Design considerations

For offshore wind farms

Offshore Wind Farm Design

Michiel Zaaijer

2007-2008

DUWIND

Delft University of Technology

Overview

- Introduction
- Overall system and planning
- Considerations per part or phase
- Cost of energy

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Introduction

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Hardware components of the farm

- Offshore wind turbines
  - Rotor-nacelle assembly
  - Support structure
- Electrical infrastructure
  - Power collection system
  - Power transmission system
- Facilities (& remainder)
  - Central platform
  - Met-mast
  - Auxiliary equipment
  - Onshore premises

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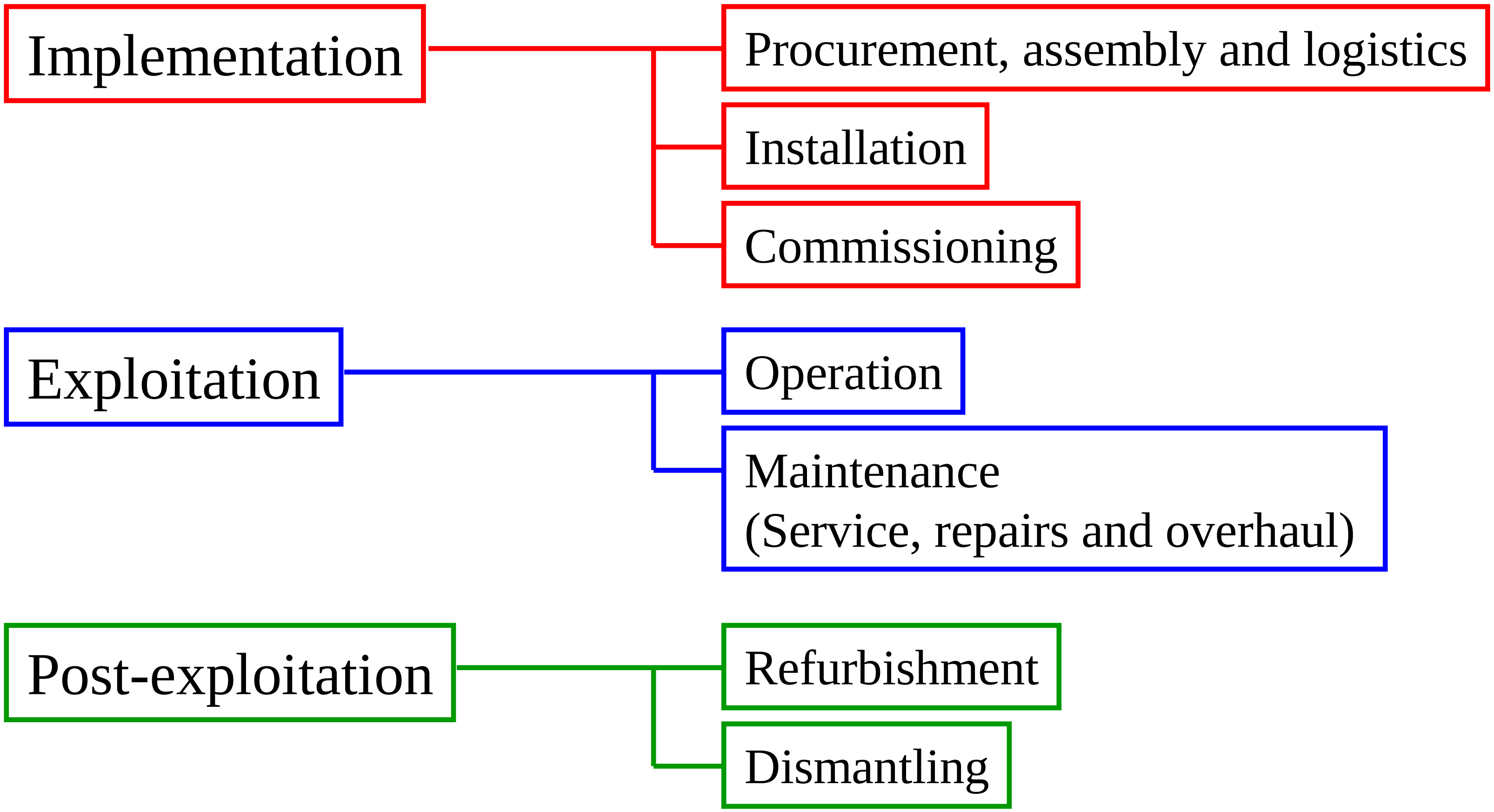
Procedures


Implementation
Procurement, assembly and logistics
Installation
Commissioning
Exploitation
Operation
Maintenance
(Service, repairs and overhaul)
Post-exploitation
Refurbishment
Dismantling

Design as part of development phase

- Feasibility study, project identification
  Conceptual design (cost-benefit, showstoppers)
- Permitting, financing, investment decision
  System layout (costs, EIA, visual impact)
- Contracting
  Preliminary design (reference, budgeting)
- Go ahead
  Final design, specifications, planning

"The example"

Throughout this lecture "Horns Rev" will be used to exemplify the design of a state-of-the-art large scale offshore wind farm

The pictures and illustrations of this wind farm, developed by Elsam and Eltra, are taken from the website www.hornsrev.dk. Copyright: Elsam A/S

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Overall system and planning

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General considerations

- Company / consortium skills (needed and available)
- Requirements, standards and recommended practices
- Legal framework
- (International) developments and policy
- Safety / risk / lifetime
- Environmental impact
- Technological preferences or constraints
- General targets (e.g. size, indication of location)
- Cost-benefit (see next slide)

Cost-benefit considerations

- Costs
- Tax incentives
- Financing and insurance
- Energy quality and quantity, including availability and controllability
- Predictability (particularly wind forecast)
- Market value
- Other revenues (green certificates, subsidy)

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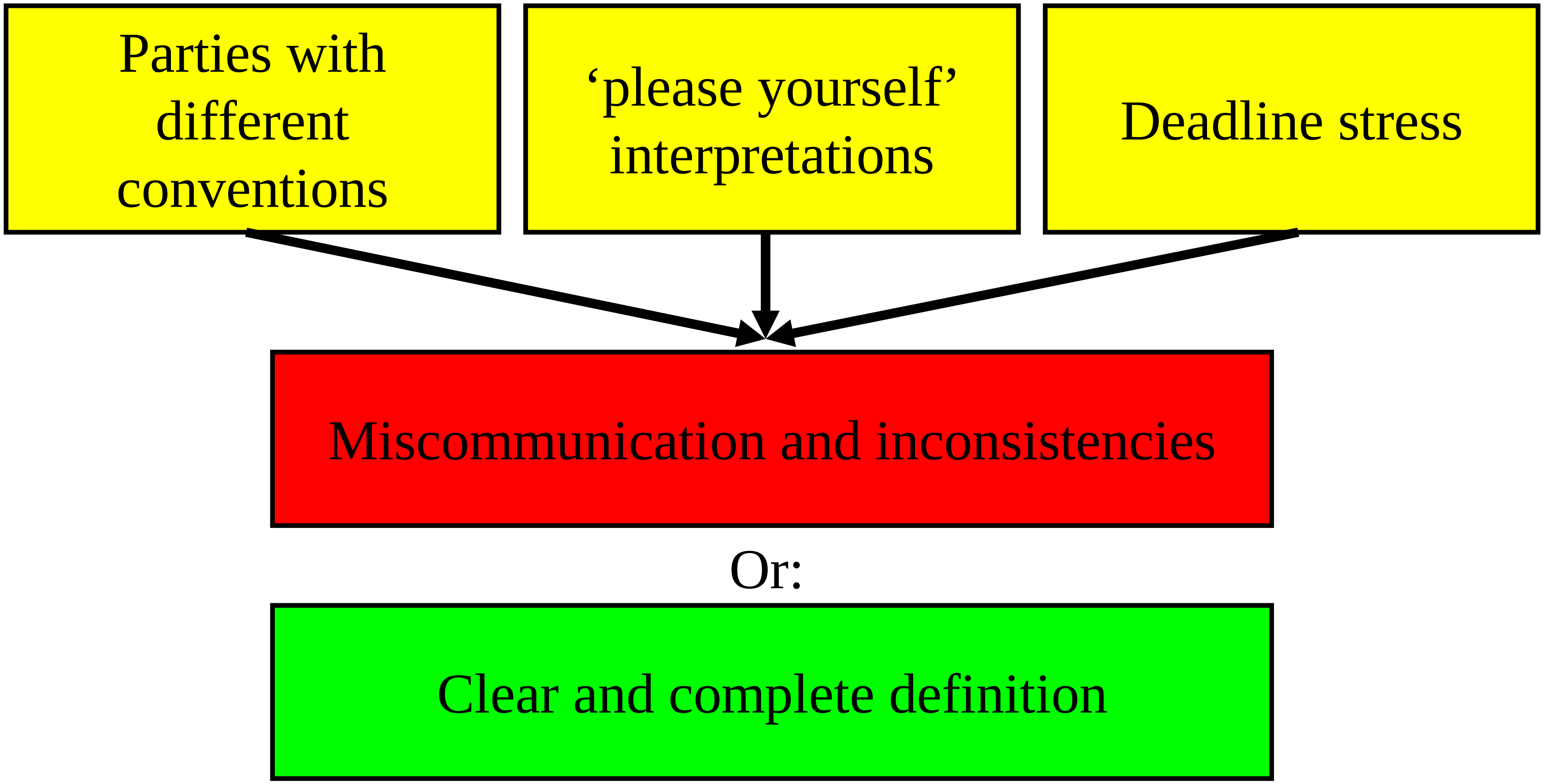
Know (and show) what you're talking about



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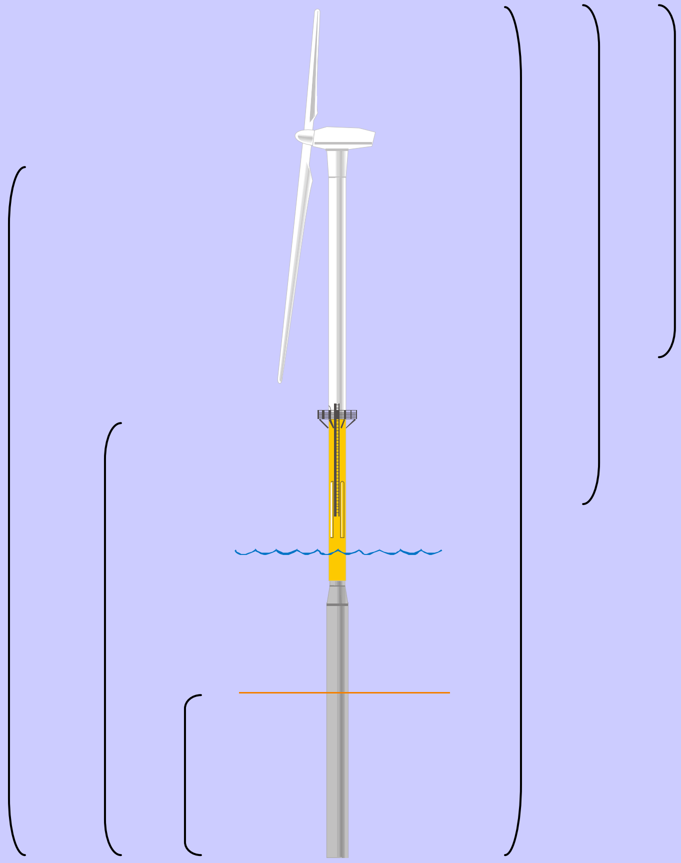
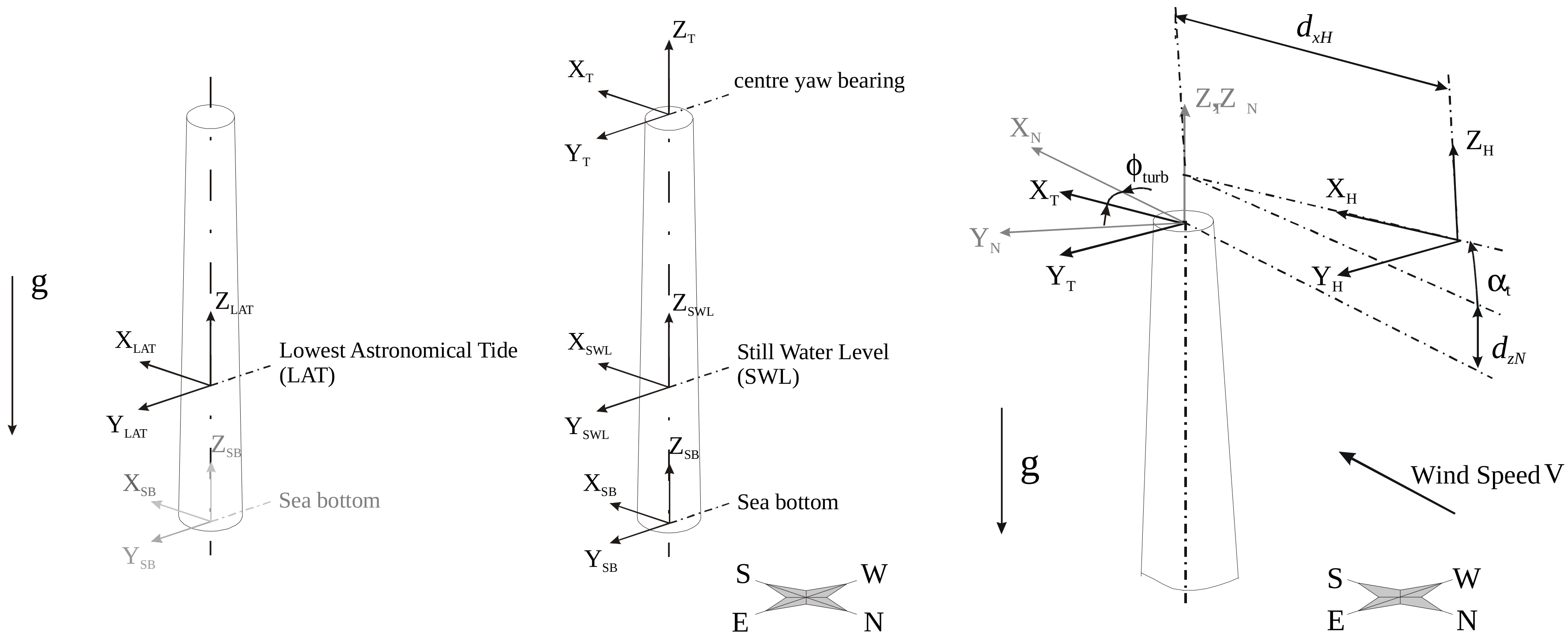
Definition of terms



Wind turbine?

Foundation?

