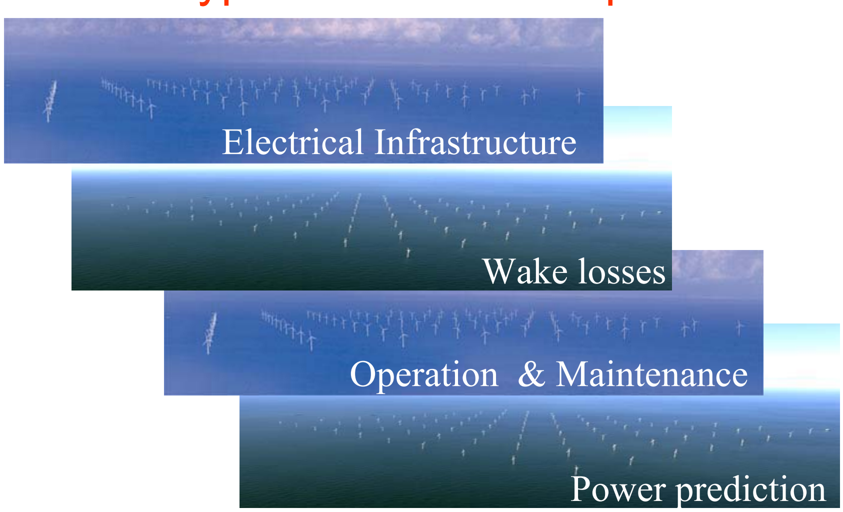
Typical wind farm aspects

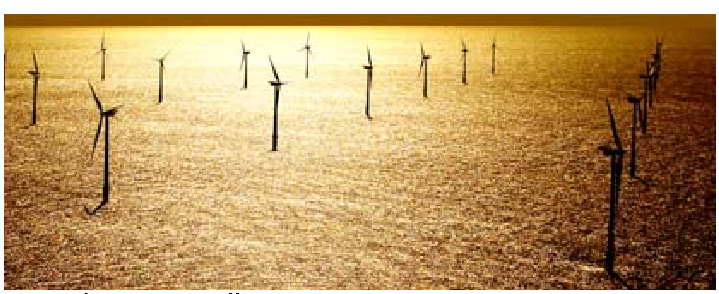


Contents

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

"The example"

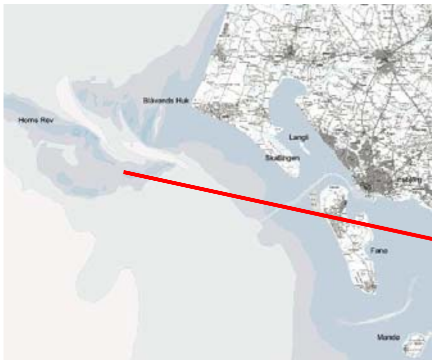
Horns Rev, an 80 unit offshore wind farm
in the North Sea



www.hornsrev.dk

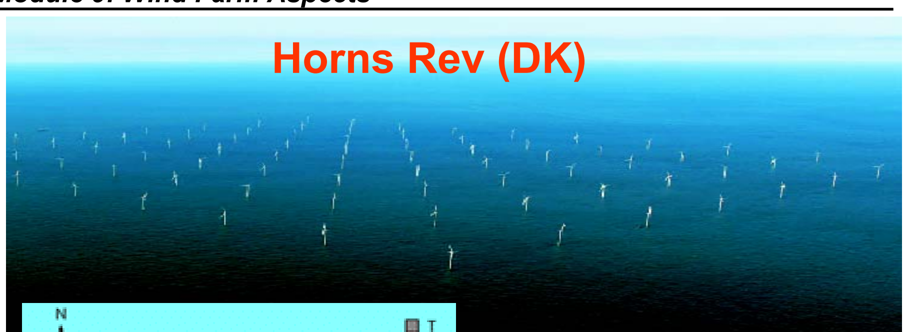
Horns Rev (DK)

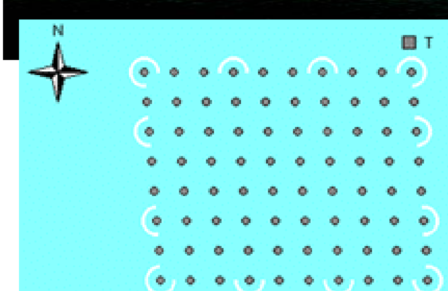
80 x 2 MW = 160 MW



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

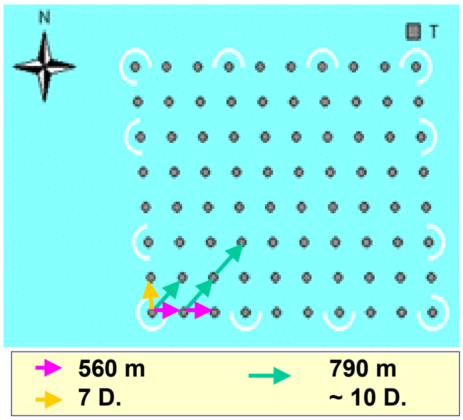
Horns Rev (DK)

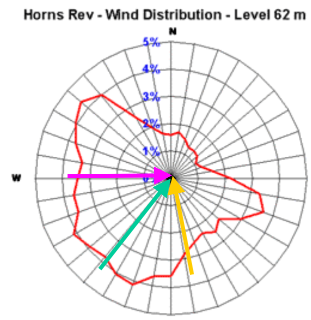




Array:
- **10 rows of 8 turbines**
- **560 m apart (7 rotor diameters)**
- **slightly skewed geometry**

Wind farm optimisation

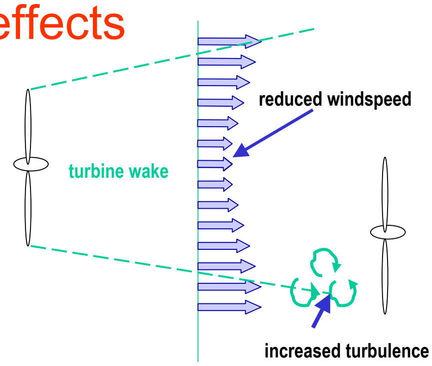




- With respect to ambient wind
- Available area
- Environmental restrictions
- visibility

