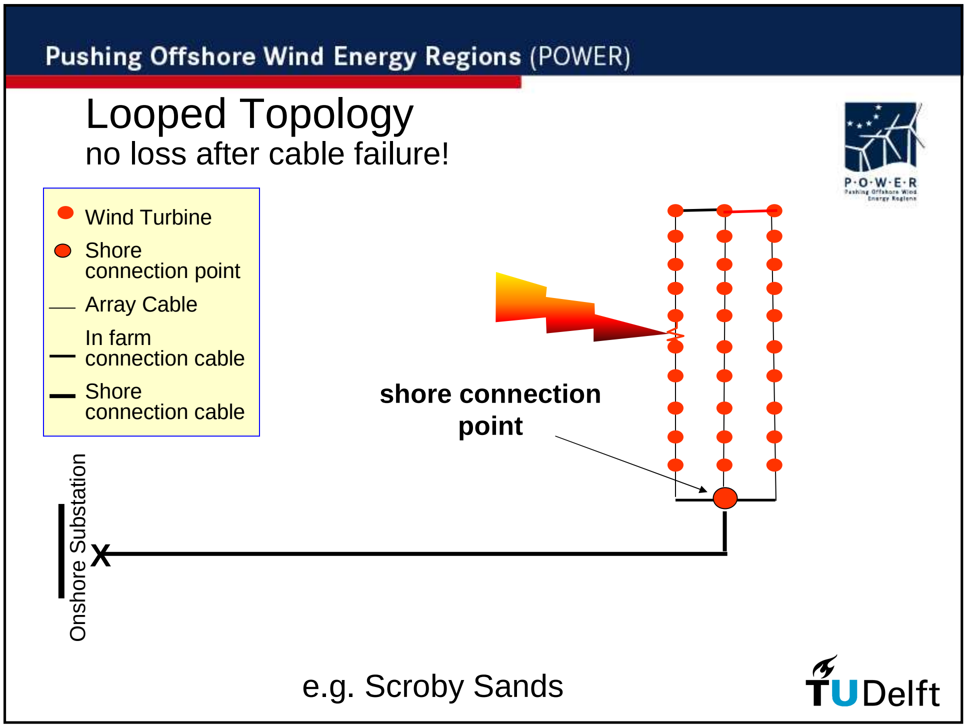
loss after cable failure

- ● Wind Turbine
- ● Shore connection point
- — Array Cable
- — In farm connection cable
- — Shore connection cable

shore connection point

Onshore Substation

X



Pushing Offshore Wind Energy Regions (POWER)

Looped Topology

no loss after cable failure!

- ● Wind Turbine
- ● Shore connection point
- — Array Cable
- — In farm connection cable
- — Shore connection cable