Definition of used reference system



LAT (installation)
Seabed (structural loads)

SWL (hydrodynamic loads)
Tower top (interface WT)

Nacelle
Hub (non-rotating)

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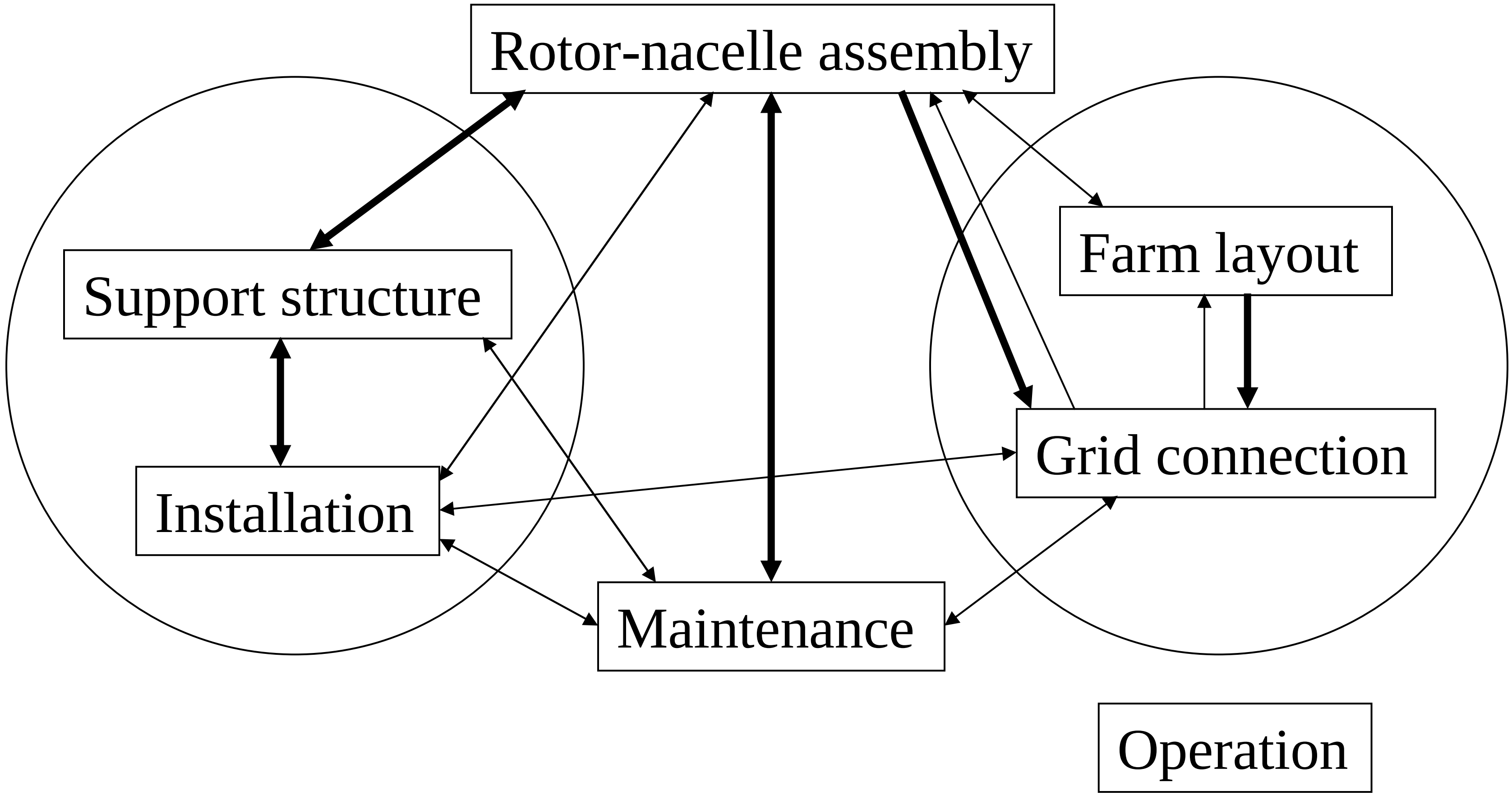
Reference report

“Terminology, reference systems and conventions”

Available on blackboard in folder ‘Course Documents’

(Report used in the project “Design methods for offshore wind turbines at exposed sites (OWTES)” under contract with the European commission)

Interactions in the design process



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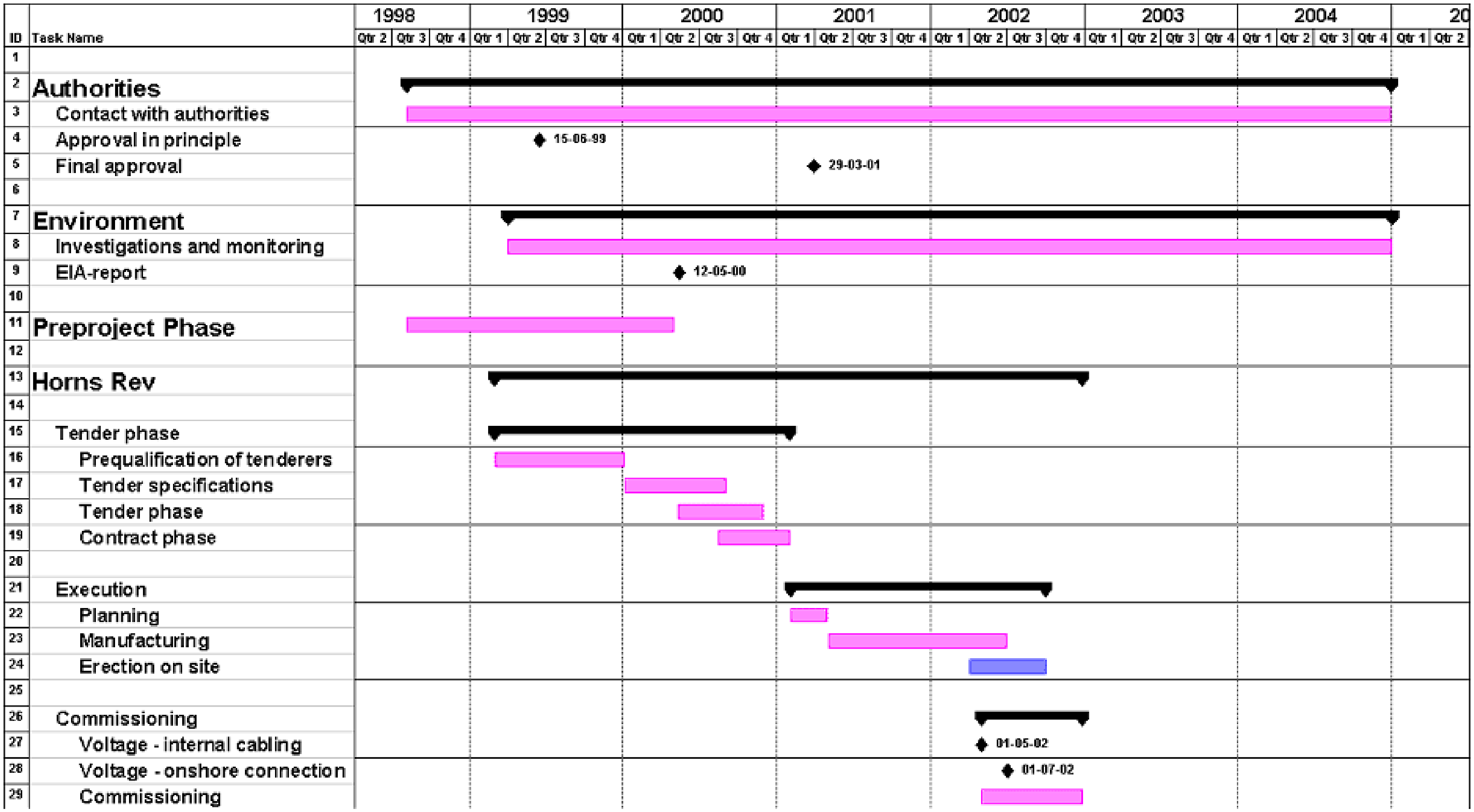
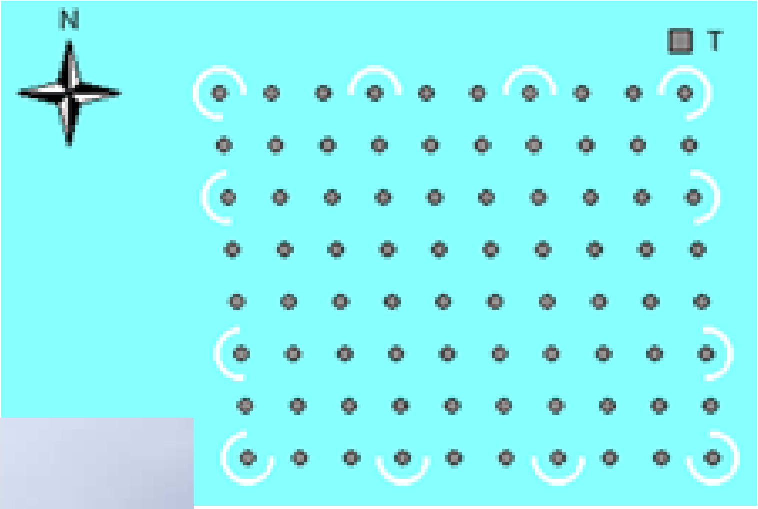
General considerations (example)



General considerations (example)

- Total investment: 2 GDKK (270 M€)
- Total energy yield: 600 GWh/year → around 150.000 households
- Fixed price: 0.33 DKK/kWh (0.045 €/kWh) (up till energy production of around 10 years)
- Green certificate trading: 0.10-0.27 DKK/kWh (0.014-0.036 €/kWh)

General considerations (example)



Safety

- Yellow lights at outer turbines
- Two red warning lights on each nacelle
- Orange blade tips

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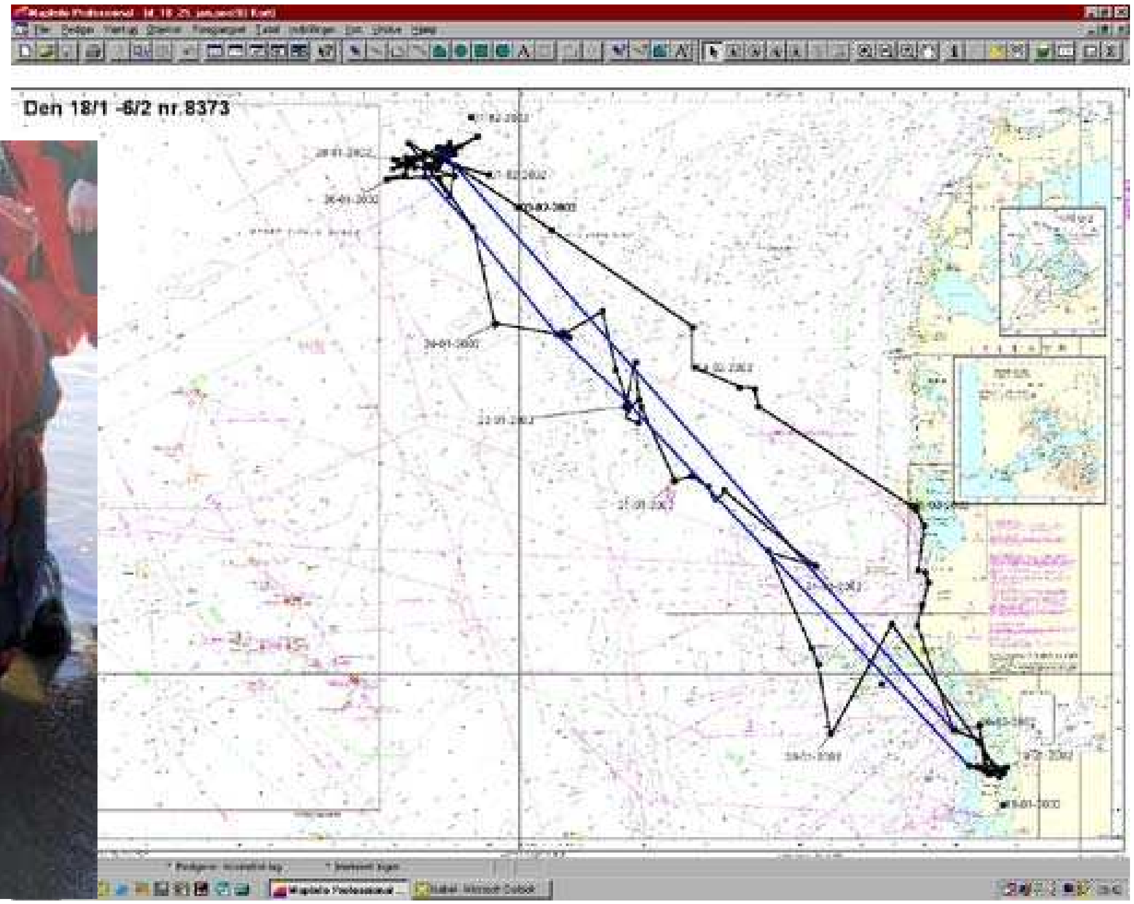
General considerations (example)

Seal monitoring programme



Site selection

Site selection

Design choices:

•Location

•General size and shape

Considerations:

•Resources/potential

•Planning (users/infrastructure)

•Indication of costs and technical feasibility

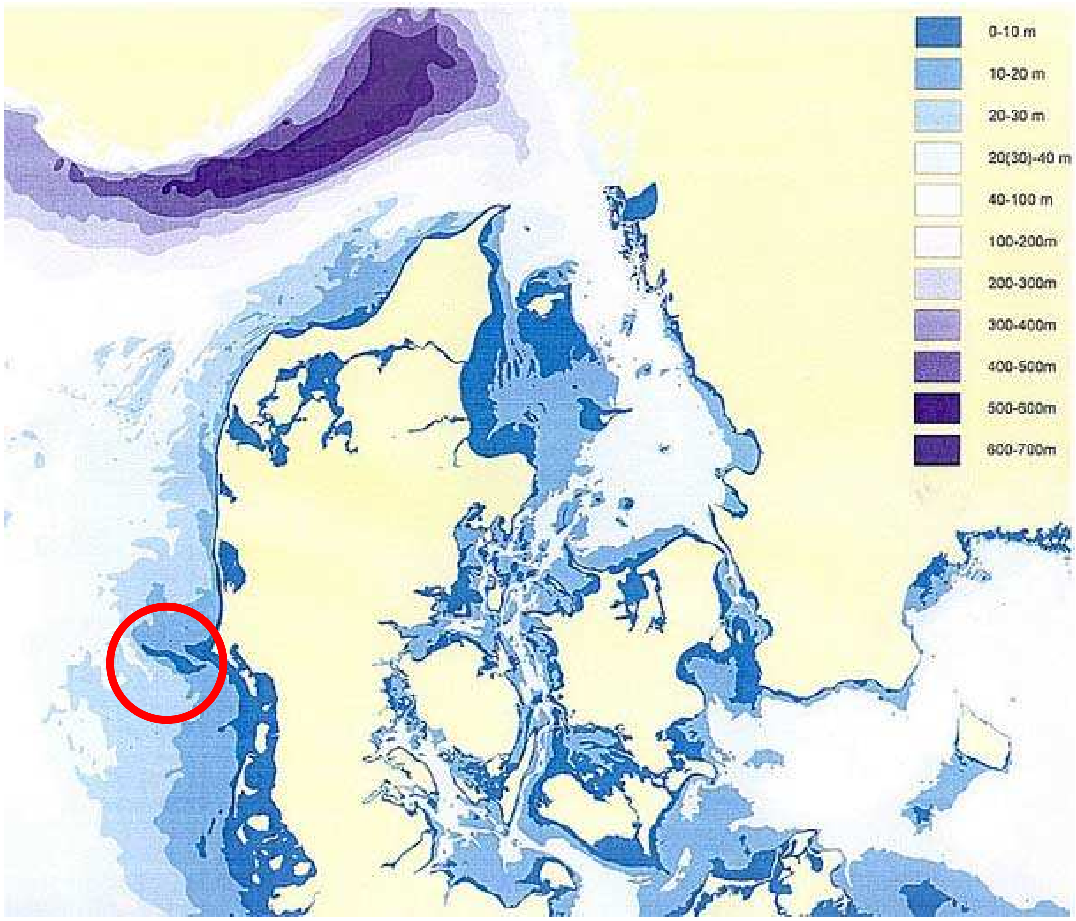
•Relevant developments

•Regulations

Site selection (example)