Module 9: Wind Farm Aspects

Wake effects



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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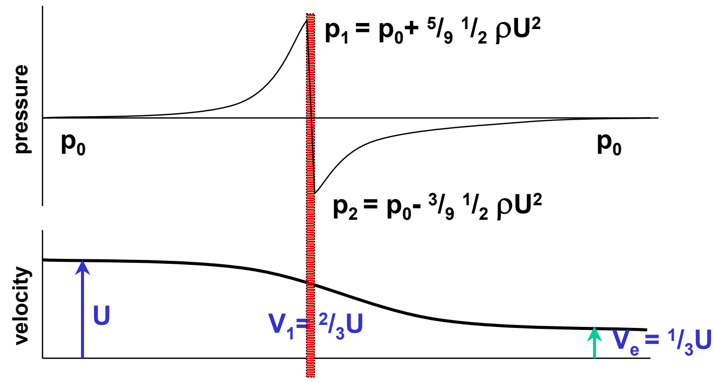
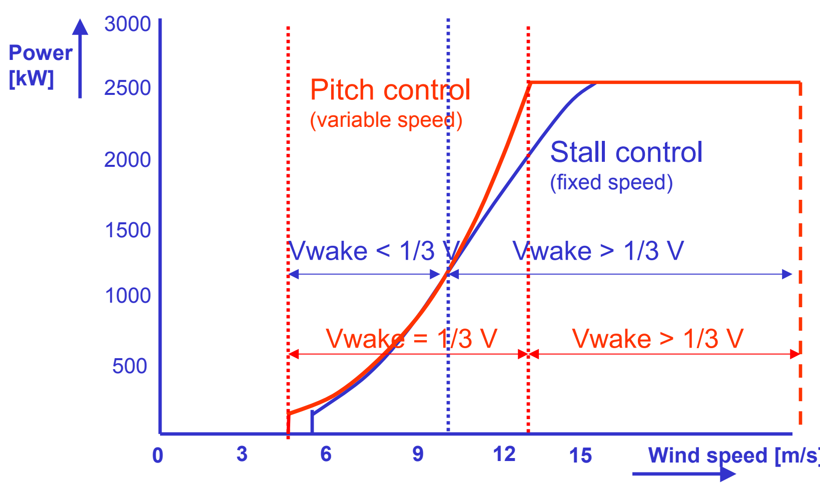
Axial momentum theory

Optimal pressure and velocity distribution

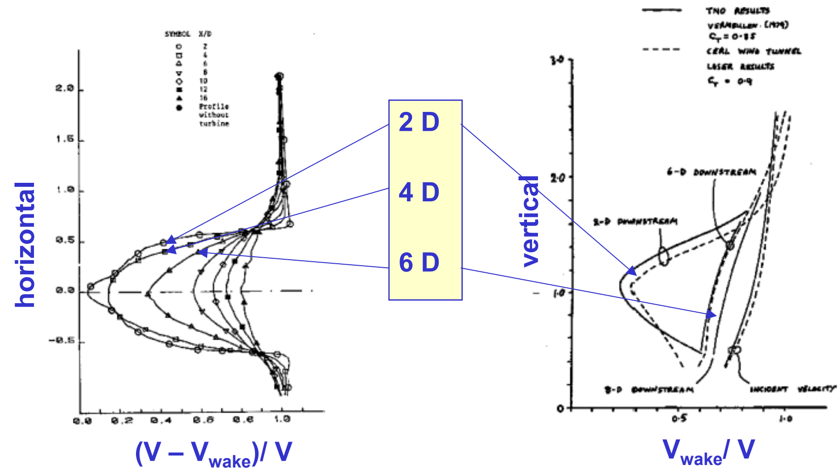


pressure drop: $\Delta p = {}^8/_9 \cdot {}^1/_2\ \rho U^2$ velocity drop: $\Delta V = {}^2/_3\ U$

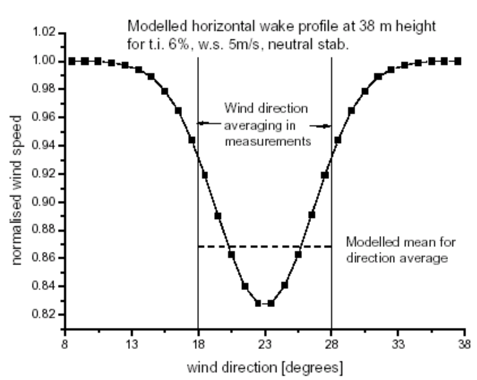
(Near) wake velocities

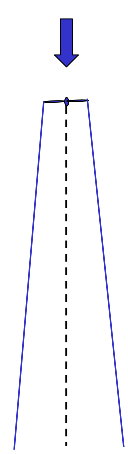


Measured (nearer) wakes



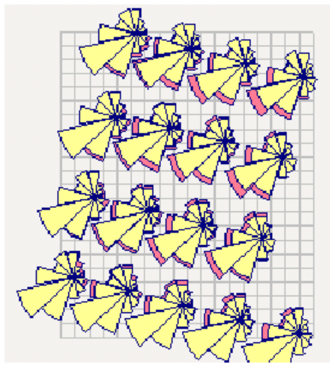
Wake effects

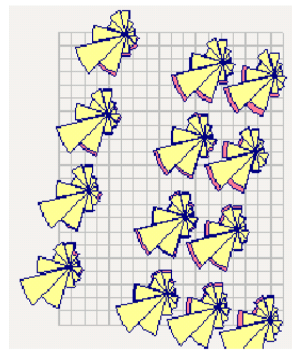




Calculated (single) offshore wake at 10 D behind a turbine (ENDOW project)

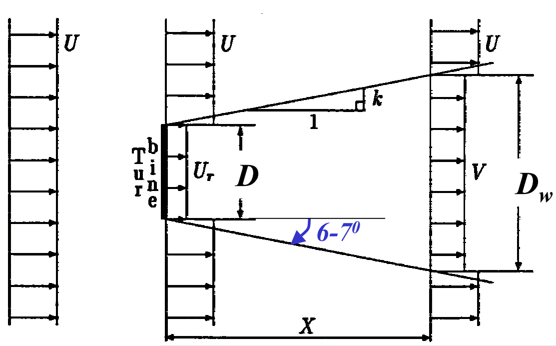
Wake interference





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

Jensen's (far) wake model

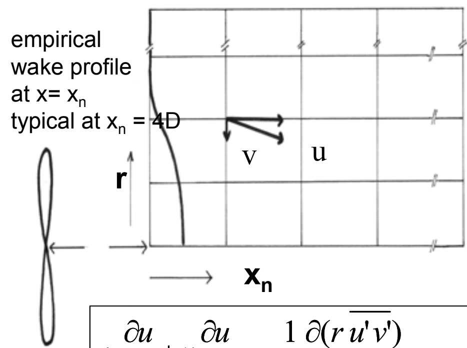


- **2 explicit equations for wake width and depth**
- **linear wake expansion**
- **linear velocity decay**
- **no wind speed profile, no turbulence**

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

Jensen, 1984
Katic et al., 1986

Ainslie wake model



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

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

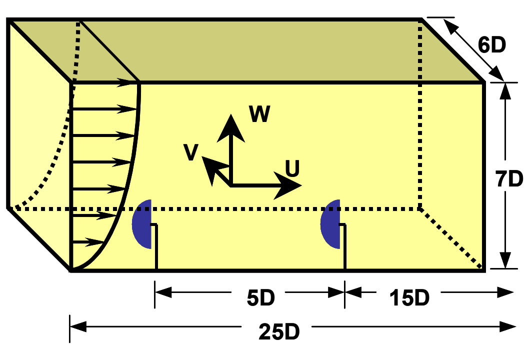
$$\frac{\partial u}{\partial x}+\frac{1}{r}\frac{\partial(rv)}{\partial r}=0 \quad \text{mass}$$