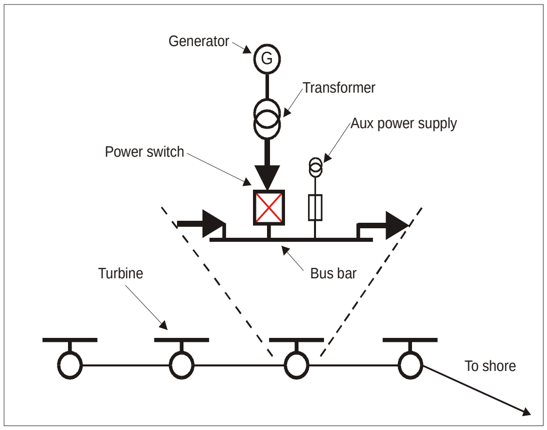
shore connection point

Onshore Substation

X

e.g. Scroby Sands

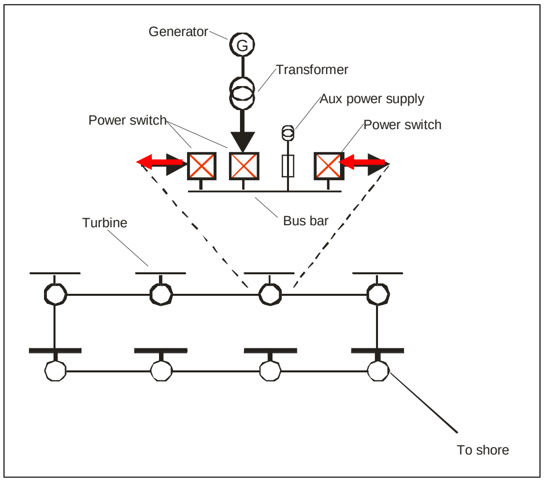
String and Star Topology



Fairly simple power connection:

- Single power switch => reliable
- No redundancy
- Loss of auxiliary power

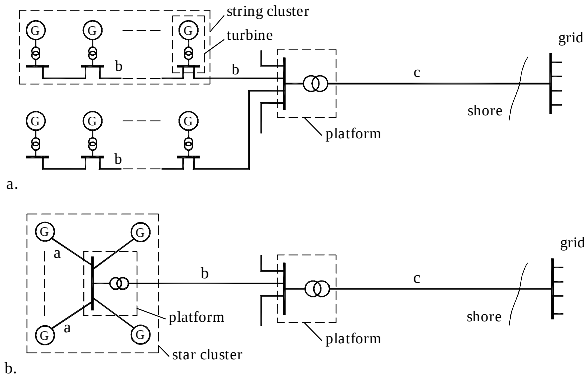
Looped Topology



Complex power connection:

- Triple power switch => more complex
- Redundant
- No loss of auxiliary power

Lay-out of infield wind farm connections



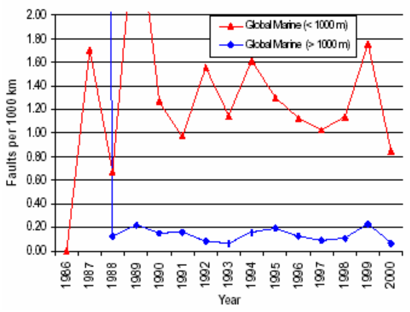
string cluster:

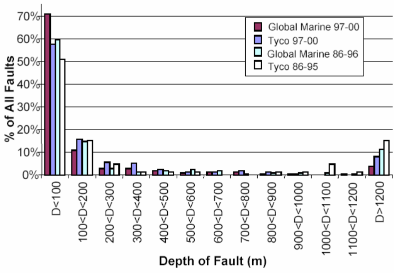
- two voltage levels
- individual trafo's

star cluster:

- three voltage levels possible
- option: shared trafo
- extra substation ??

Power cable failure rates





~ 1 failure per 1000 km per year

Pushing Offshore Wind Energy Regions (POWER)

Electric failure rates
(for 30 offshore wind turbines)

Component	Number of Failures in 20 year life of Wind Farm	
	String Network	Looped string Network
Array Cable	3.09	3.35
Shore Link Cable	3.12	3.12
MV Switchgear	0.24	0.74
Terminations	2.98	2.98
Total (20 yrs):	**9.43**	**10.19**

Source: Econnect UK

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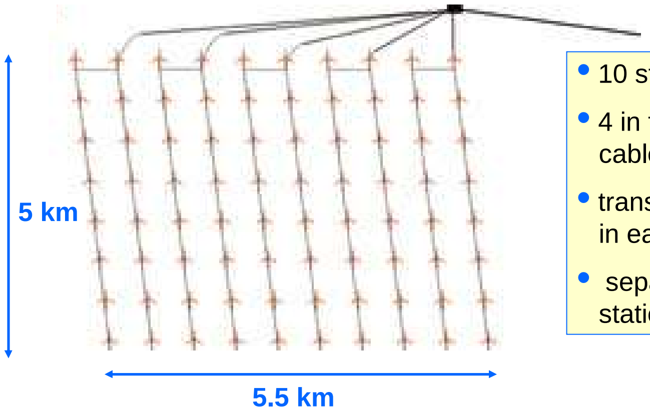
Pushing Offshore Wind Energy Regions (POWER)