- Studies started in 1993
- 4 preferred areas
- 1997: "Action plan for offshore windfarms in Danish waters"
- 1998: Contract negotiations with electricity suppliers
- 1999: Preliminary go-ahead for 4 sites

Site selection (example)



- Hard sand reef of moraine gravel of early ice ages
- Water depth between 1 and 10 m
- But… harsh sea conditions: “The Devil’s Horn”

Wind farm layout

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Wind farm layout

Design choices:

- Number of turbines and turbine rating
- Outline shape
- Spacing
- Relative positions
- Positions w.r.t. geographical marks
- Number of support structure designs

Considerations:

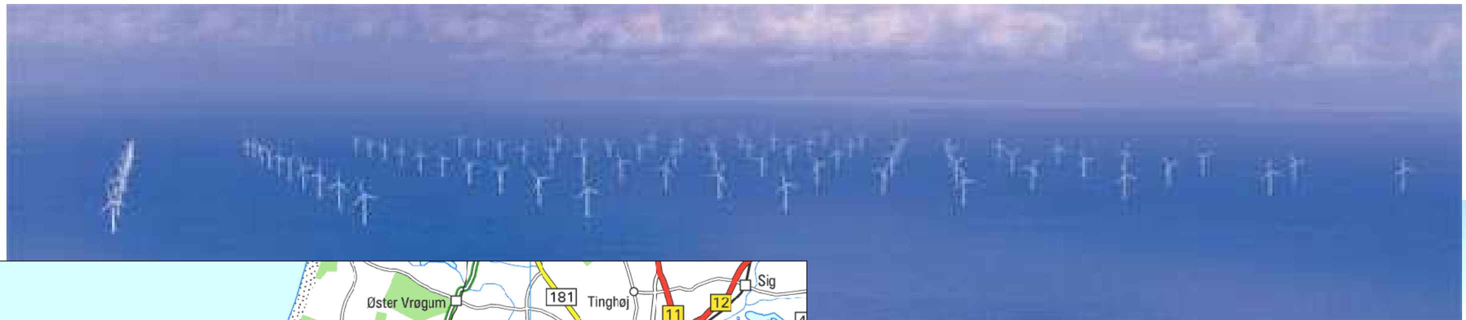
- Wake losses
- Electrical losses and costs E-infrastructure
- (Annual) Energy yield
- Indication of costs and technical feasibility
- Planning (users/infrastructure)

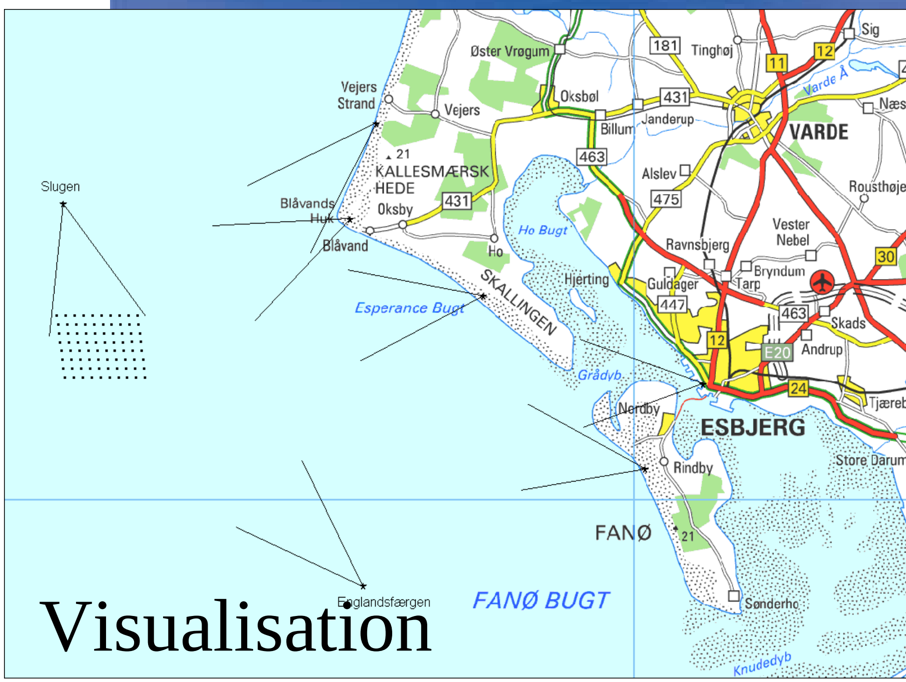
Wind farm layout (example)

Filling the shallow with a 10x8 array (6-14 m depth, 560 m spacing, 20 km^2)

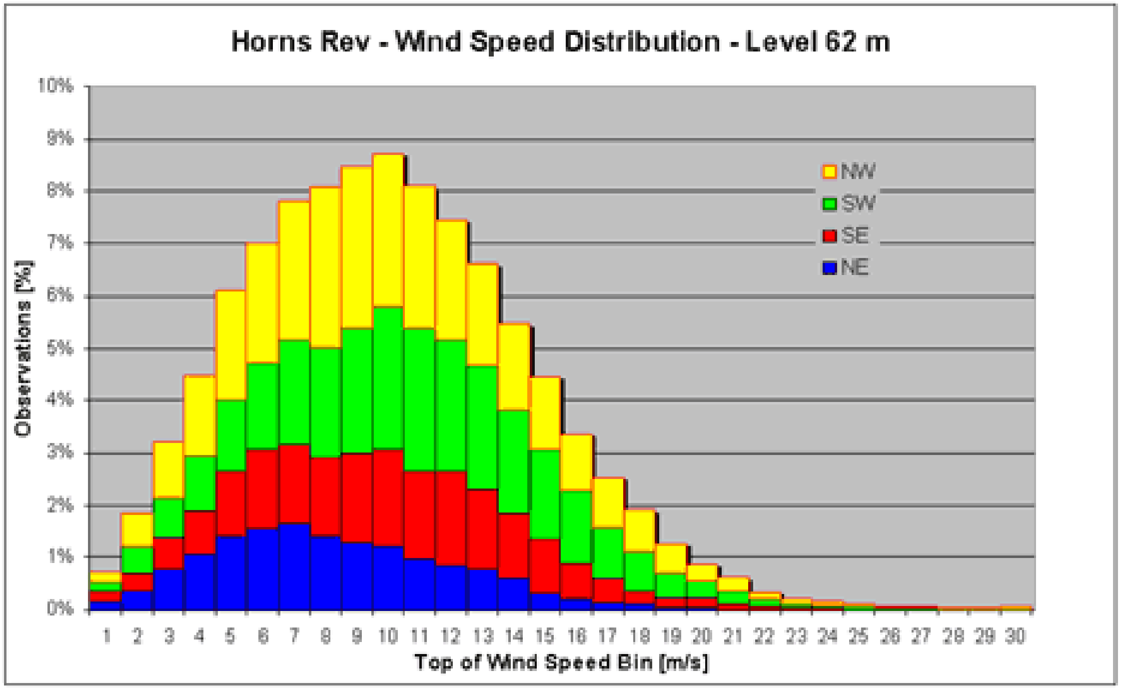
160 MW = 80 x 2 MW

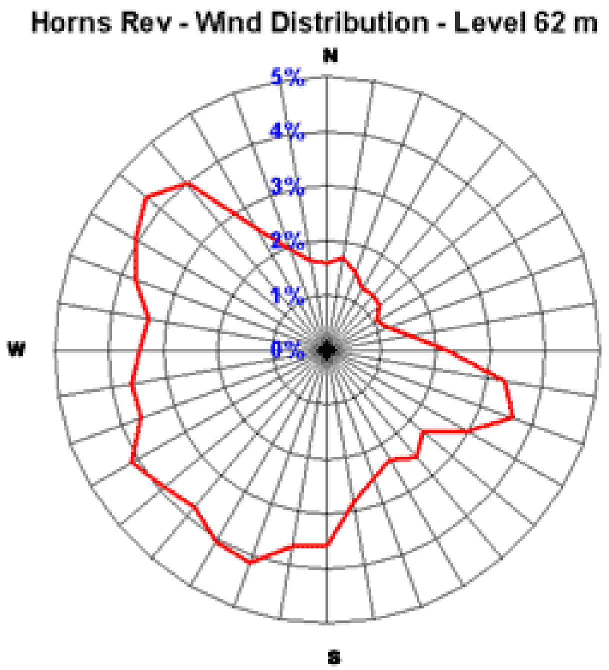
Wind farm layout (example)





Wind farm layout (example)





Indication of energy yield, site optimisation, orientation w.r.t prevailing wind direction

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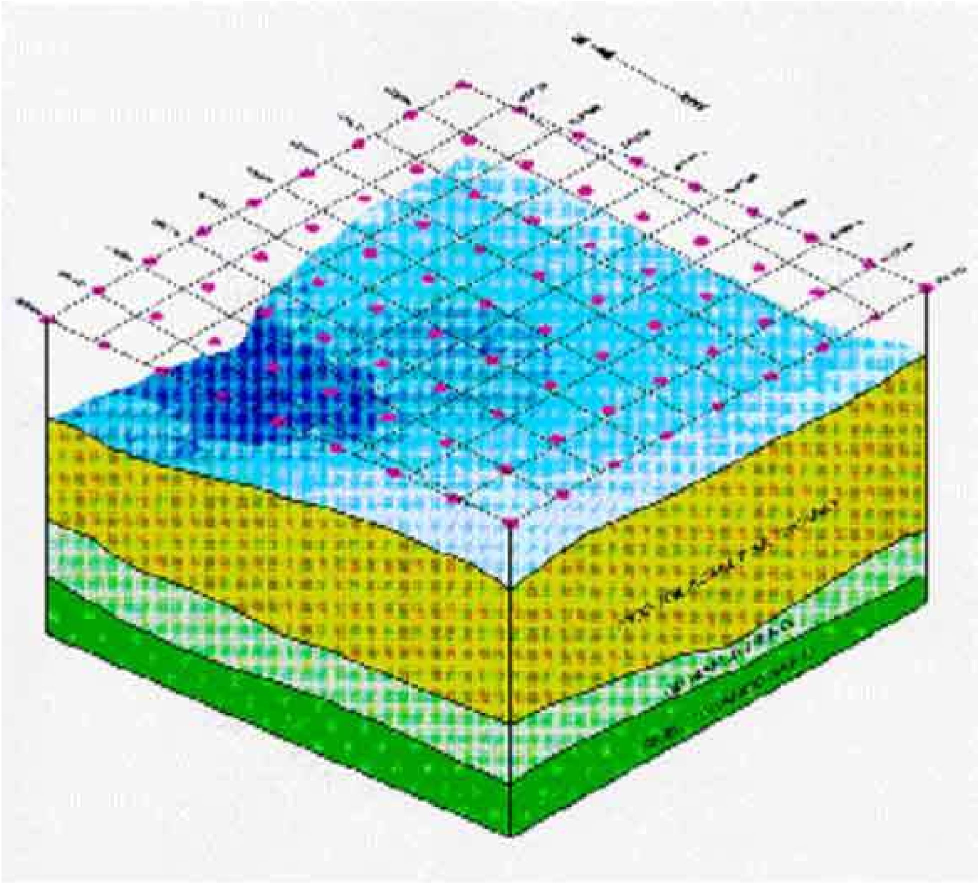
Wind farm layout (example)



Stable bank, consisting of:

- Sand
- Gravel
- Pebble gravel
- Stones

Variation within farm resulted in single monopile design, with variable length.