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

closure

Ainslie, 1988

Advanced Navier-Stokes solver



- **Fully elliptic 3D turbulent Navier-Stokes solver**
- **with k- ε turbulence closure (3D-NS)**

Rados et al., 2002

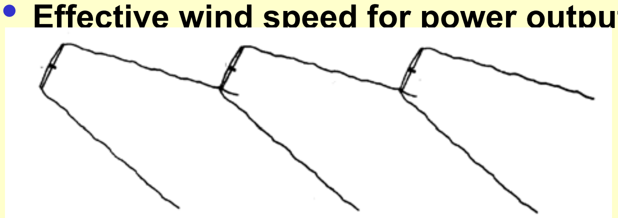
Wind farm (wake) power output predicition programs

Numerical tools for farm output modelling:

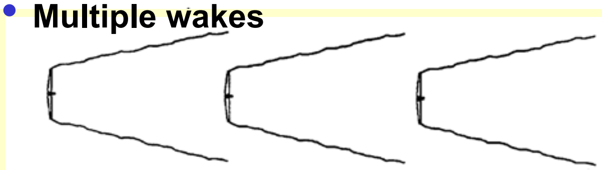
- WAsP/PARK (Riso): Jensen model
- Windfarmer (Garrad Hassan): Ainsly model
- FLaP (Univ. Oldenburg): NS solver

Wind farm model

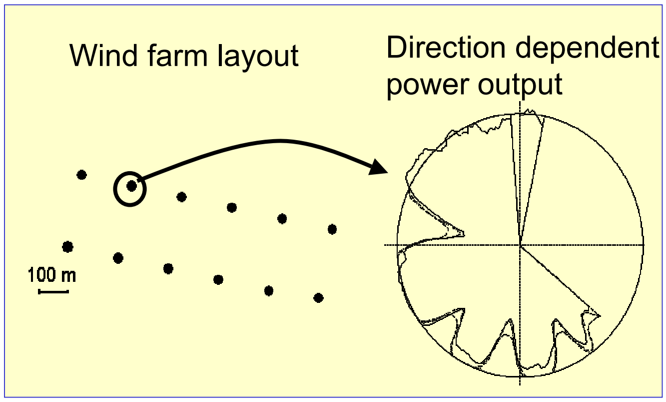
- **Effective wind speed for power output**



- **Multiple wakes**



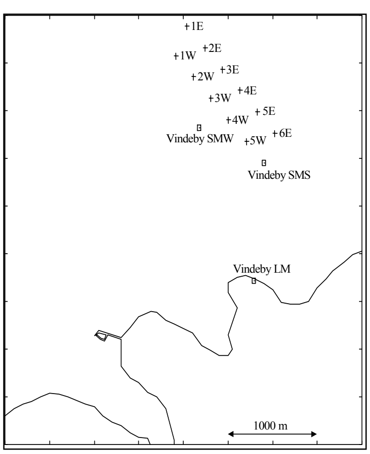
Example of modelled farm losses



Beyer et al., 1996

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

The Vindeby wind farm (DK)

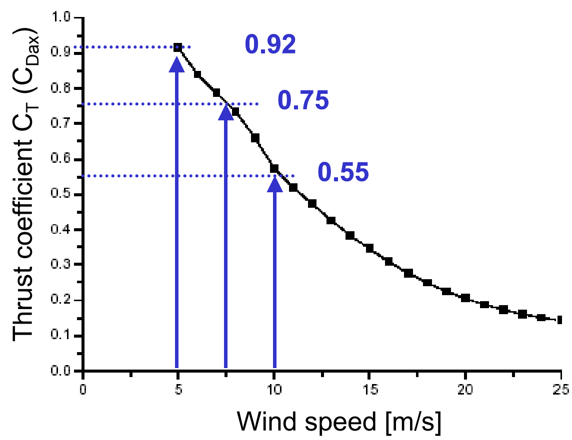


Barthelmie et al., 1994

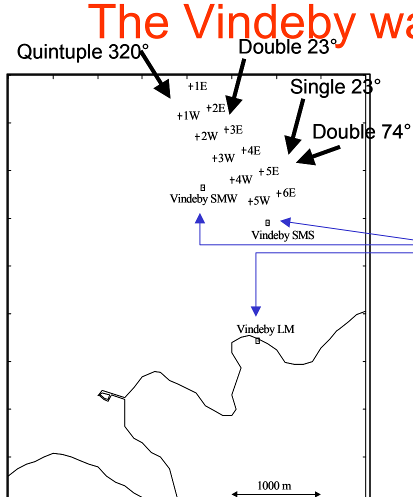
Offshore wind farm with 11 turbines

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

Thrust coefficient of Bonus 450 kW



The Vindeby wake measurements



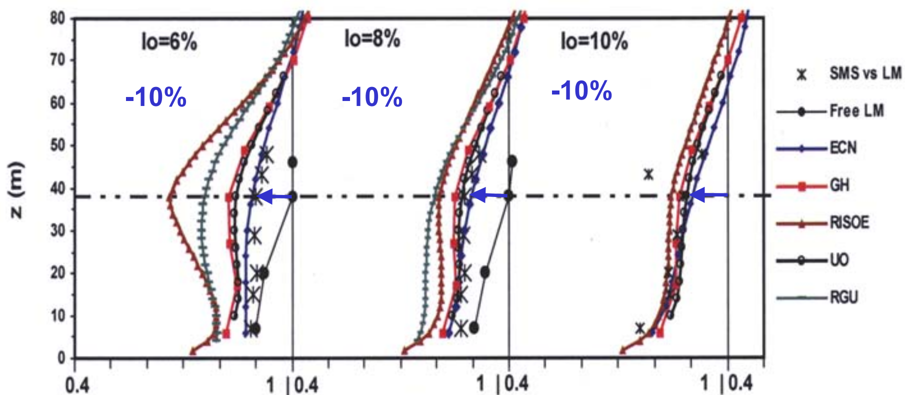
Barthelmie et al., 1994

Offshore wind farm with 11 turbines

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

Vindeby Single wakes (9.6 D)

- **Ambient conditions: v=7.5m/s**



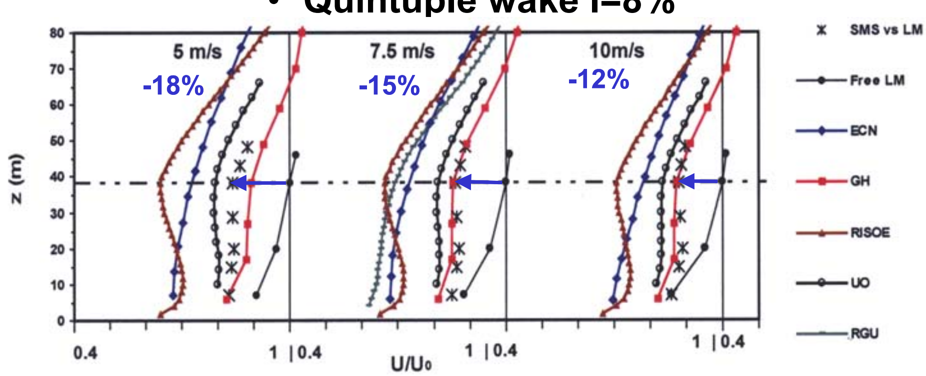
Schlez et al., 2002

Measurements: wake
ambient (free wind)