Horns Rev lay out



- 10 strings of 8 turbines
- 4 in farm connection cables (16 turbines each)
- transformer 690 – 36 kV in each turbine
- separate transformer station: 36kV/150kV

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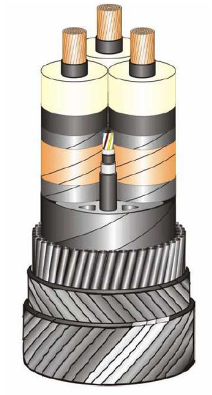
Electrical collection (Horns Rev)

- 5 double strings, AC 36 kV (Medium Voltage)
- no submerged connections (connections in turbines)



- triple-core copper cable with led shielding incl fibre optics for communication
- 95 and 150 mm^2 in strings
- 400 mm^2 from cluster to trafo platform
- 80 – 140 mm diameter
- 20 – 42 kg/m

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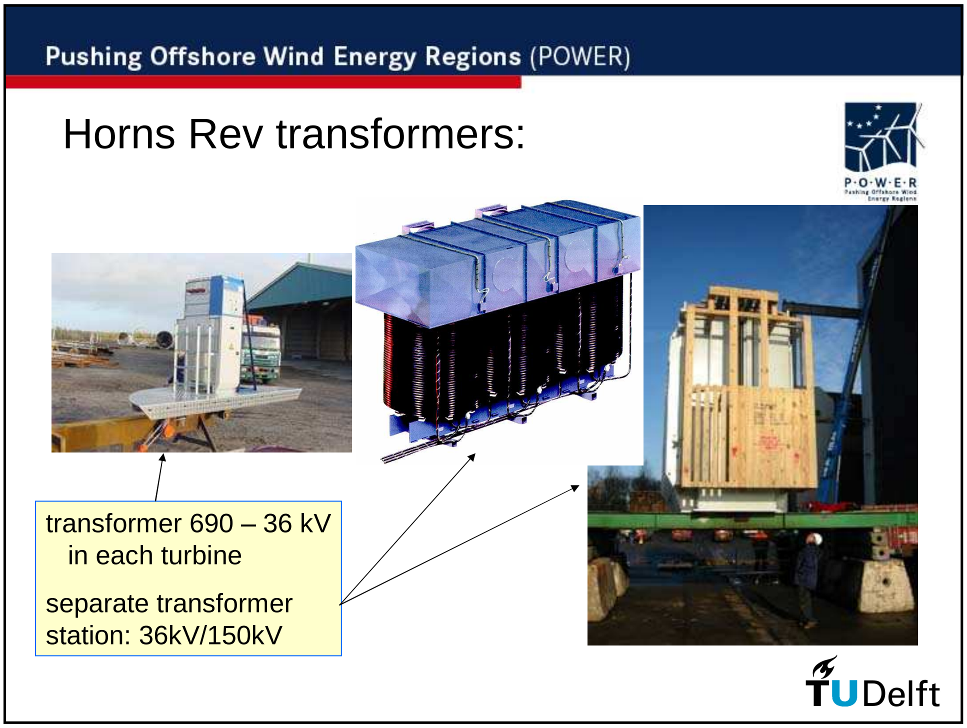
Summary infield power collection

- high cable laying costs
- buried at 1-2 m depth or more (currents, anchors)
- most times string lay out
- sometimes looping yet applied
- connections in wind turbine
- no substations apart from power collection point (larger wind farms)