Rotor-nacelle assembly

Rotor-nacelle assembly

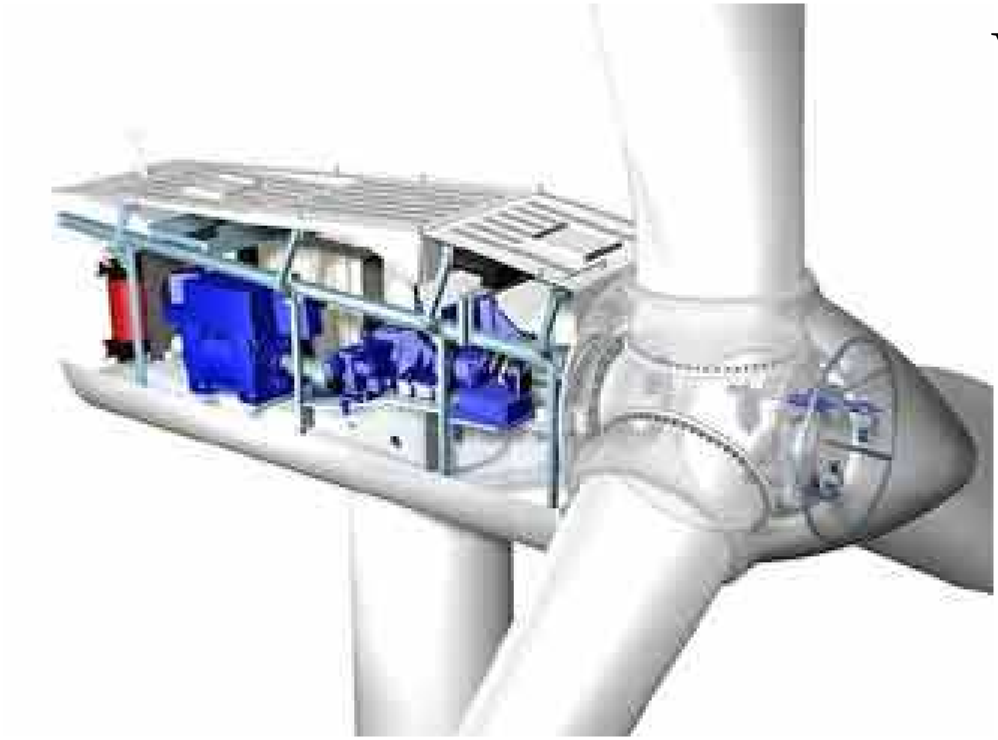
Design choices: (Generally selection and not design)

- Rating, power and thrust
- Control concept
- Electrical system
- Gearbox / direct drive
- Rotor size, number of blades and bending
- Hoisting systems
- Climate conditioning

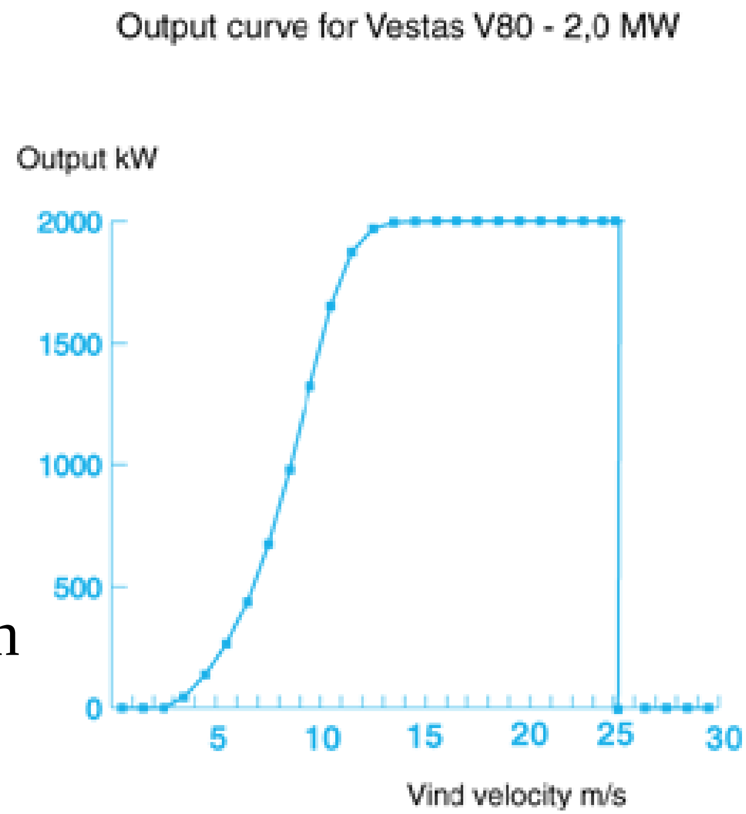
Considerations:

- Efficiency / yield
- Controllability
- Loading and dynamics
- Minimum hub height and tip clearance
- Reliability / maintainability / serviceability
- Installation

Rotor-nacelle assembly (example)



Vestas V80



2 MW, 80 m rotor, variable speed, pitch control, rated wind speed 13 m/s, doubly fed generator

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Support structure

Support structure

Design choices:

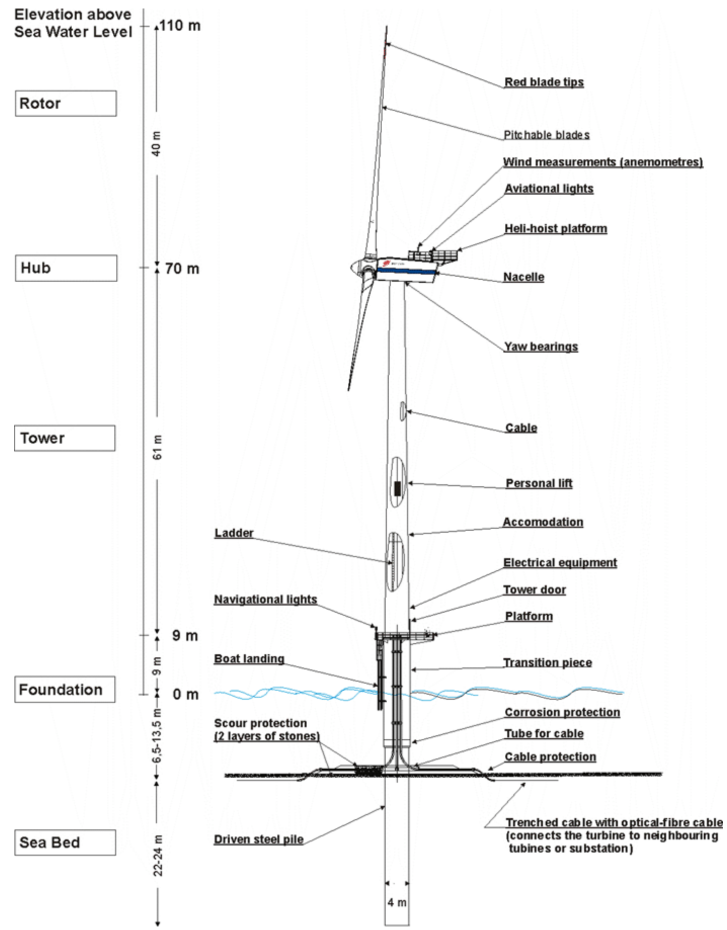
- Concept and material
- Hub height
- (Element) shape and size
- Access facilities
- Cable tie-in
- Transition piece

Considerations:

- Rotor clearance / air gap
- Energy yield w.r.t. shear
- Structural reliability and lifetime
- Seabed scour
- Manufacture and onshore logistics
- Installation
- (Turbine) maintenance

Support structure (example)

- 4 m foundation piles
- Wall thickness 5 cm
- 22 - 24 m penetration
- Transition piece
  - 4.6 m diameter
  - 6 m grout
- Platform 9 m above sea
- 61 m conical tower
- 70 m hub height
- Total mass 340-390 ton



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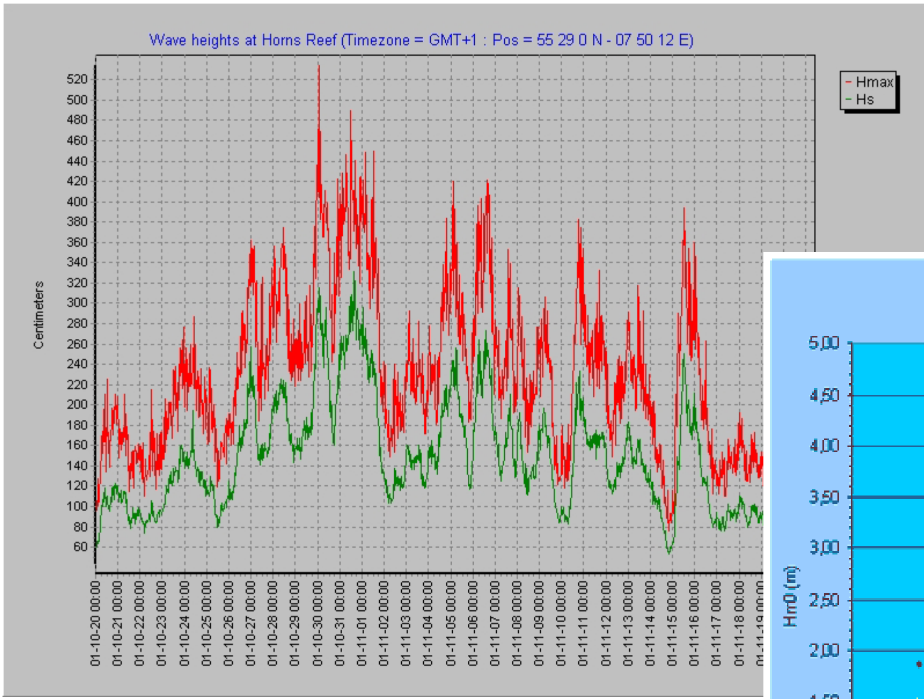
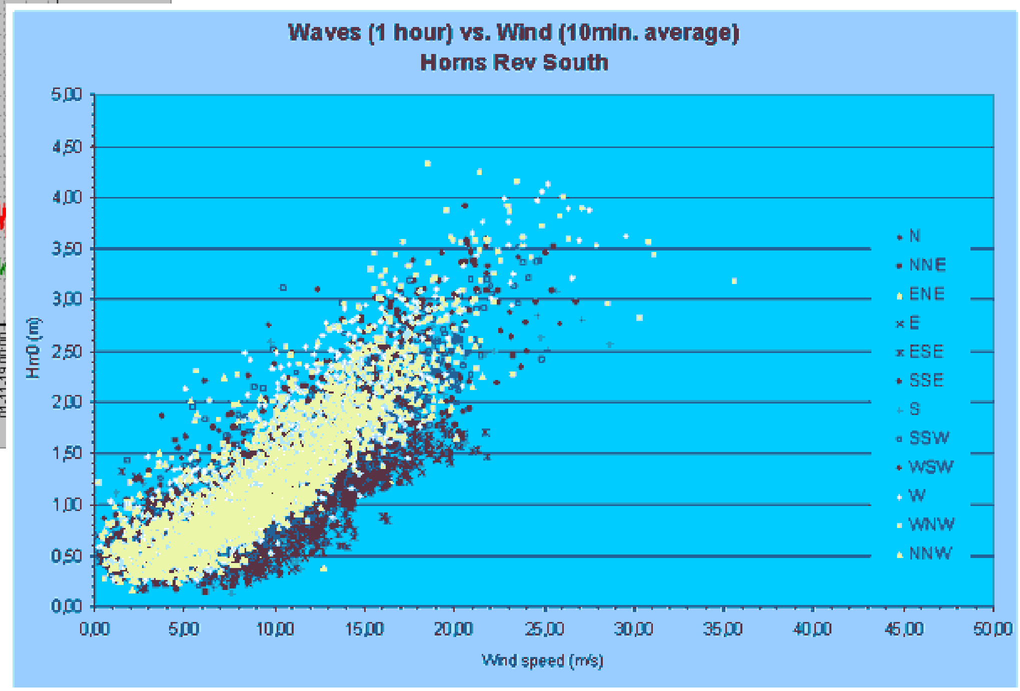
Support structure (example)



Environmental conditions: wind, waves AND correlation (scatter diagram)



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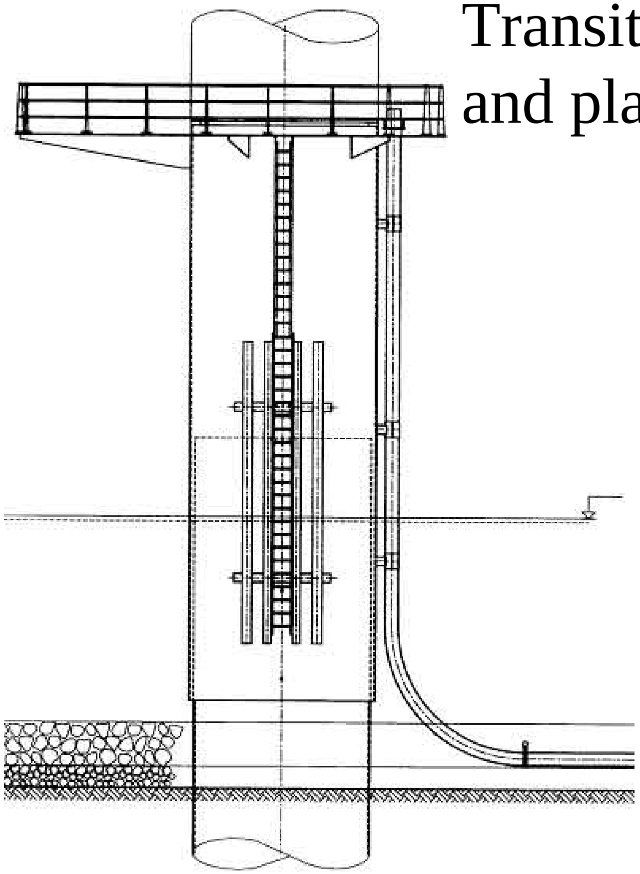
Support structure (example)



Transition piece with boat landing and platform

Cable tie-in and J-tubes (1x, 2x or 3x, PVC)

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Scour protection

Scour protection

Design choices:

- Apply or not?
- Concept
- Overall size
- Specification of elements (rock)

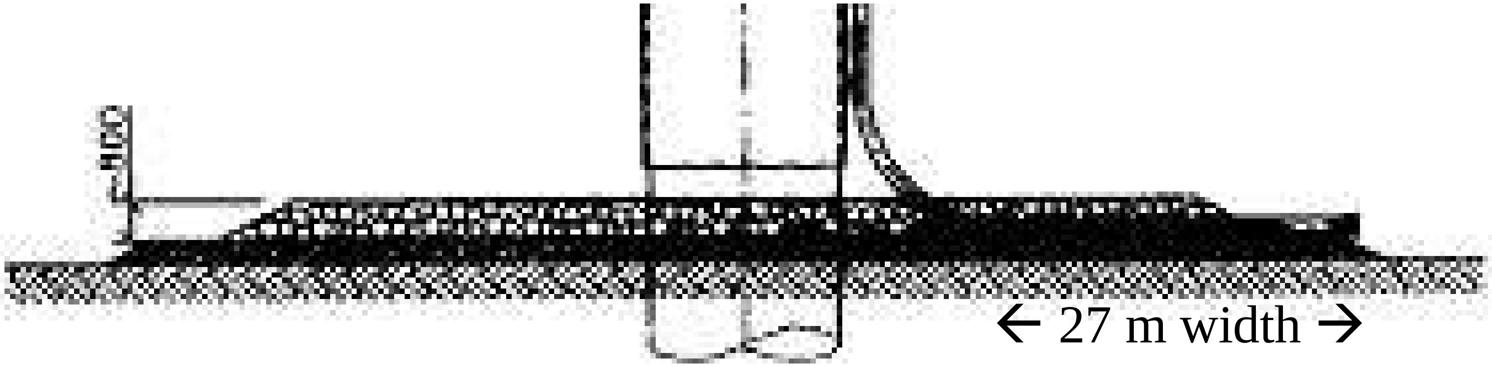
Considerations:

- Necessity
- Support function of soil
- Filter effect
- Stability (self and surrounding soil)
- Installation

Scour protection (example)

Gravel mattress (soil filter)
0.5 m, grading 0.03-0.2 m
Gravel/stone armour layer
0.8 m, grading 0.35-0.55 m

Specialised installation
equipment (existing)



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Electrical collection

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Electrical collection

Design choices:
- Topology
- Voltage level
- AC or DC
- Cable type and size
- Transformers, inverters, rectifiers, switches, …
- Cable protection
- Connections (above/below surface)

Considerations:
- Installation
- Risks (switch/re-route)
- Hydrodynamic conditions
- Capacity and losses
- Necessary conversions
- Controllability