Module 9: Wind Farm Aspects

Vindeby Multiple wakes (8.6 D)

- **Quintuple wake I=8%**



Measurements: wake
ambient (free wind)

Schlez et al., 2002

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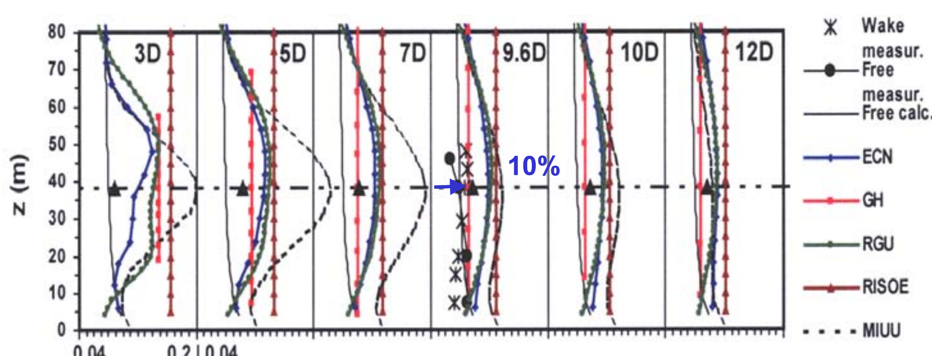
Wake turbulence intensity

- **Emperical model**
  - fit to results of wind tunnel and/or field experiments
- **Field models**
  - from eddy-viscosity or turbulent kinetic energy

Turbulence in a wake

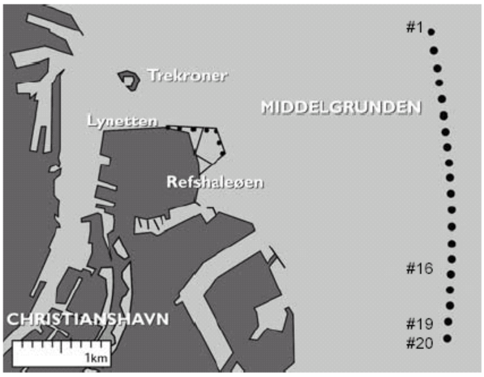
Ambient conditions: v=7.5m/s I=8%



Measurements: wake
ambient (free wind)

Rados et al., 2002

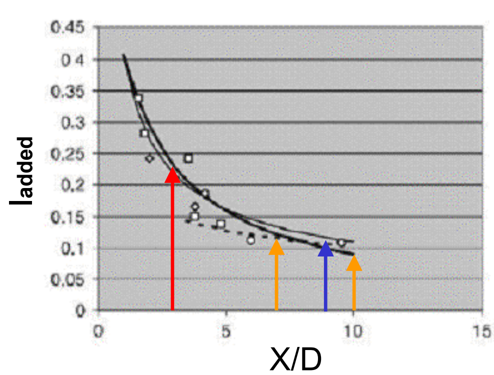
Middelgrunden wind farm



- **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



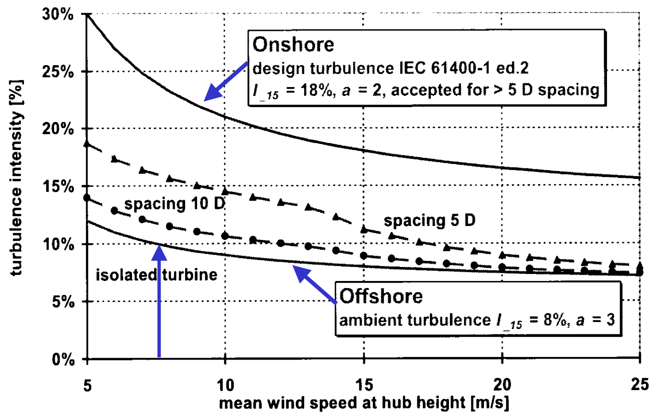
Added turbulence at hub height

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

Vindeby
Horns Rev
Middelgrunden

Various sources compiled by Ghaie (1997)

Turbulence in offshore wind farms

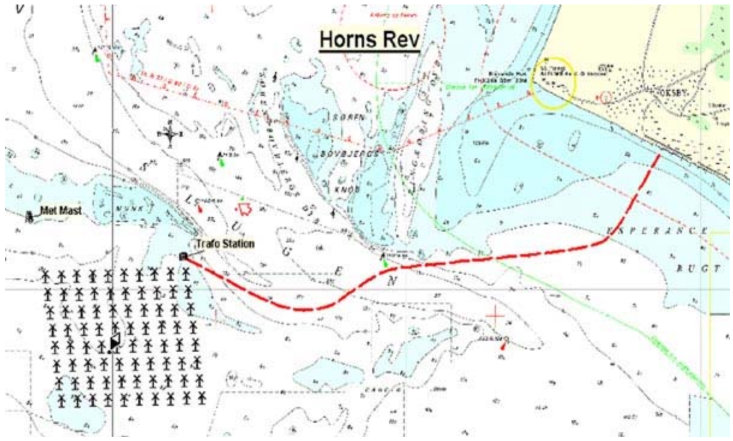


Vindeby

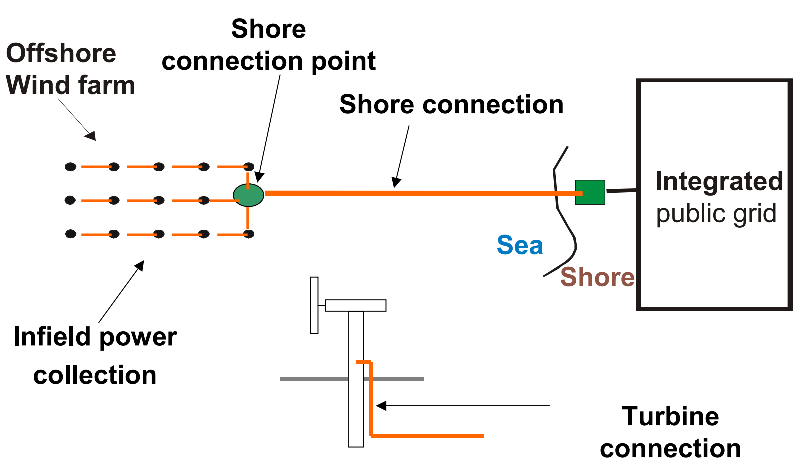
Summary wakes and wake losses

- 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)