TU Delft

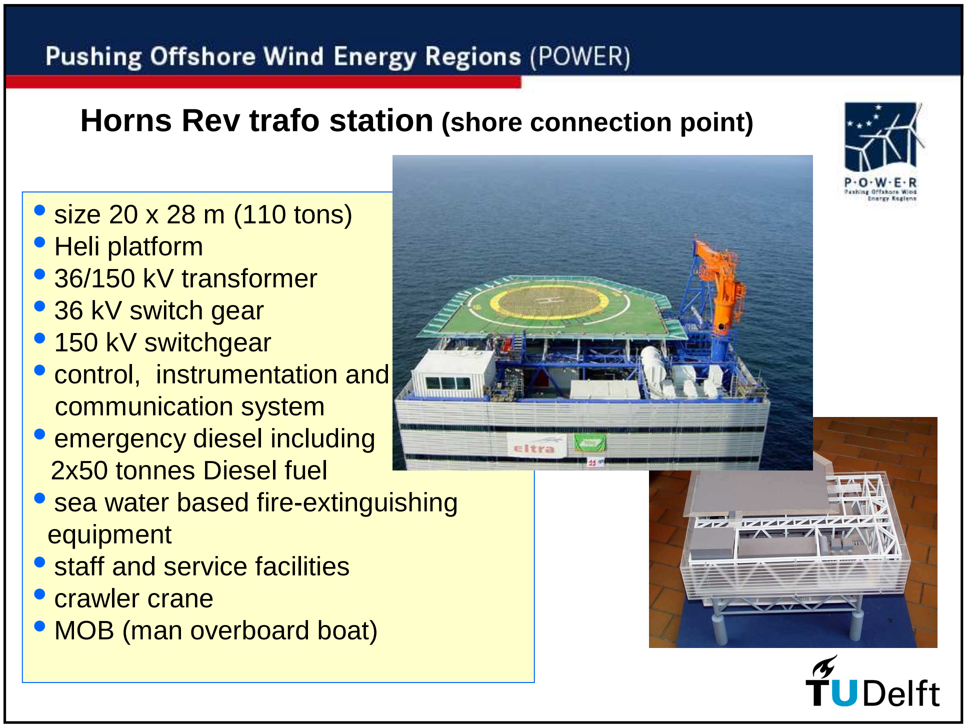


Pushing Offshore Wind Energy Regions (POWER)

Horns Rev transformers:

transformer 690 – 36 kV in each turbine

separate transformer station: 36kV/150kV



Pushing Offshore Wind Energy Regions (POWER)

Horns Rev trafo station (shore connection point)

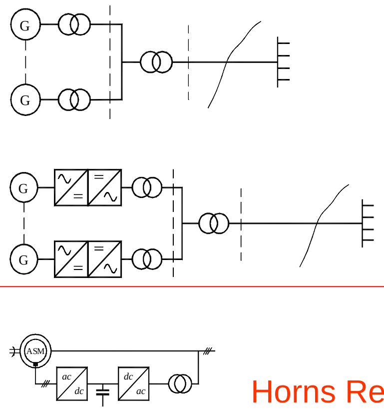
- size 20 x 28 m (110 tons)
- Heli platform
- 36/150 kV transformer
- 36 kV switch gear
- 150 kV switchgear
- control, instrumentation and communication system
- emergency diesel including 2x50 tonnes Diesel fuel
- sea water based fire-extinguishing equipment
- staff and service facilities
- crawler crane
- MOB (man overboard boat)

Summary substations and connection cables

- substations are costly and brings (some) extra failure risks
- cables (+laying) are costly
- simplest approach is usually adopted to reduce investment (and costs ??)
  - → substations avoided if possible
    - losses higher than technically feasible
    - transmission voltage = collection voltage
  - → no meshing/looping (→no redundancy)
  - → no double shore connections (→no redundancy)

Present electrical system in wind farm with individual turbine control

(State of the art wind farms)



Constant speed

Variable speed

“synchronous”

Asynchronous doubly fed generator

Horns Rev

Summary grid connection and control

- Reactive power compensation required for medium length cables (AC connection)
- Maximum distance with AC is limited to 50-60 km
- DC-links required for remote offshore farms