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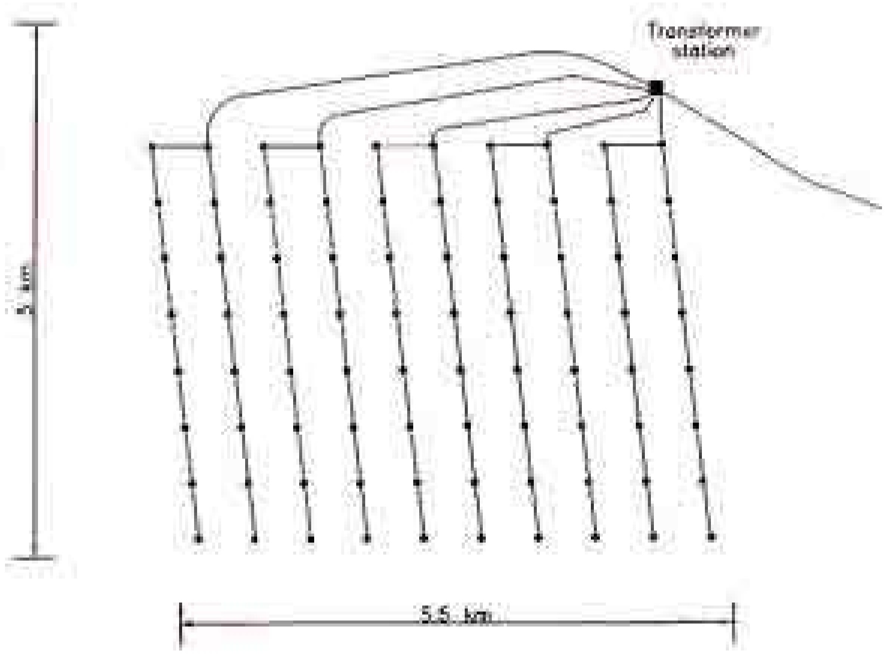
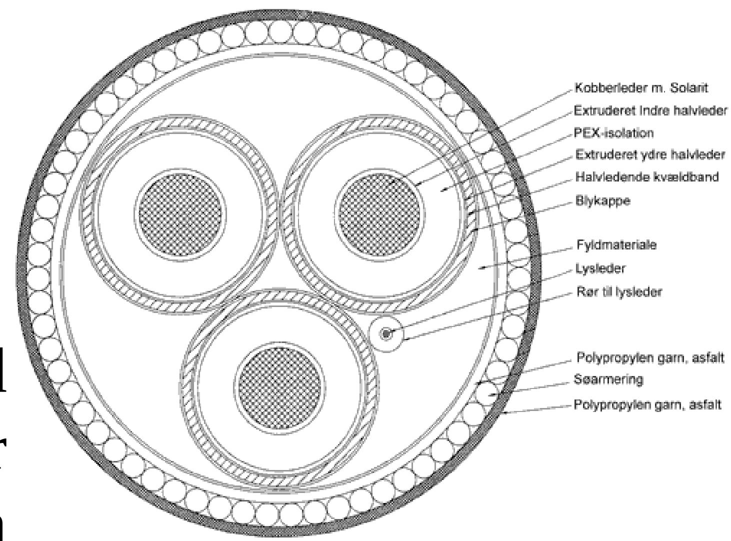
Electrical collection (example)



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



Triple-core copper cable with lead shielding houses fibre optics for communication

Electrical transmission

Electrical transmission

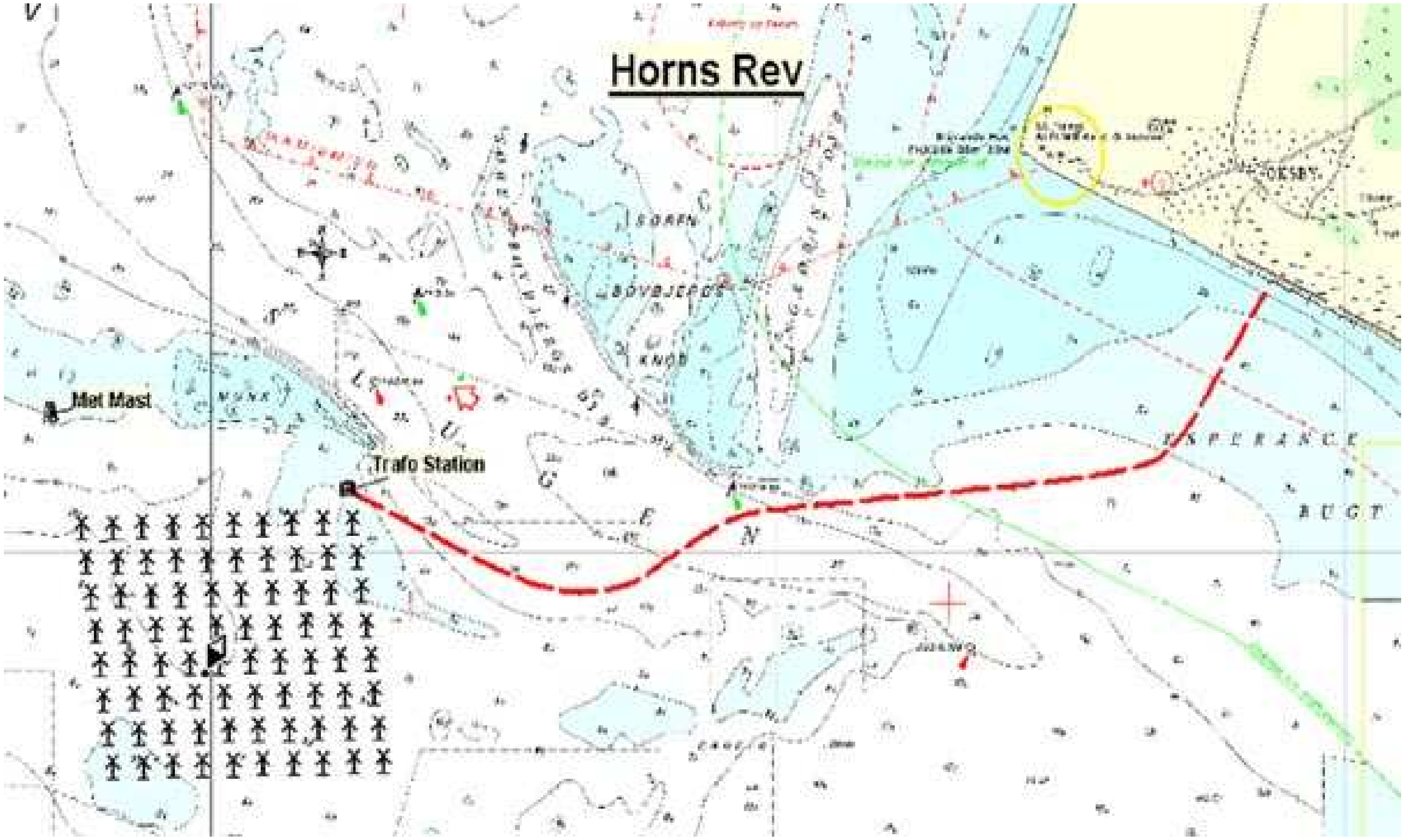
Design choices:

- Route
- Voltage level
- AC or DC
- Cable type, size and number
- Transformers, inverters, rectifiers, switches, shunt inductors, …
- Cable protection

Considerations:

- Installation
- Planning
- Risks (cable ploughing)
- (Extreme) hydrodynamic conditions
- Capacity and losses
- Necessary conversions
- Controllability

Electrical transmission (example)



AC, 150 kV (High Voltage) - Triple-core trenched cable

Other structures

Other structures

Design choices:

•Met-mast

•Transformer platform

•O&M base

•Shunt inductor platforms (electrical transmission)

Considerations:

•Necessity

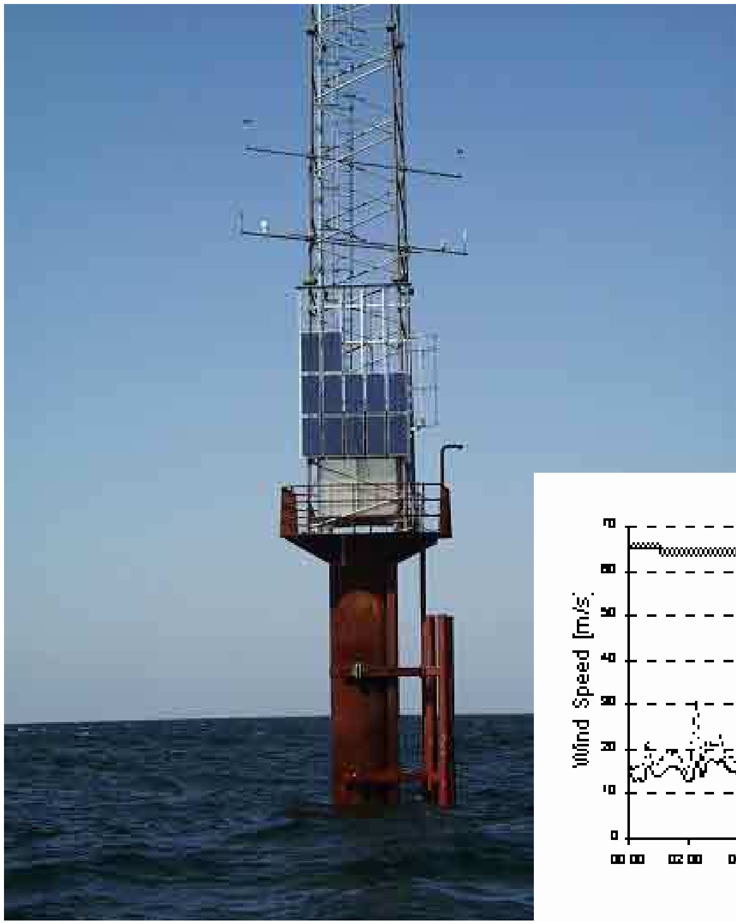
•Possible combinations (also with turbine support structures)

•Function

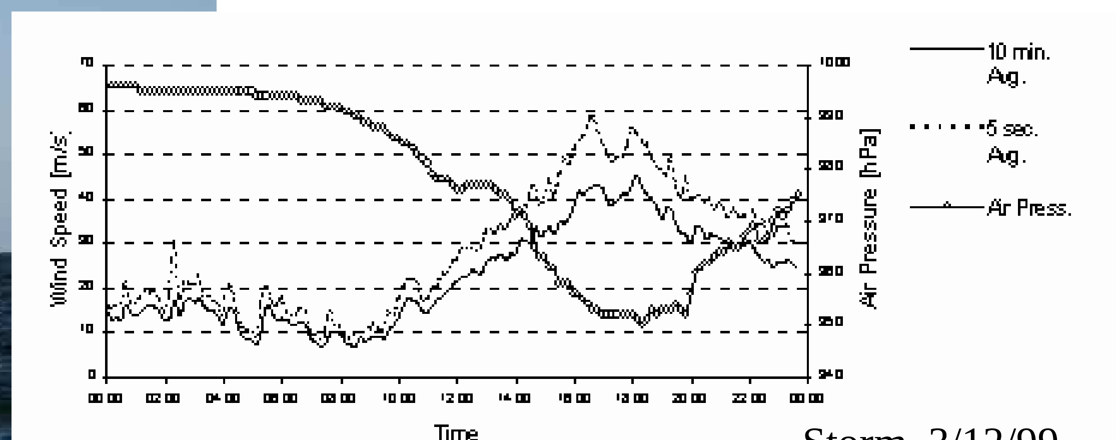
•Structural reliability

•Moment of installation (met-mast)

Other structures (example)



- Installed spring 1999
- Stand-alone (energy, data tx)
- 1.7 m monopile, square lattice
- 15, 30, 45, 62 m met. sensors
- 58 m extra, separate system
- 2 wave riders + Doppler radar



Storm, 3/12/99

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Other structures (example)

20 x 28 m substation, housing

- Transformer 36/150 kV
- Electronic systems
- Emergency diesel generator
- Fire extinguisher (sea water)
- Staff facilities
- Helipad
- Crawler crane
- Man over board boat

Existing installation equipment (oversized for turbines)

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Installation

Installation

Design choices: (installation of structures, cables and (scour) protection)

- Equipment
- Adaptations
- Logistics
- Procedures
- Workability limits

Considerations:

- Duration (w.r.t. season)
- Workability
- Stability of equipment as working platform
- Component weights, dimensions, connections
- Equipment availability

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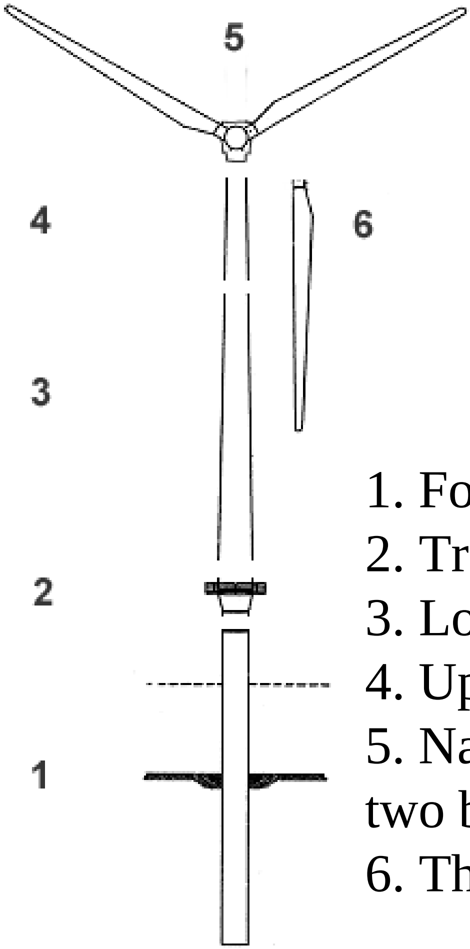
Installation (example)