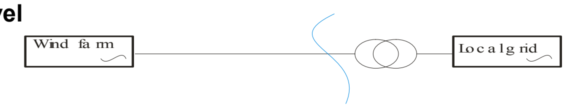


Topology of grid connection



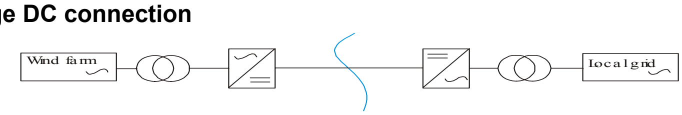
Shore connection options

- **AC Connection at onshore wind farm voltage level**

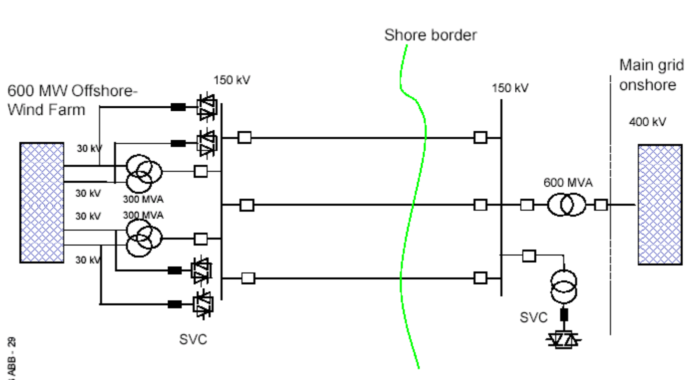


- **AC Connection with transformation**

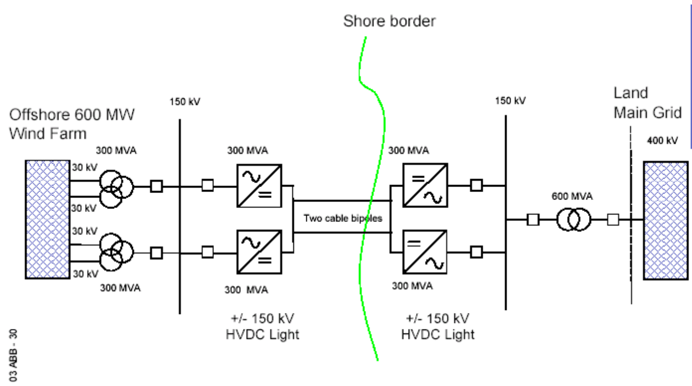
- **High voltage DC connection**



600 MW AC connection



600 MW DC connection



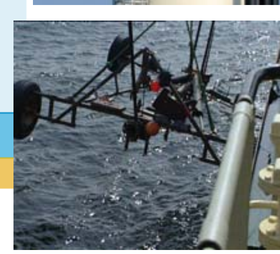
Components for power collection and transmission

- 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



Offshore wind farm electrical systems

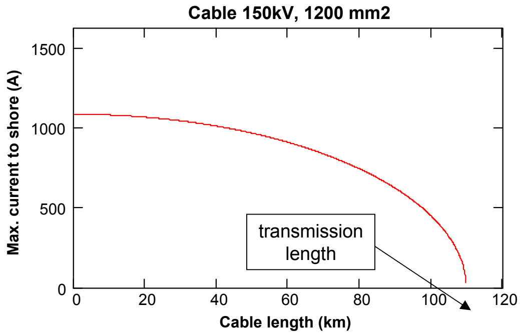
Wind farm name	Power	Collection voltage	Transm. Voltage	Distance to shore	
Utgrunden (S)	**7 x 1.4 MW**	**20 kV**	**20 kV**	**8 km**	**AC**
Middelgrunden (Dk)	**20 x 2 MW**	**30 kV**	**30 kV**	**3 km**	**AC**
Horns Rev (Dk)	**80 x 2 MW**	**36 kV**	**150 kV**	**15 km**	**AC**
Nysted Rodsand (Dk)	**158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

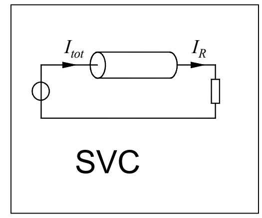
- no DC connections yet
- larger farms at 110-150 kV level

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

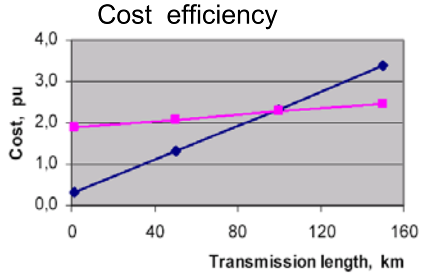
Allowable load current AC cables

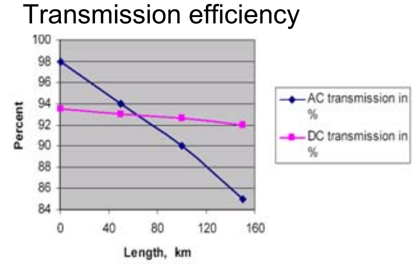




- compensation of capacitive current required for medium length cables using SVC's (Static VAR Compensators)
-

AC versus DC connection

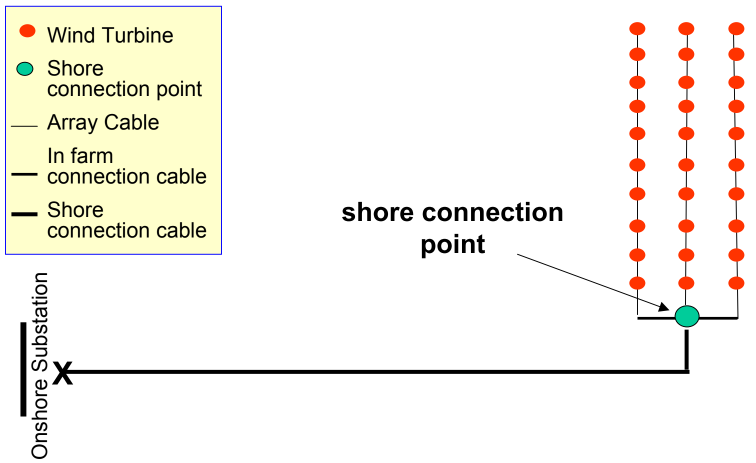




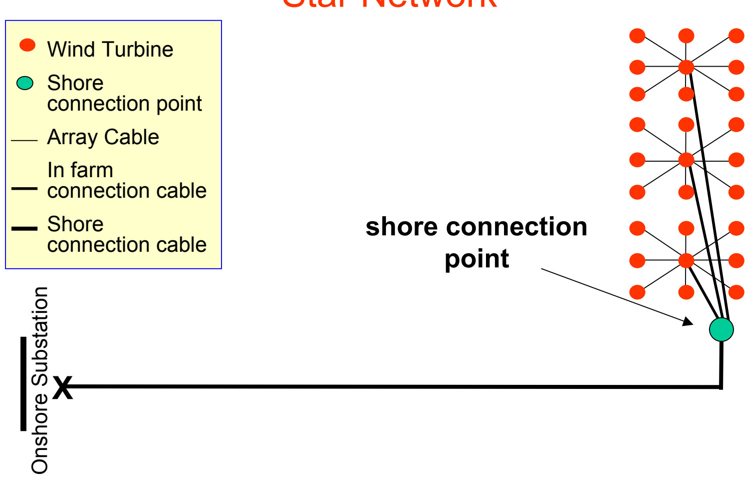
with 1 pu cost = DC investment 0 km
Losses evaluated with 9,1 €C/kWh, 20 years 7 %