1. Foundation
2. Transition piece
3. Lower tower
4. Upper tower
5. Nacelle with two blades
6. Third blade

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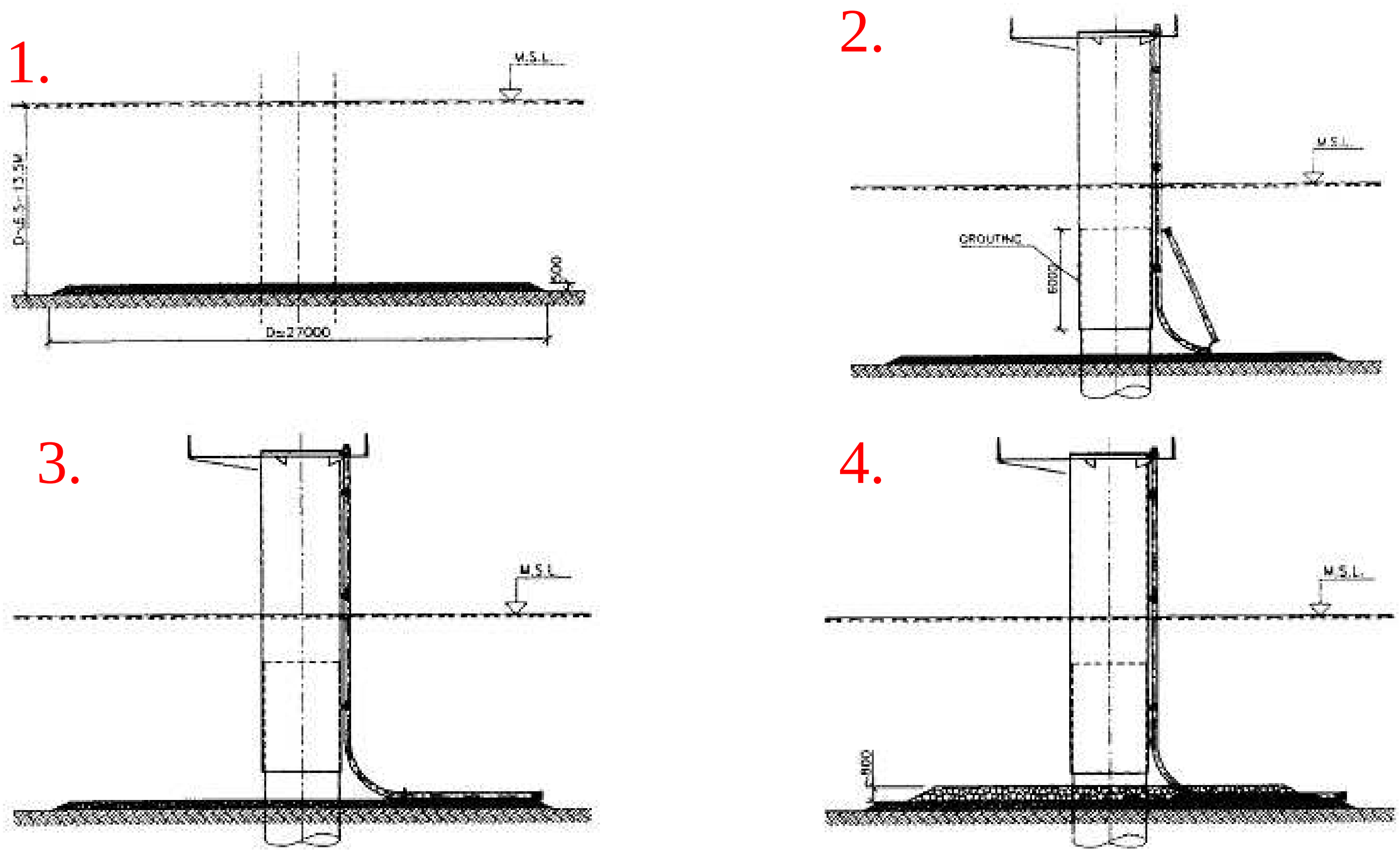
Installation (example)



Pile, scour protection and transition piece installation sequence

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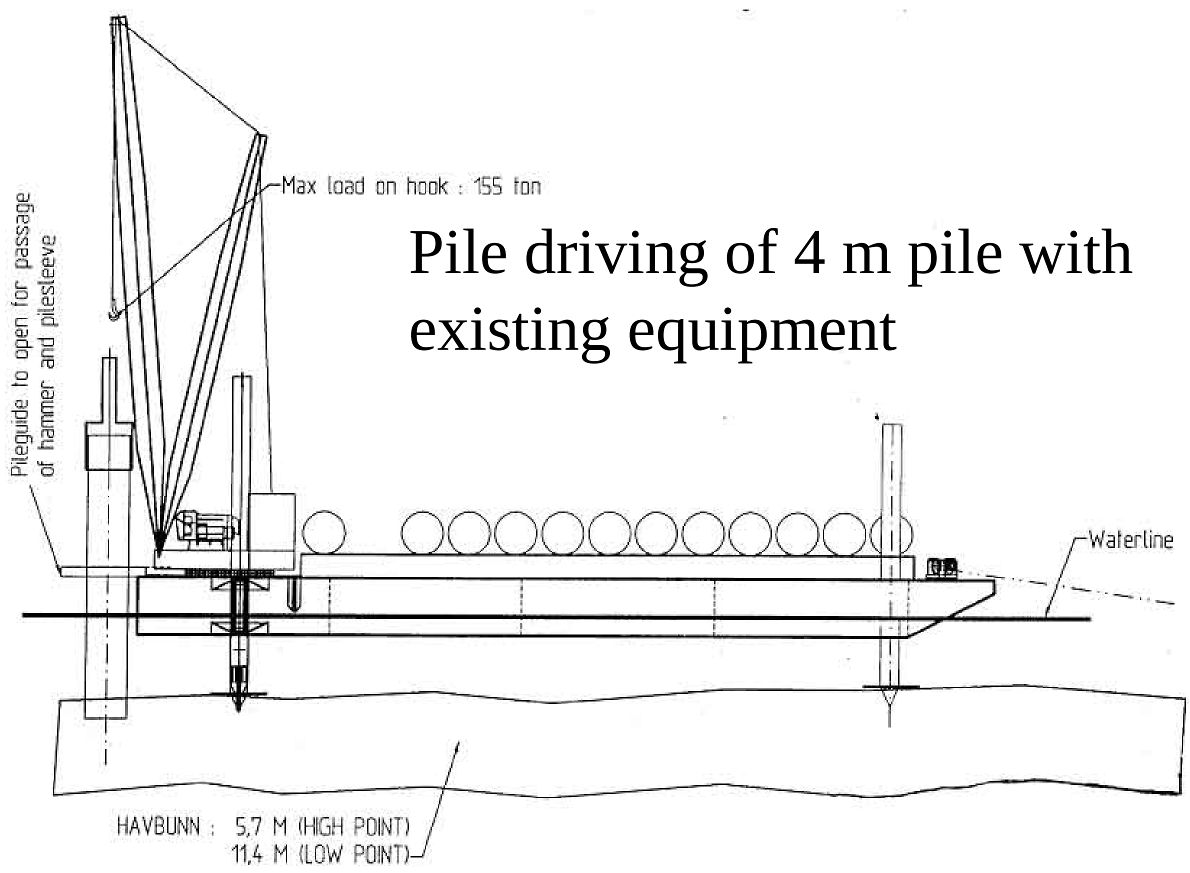
Installation (example)

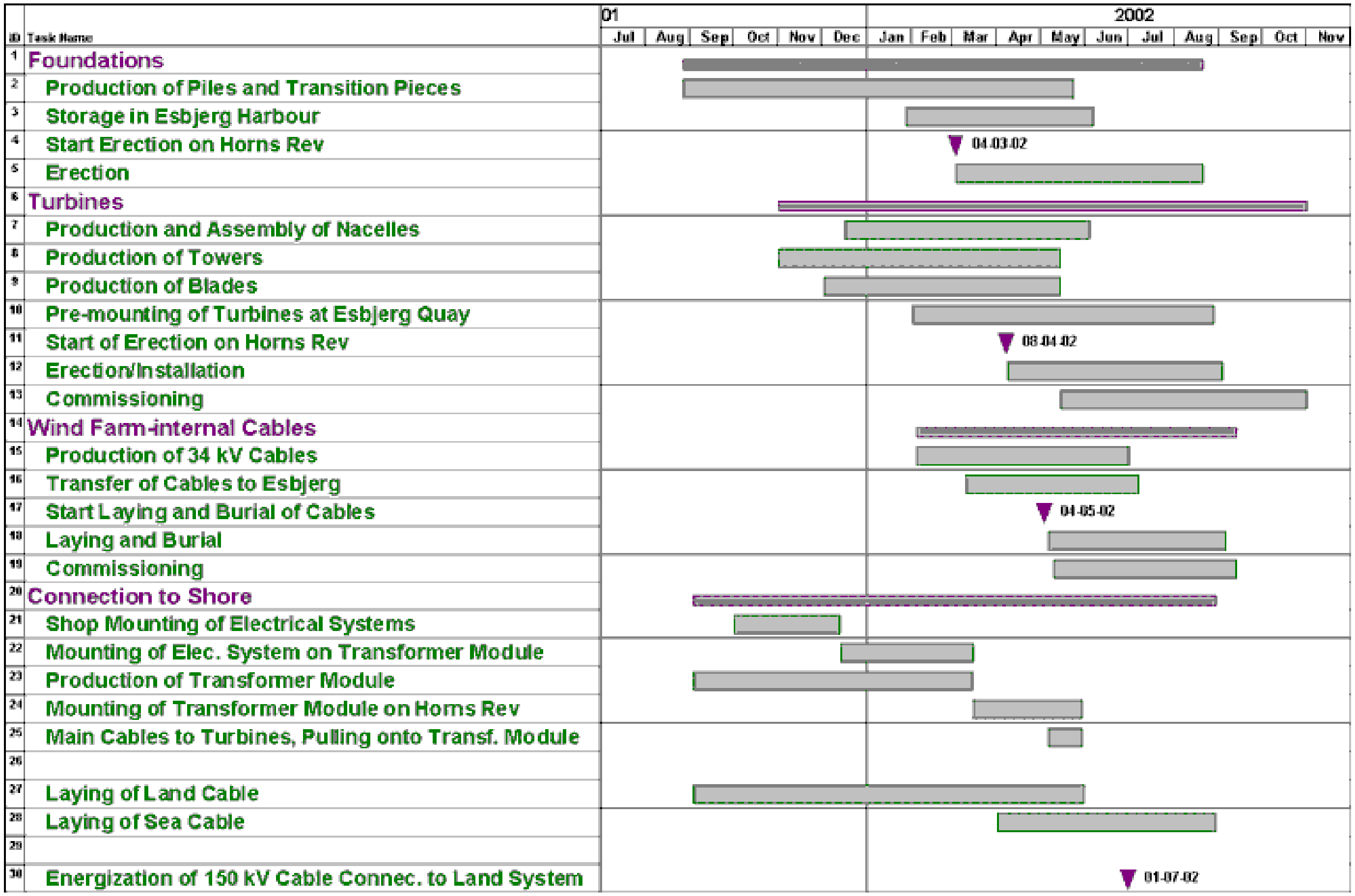


Pile driving of 4 m pile with existing equipment

Installation (example)

Specialised installation equipment (existing)

Installation (example)



The overall schedule

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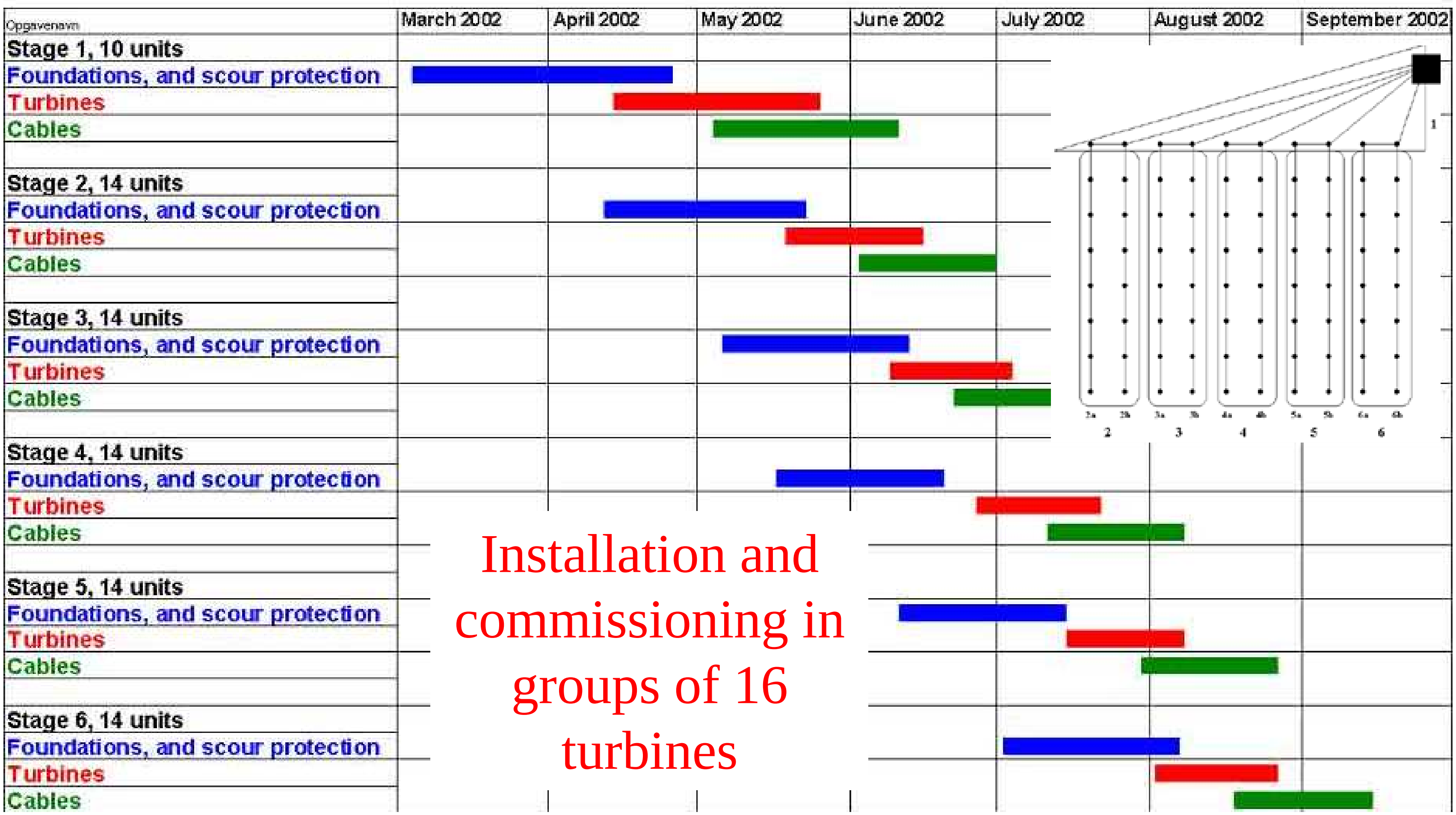
Installation (example)



Installation and commissioning in groups of 16 turbines

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Operation

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Operation

Design choices:

- Periods for scheduled service
- Farm/power plant control
- Spot market strategy

Considerations:

- Service needs
- Controllability
- Value of energy quantity, power and control quality
- Persistence of power
- Predictability of wind

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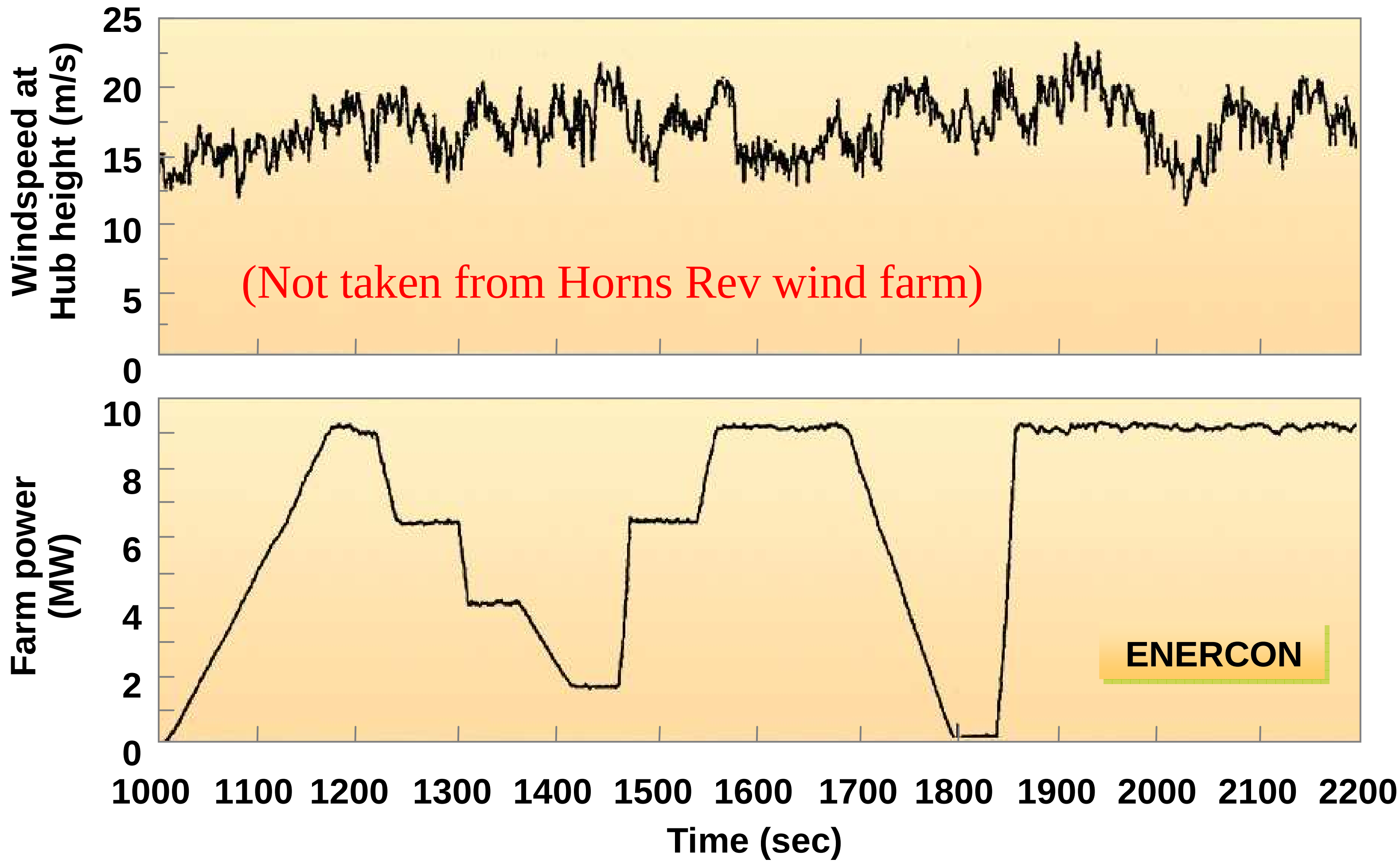
Operation (Example)



Maintenance

Maintenance

Design choices:

•Equipment

•Logistics

•Procedures

•Workability limits

•Crew deployment

•Decision support

Considerations:

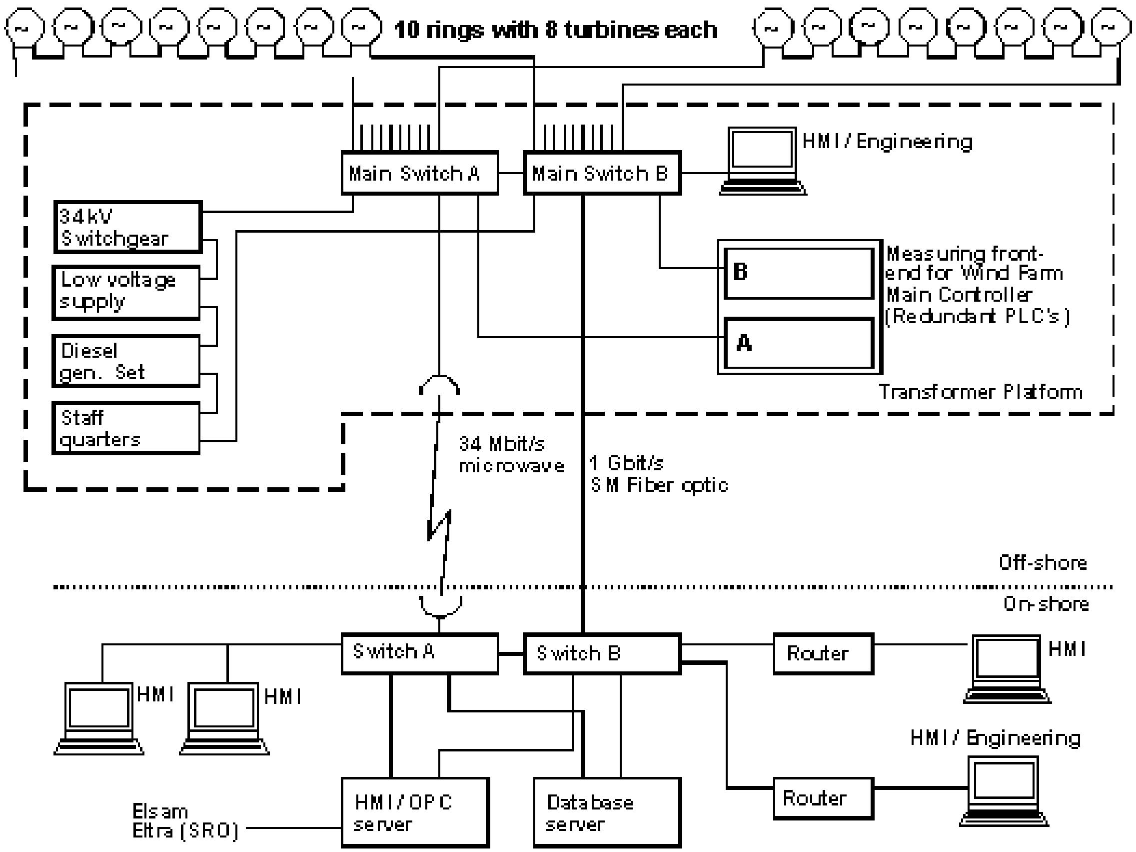
•Component reliability

•Difference and similarity of maintenance needs

•Accessibility/workability

•Duration of procedures (w.r.t downtime and weather windows)

Maintenance (example)



Scada – Supervisory control & data acquisition

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Maintenance (example)

Access of personnel
and small parts

Combination of boat and
helicopter access

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Maintenance (example)

(Prototype at Tjæreborg)

Two annual general service inspections planned per turbine

In addition 1-3 service checks after failure

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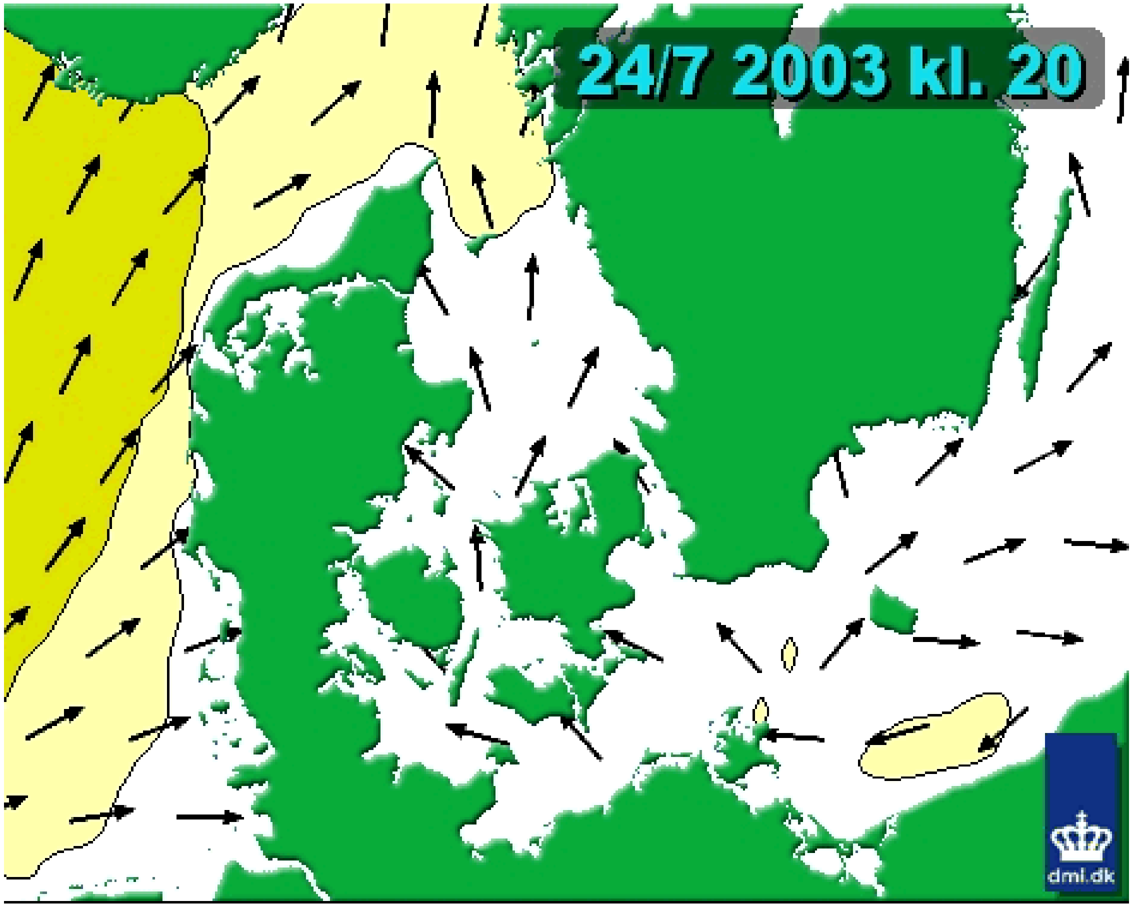
Maintenance (example)



Weather climate used to predict general workability

Weather forecast used to plan activities. Here: Wave conditions according to DMI (Danmarks Meteorologiske Institut)

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Dismantling

Dismantling

Design choices:

•Equipment

•Adaptations

•Logistics

•Procedures

•Workability limits

Considerations:

•Duration (w.r.t. end of license)

•Workability

•Reusable components

•Waste and pollution

•Off-season for equipment (less time critical)

Dismantling (example)

Fortunately no example of dismantling for Horns Rev!

Cost of energy

Levelised Production Cost

$$LPC = \frac{\text{(Actualised-nominal values)}}{\text{(Weighted for amortisation benefit)}}$$

$$LPC = \frac{\sum_{t=0}^{T} C_t (1+r)^{-t}}{\sum_{t=0}^{T} E_t (1+r)^{-t}}$$

C = costs
E = energy production
r = real interest rate
t = year in lifecycle
T = economic lifetime

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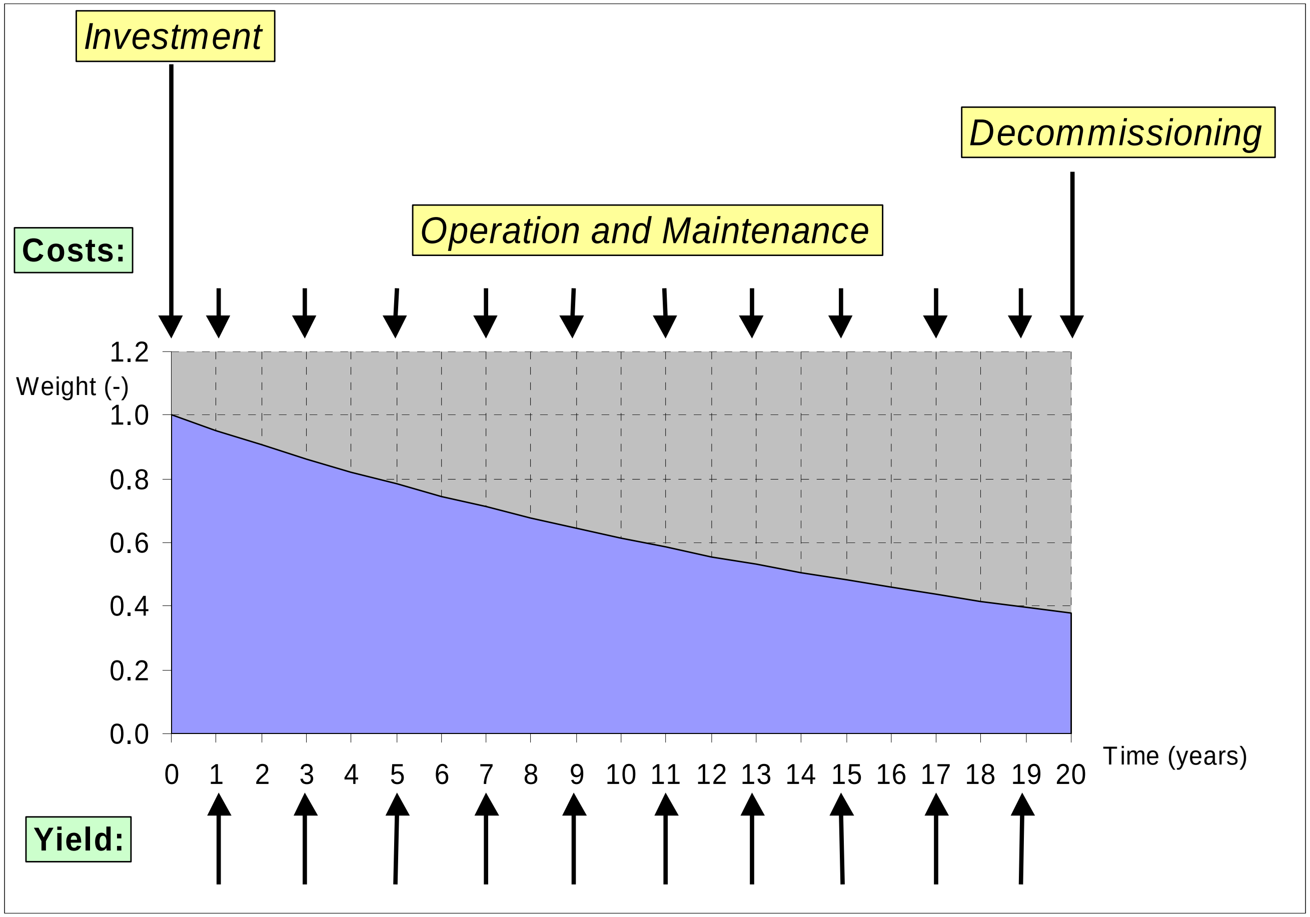
Distribution of costs and yield



Typical contributions to LPC (1)

Assumptions

- Start-up of entire farm after construction
- Annual O&M costs are constant
- Annual energy production is constant
- Decommissioning after shut-down of farm

$$LPC = \frac{C_{invest}'}{aE_y} + \frac{C_{O\&M}}{E_y} + \frac{C_D (1+r)^{-T'}}{aE_y}$$