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

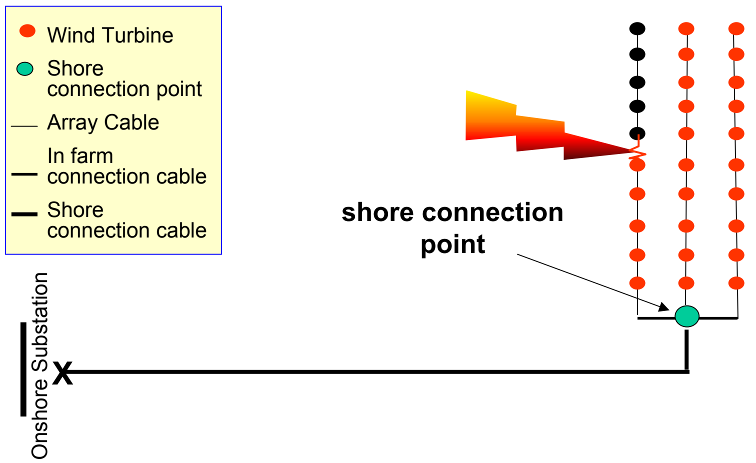
Network Topologies
String or Radial Network



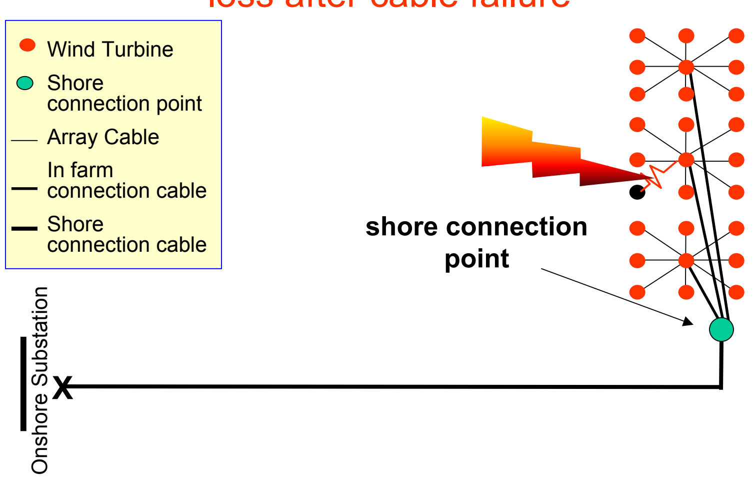
Network Topologies
Star Network



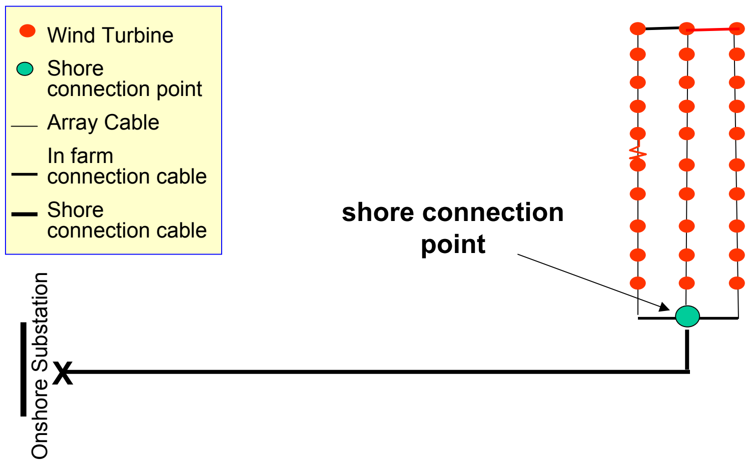
String Topology
loss after cable failure



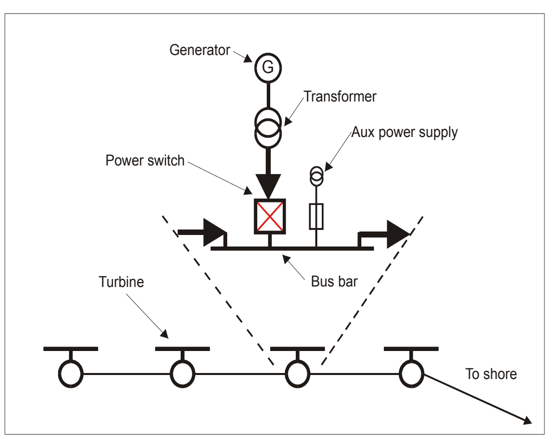
Star Topology
loss after cable failure



Looped Topology
no loss after cable failure!



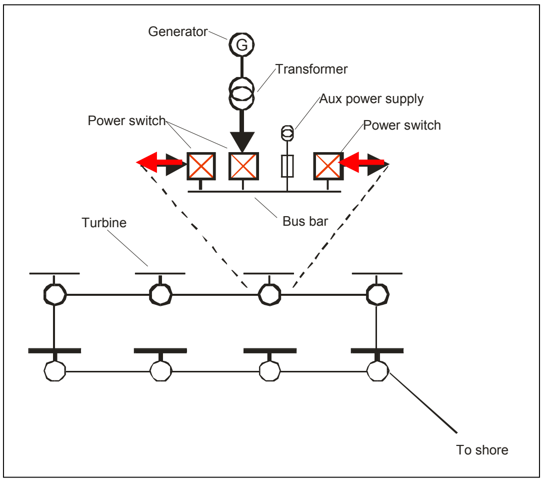
String and Star Topology



Fairly simple power connection:

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

Looped Topology

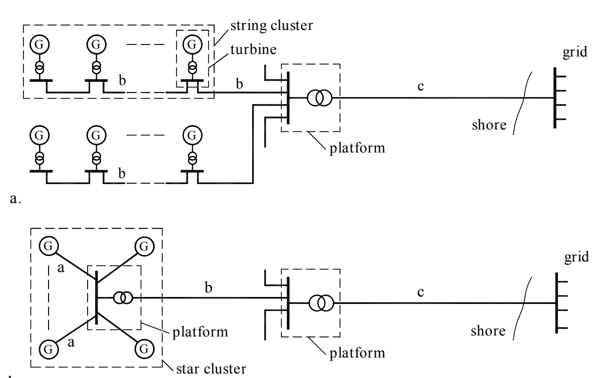


Complex power connection:

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

Module 9: Wind Farm Aspects

Lay-out of in wind connections



string cluster:

- two voltage levels
- individual trafo's

star cluster:

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

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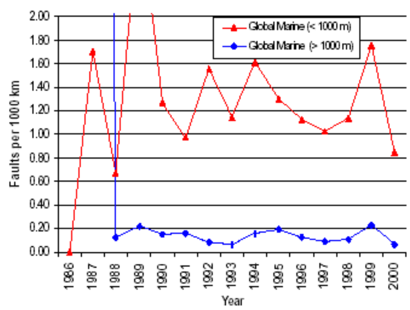
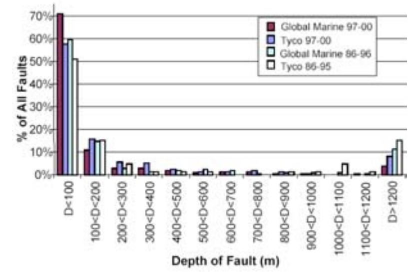
DELFT UNIVERSITY WIND ENERGY RESEARCH INSTITUTE

Power cable failure rates





~ 1 failure per 1000 km per year

Electric failure rates

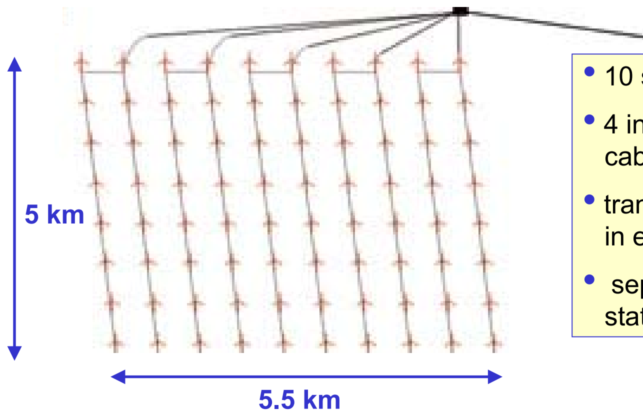
(for 30 offshore wind turbines)

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

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

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

Summary infield power collection

- high cable laying costs
- buried at 1-2 m depth or more (currents, anchors)
- mostly XLPE cables (='low cost'),
- string lay out
- meshing/looping in farms not yet applied
- connections in wind turbine
- no substations apart from power collection point (larger wind farms)

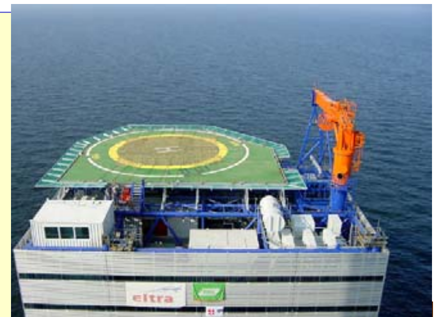
Horns Rev transformers:

transformer 690 – 36 kV in each turbine

separate transformer station: 36kV/150kV

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)

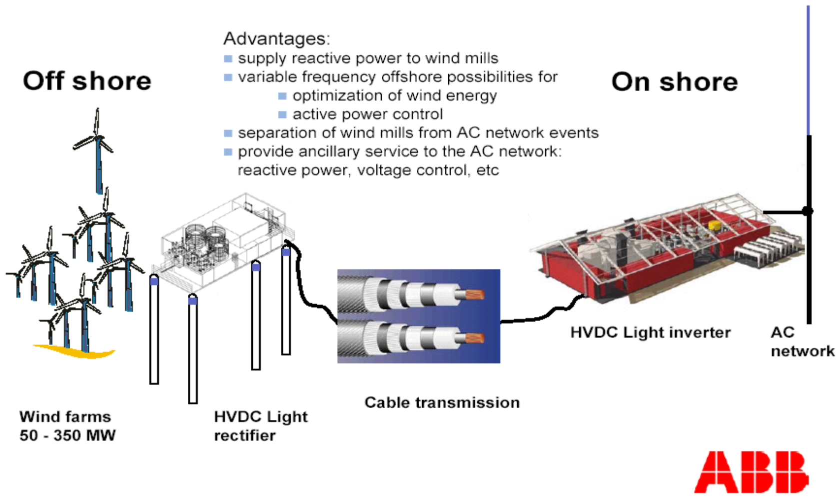


Summary substations and connection cables

- 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 (→no redundancy)
  - → no double shore connections (→no redundancy)

Future HVDC "light" grid connection

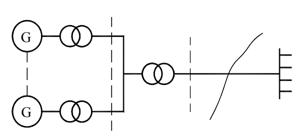
Advantages:
- supply reactive power to wind mills
- variable frequency offshore possibilities for
  - optimization of wind energy
  - active power control
- separation of wind mills from AC network events
- provide ancillary service to the AC network: reactive power, voltage control, etc



Present electrical system in wind farm with individual turbine control

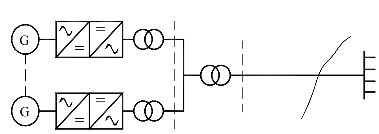
(State of the art wind farms)

Constant speed

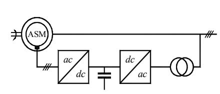


Variable speed

"synchronous"

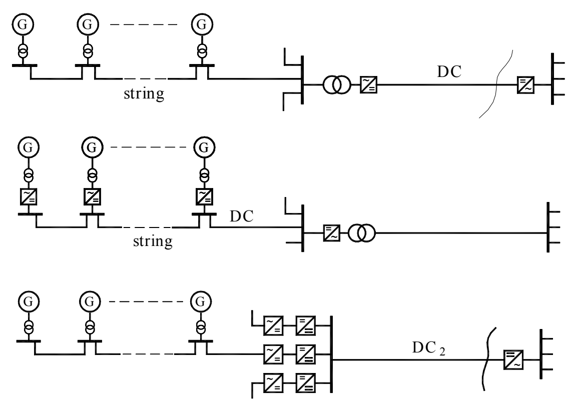


Asynchronous doubly fed generator



Horns Rev

Advanced systems with DC in the farm

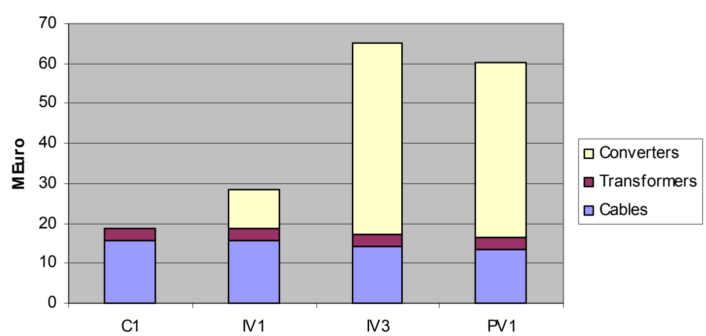


HVDC grid connection constant speed or farm coupled variable speed

AC grid connection individual variable speed

HVDC grid connection cluster coupled variable speed

Cost Breakdown of some electrical systems



C1 : constant speed with strings
IV1: individual variable speed with strings
IV3: individual variable speed with strings, HVDC light
PV1: park coupled variable speed

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
- In the future coupled speed systems might become interesting if the cost of power electronics decreases