(a = Annuity factor)

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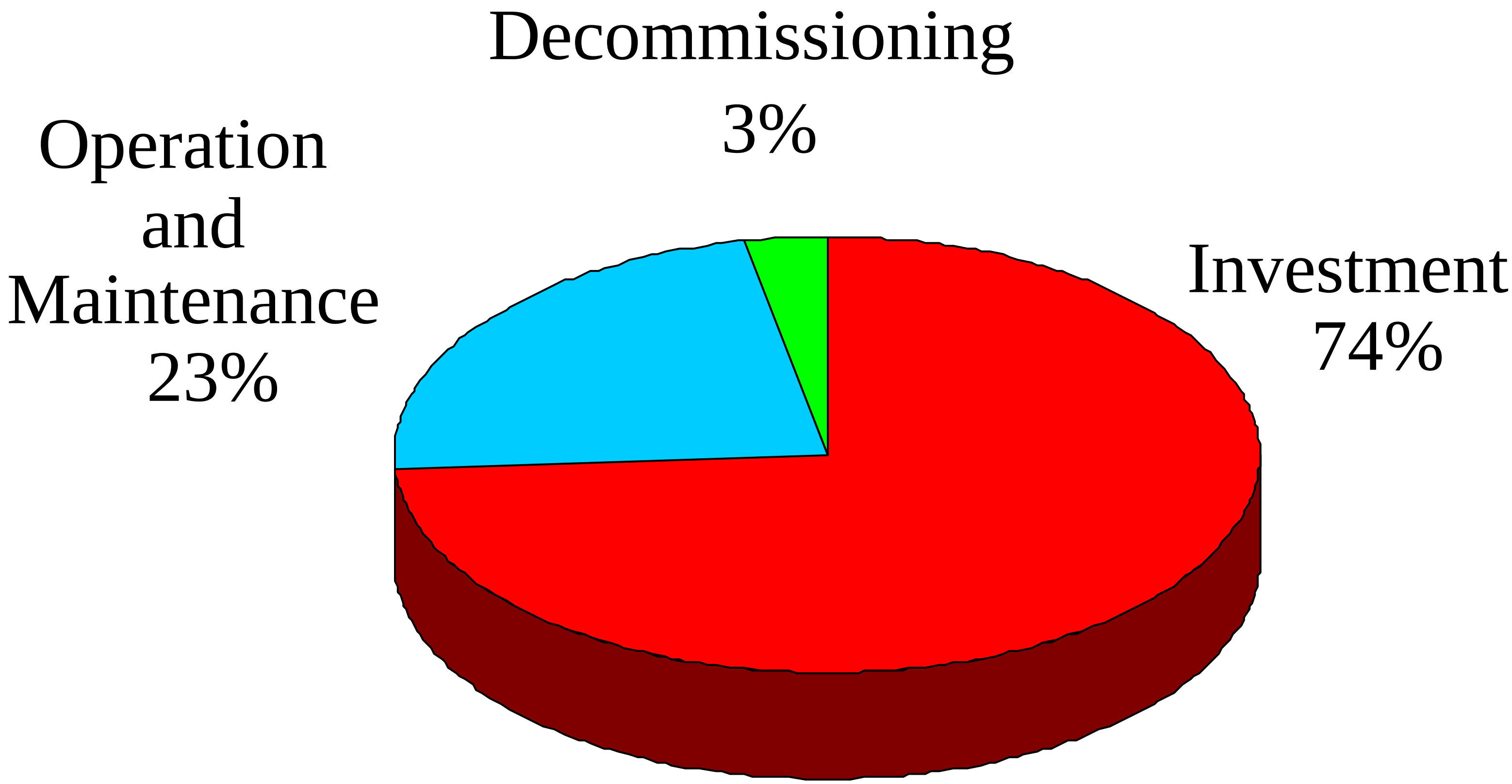
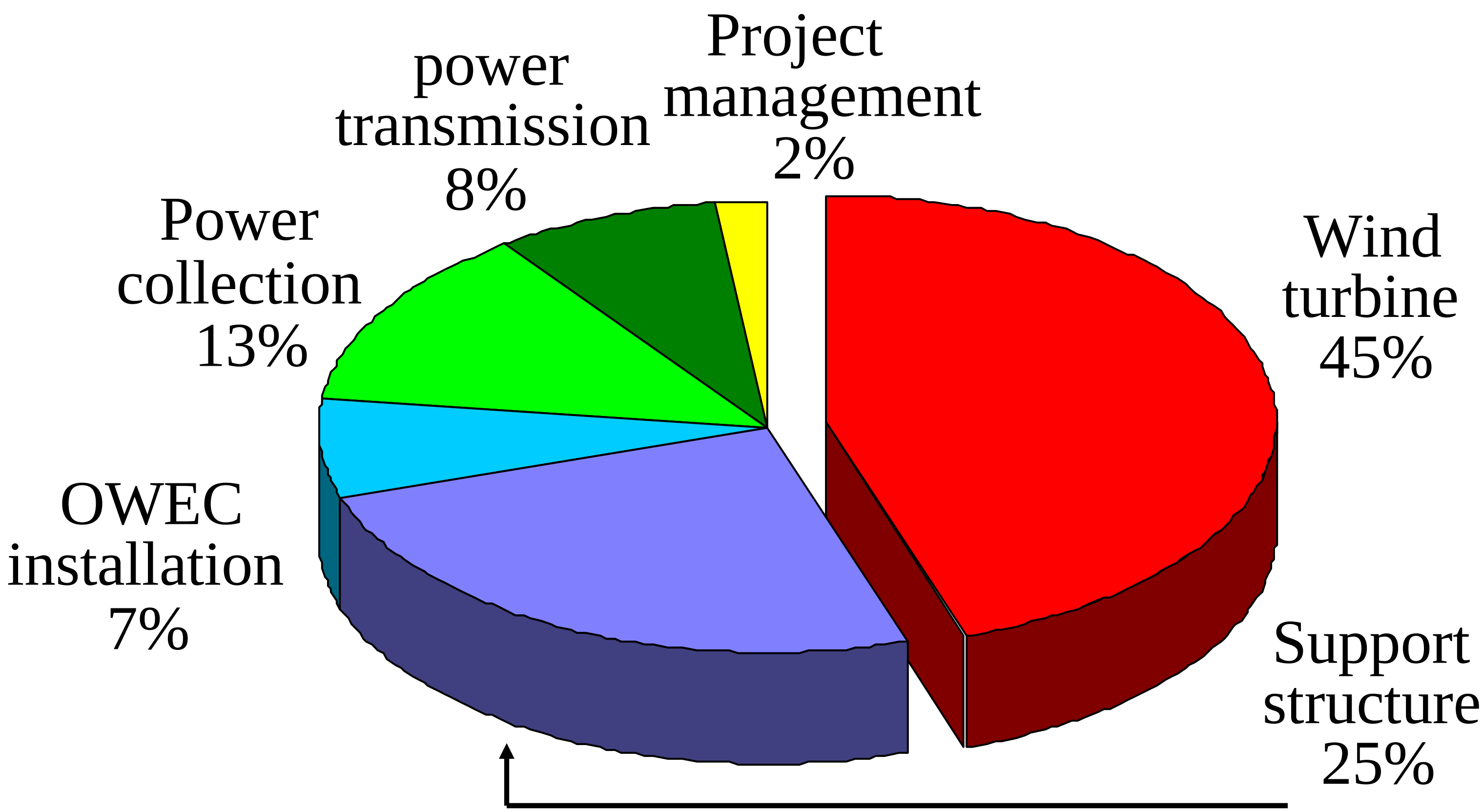
Typical contributions to LPC (2)

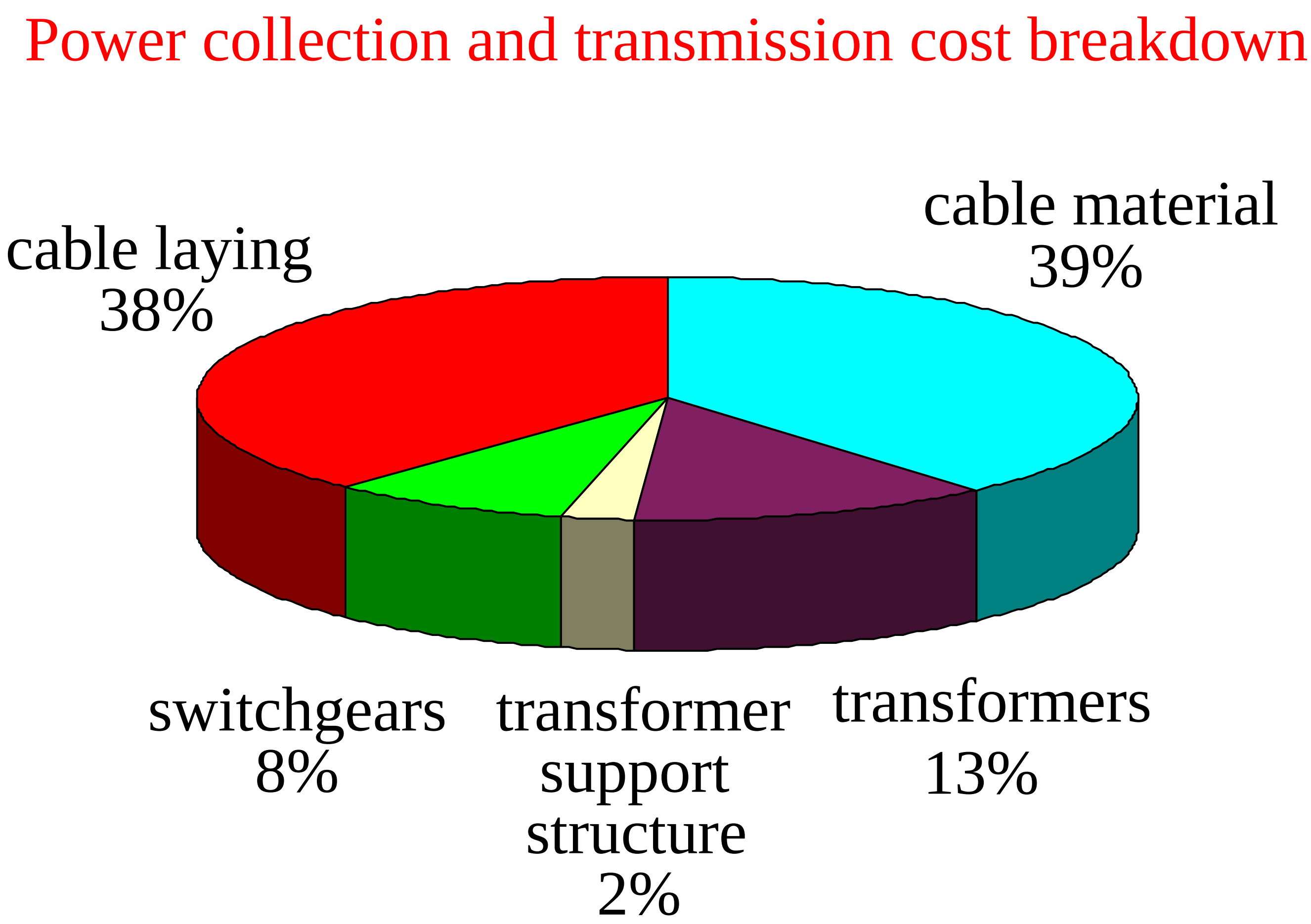


Cost component breakdown

Investment cost breakdown



Detailed breakdown



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Appendix

Necessary information for design considerations

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Site selection

Necessary information:

- Wind speed distribution – general wind farm scale
- General water depth – bathymetry (w.r.t. structure and offshore equipment)
- General environmental conditions (w.r.t loading, accessibility, lightning, …)
- Location and specification of grid connection points, landfalls, harbours, consumers (end-clients)
- Other users and infrastructure (incl. other wind farms)
- General developments in these issues

Wind farm layout

Necessary information:

- Size (rating) of the wind farm
- Possible preferences/restriction for turbine selection
- Wind speed distribution
- Aerodynamic properties of the turbine (thrust/power)
- Trends of costs and losses of the E-infrastructure
- Variation of water depth, soil conditions and other issues w.r.t. support structure design within the area
- Other users and infrastructure

Rotor-nacelle assembly

Necessary information:

- Available turbines, preferences or pre-selection
- Turbine data
- Configurability (design adaptations or options)
- Precise environmental conditions w.r.t. design requirements (wind, lightning, …) and yield
- Installation and maintenance options

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Support structure

Necessary information:

- Rotor diameter, tilt and cone angle, blade bending
- Precise water depth
- Precise environmental conditions (w.r.t loading)
- Precise soil conditions
- Turbine loading characteristics (extremes, fatigue, damping, dynamic behaviour, mass, …)

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Scour protection

Necessary information:

- Effect of omitting scour protection
- Volume of soil active in resistance of loading
- Soil grading
- Water depth
- Dimensions of support structure
- Wave and current conditions

Electrical collection

Necessary information:

- Soil conditions
- Wind farm layout
- Quantity and variation of electricity per turbine
- Properties of electrical transmission and turbine electrical system
- Existing technology (power electronics, subsea connectors and installation options)

Electrical transmission

Necessary information:

- Soil conditions
- Other users and infrastructure
- Distance and location of public grid and landfalls
- Quantity and variation of electricity supply
- Properties of public grid and farm grid
- Existing technology (power electronics)

Other structures

Necessary information:

- Functional requirements
- Precise environmental conditions
- Precise soil conditions
- Possibility to adapt turbine support structures
- (For met-mast:) Existence and quality of data on environmental conditions (w.r.t. loading and energy)

Installation

Necessary information:

- Dimensions and properties of components that will be installed (masses, cable bending and pull strength, …)
- Connections and sequence of assembly
- General environmental conditions (w.r.t. workability)
- Equipment options (which types of equipment exist)
- Equipment data: availability, mobilisation times, workability limits/dynamic behaviour
- Facilities and location(s) of harbour(s)

Operation

Necessary information:

- Periodicity and duration of service
- Turbine controllability and park-grid controllability
- Availability and power output
- kWh prices on spot market
- Penalties for not meeting Unit Commitment
- Regulations and compensation for power control
- Wind prediction accuracy (function of prediction time, weather conditions, …)

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Maintenance

Necessary information:

- Failure modes and maintenance requirements: properties of (spare) parts, replacement prescriptions
- Onshore logistics: spare part storage and ordering
- General environmental conditions (w.r.t. workability)
- Equipment options (which types of equipment exist)
- Equipment data: availability, mobilisation times, workability limits/dynamic behaviour
- Facilities and location(s) of harbour(s)

Dismantling

Necessary information:

- Dimensions and properties of components
- Handling requirements for reusable components
- Policy and regulations for waste (e.g. cut-off piles)
- General environmental conditions (w.r.t. workability)
- Equipment options
- Equipment data: availability, mobilisation times, workability limits/dynamic behaviour