Module 9: Wind Farm Aspects

Output Power Predictability

Wind speed prediction can be used to:

- **Unit commitment (matching the load curve)**
- **Put other generation into service when low wind speed is expected**
- **Switch off loads when necessary and/or allowed**
- **Gain knowledge how much power to sell in a liberalized market**

Course OE5662 Offshore Wind Farm Design

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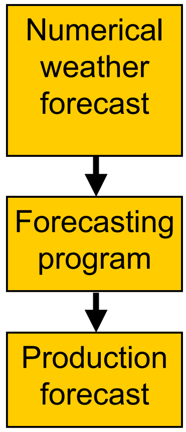
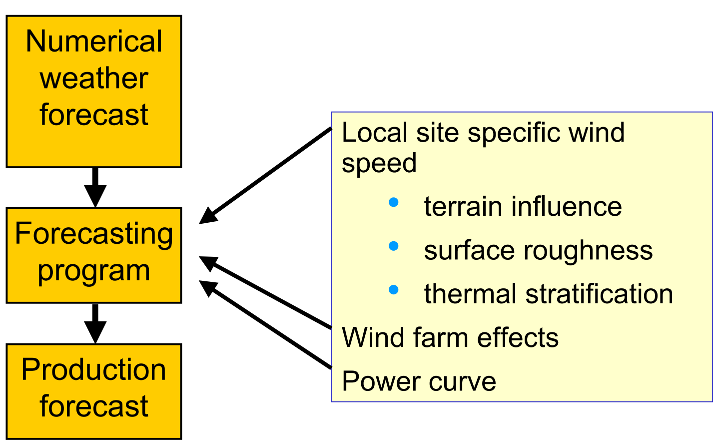
Model approaches



- **Physical approach:**
  - Prediktor
  - E-wind
  - Previento
  - ...
- **Statistical approach:**
  - WPPT
  - ISET (neural networks)
  - ...

Module 9: Wind Farm Aspects

Physical approach



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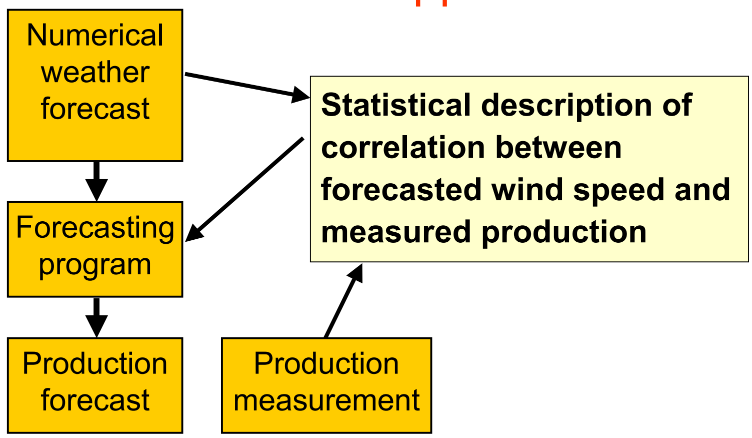
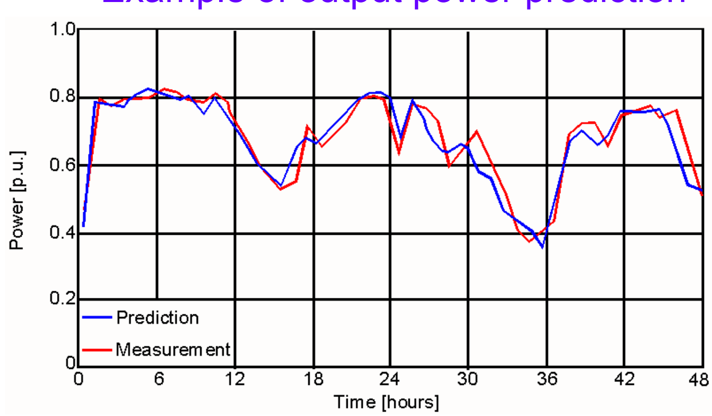
Statistical approach



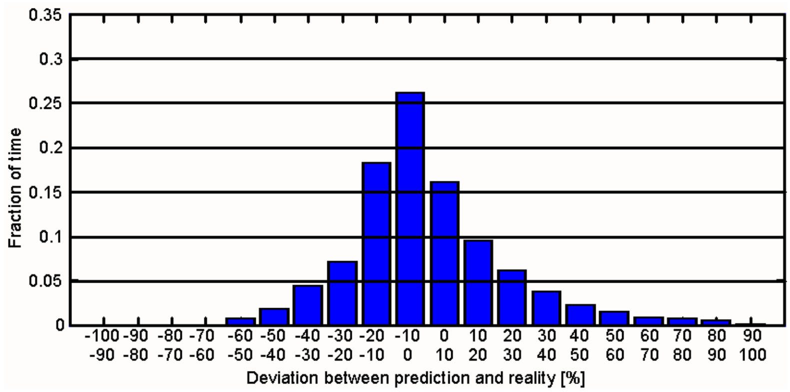
Output Power Predictability (short term)

Example of output power prediction



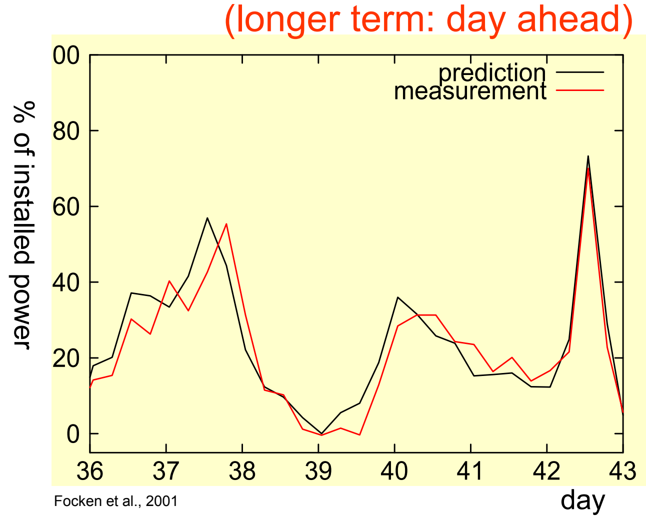
Output Power Predictability (short term)

Histogram of prediction error



Output Power Predictability

(longer term: day ahead)



Focken et al., 2001

Example:

- **Previento**
- **single site**

Forecast uncertainty

Onshore:

- **10 – 15% rms error of installed power for single site**
- **5 – 10% rms error of installed power for a regional forecast (e.g. whole Germany)**
- **similar for all models**
- **mainly due to uncertainty in weather prediction**

Offshore:

- **??? Not yet known**

Focken et al., 2002

Challenges for offshore farm performance prediction

- **Numerical weather prediction**
  - Improved parameterisation of roughness and stability
  - Currents, tide, ...
- **Physical models**
  - Improved parameterisation of roughness and stability
  - Farm effects
- **Statistical forecast models**
  - Inclusion of additional parameters: stability, tide, ...