OFFSHORE WIND ENERGY DEVELOPMENT IN THE ADRIATIC SEA: THE P.O.W.E.R.E.D. PROJECT AS PLANNING POLICY

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OFFSHORE SOLUTIONS FOR WIND TURBINE SUPPORTING STRUCTURES

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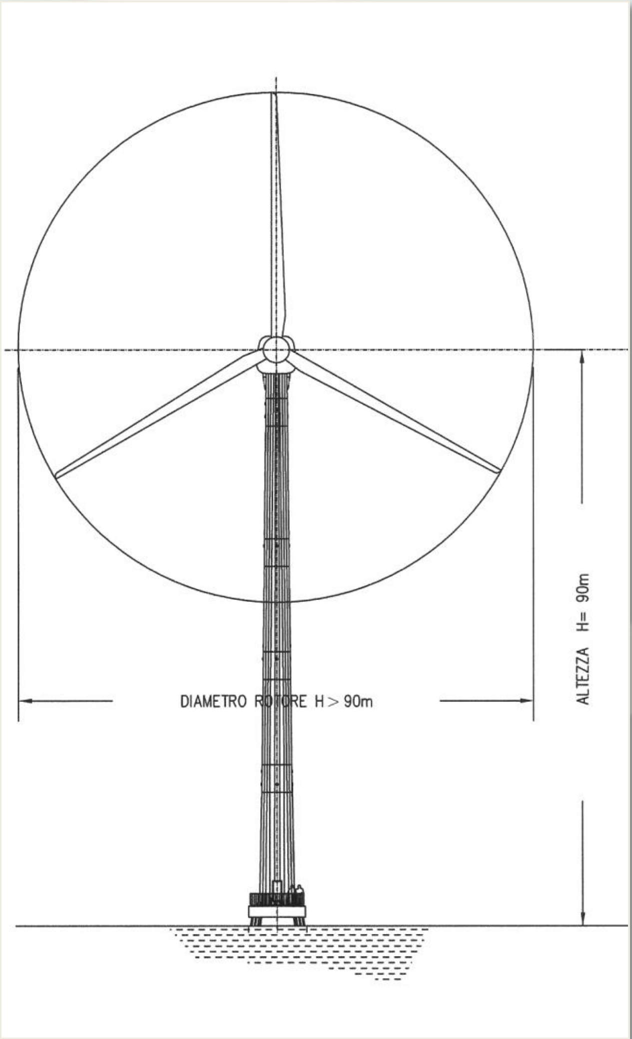
REFERENCE ELEVATIONS

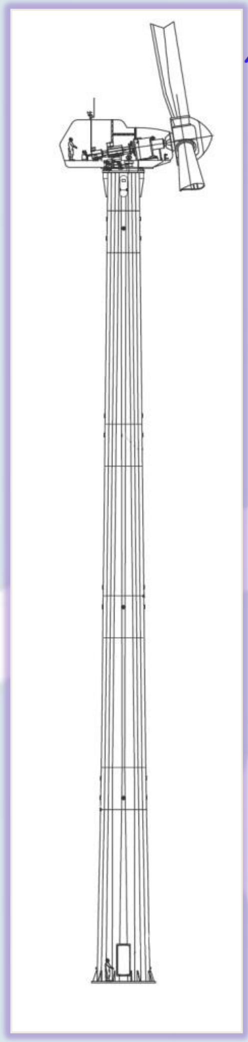
We have to consider two different elevations

•***hub height or rotor axis elevation*, which is the central point of the rotor surface and is the reference for all the wind actions on the turbine;**

•***interface level or interface between tower and substructure* at which elevation could be situated the main platform, the connection tower-substructure and tower access. It is the separation between the turbine manufacturer's responsibility and that of the support structure designer in both a physical and an organisational sense.**

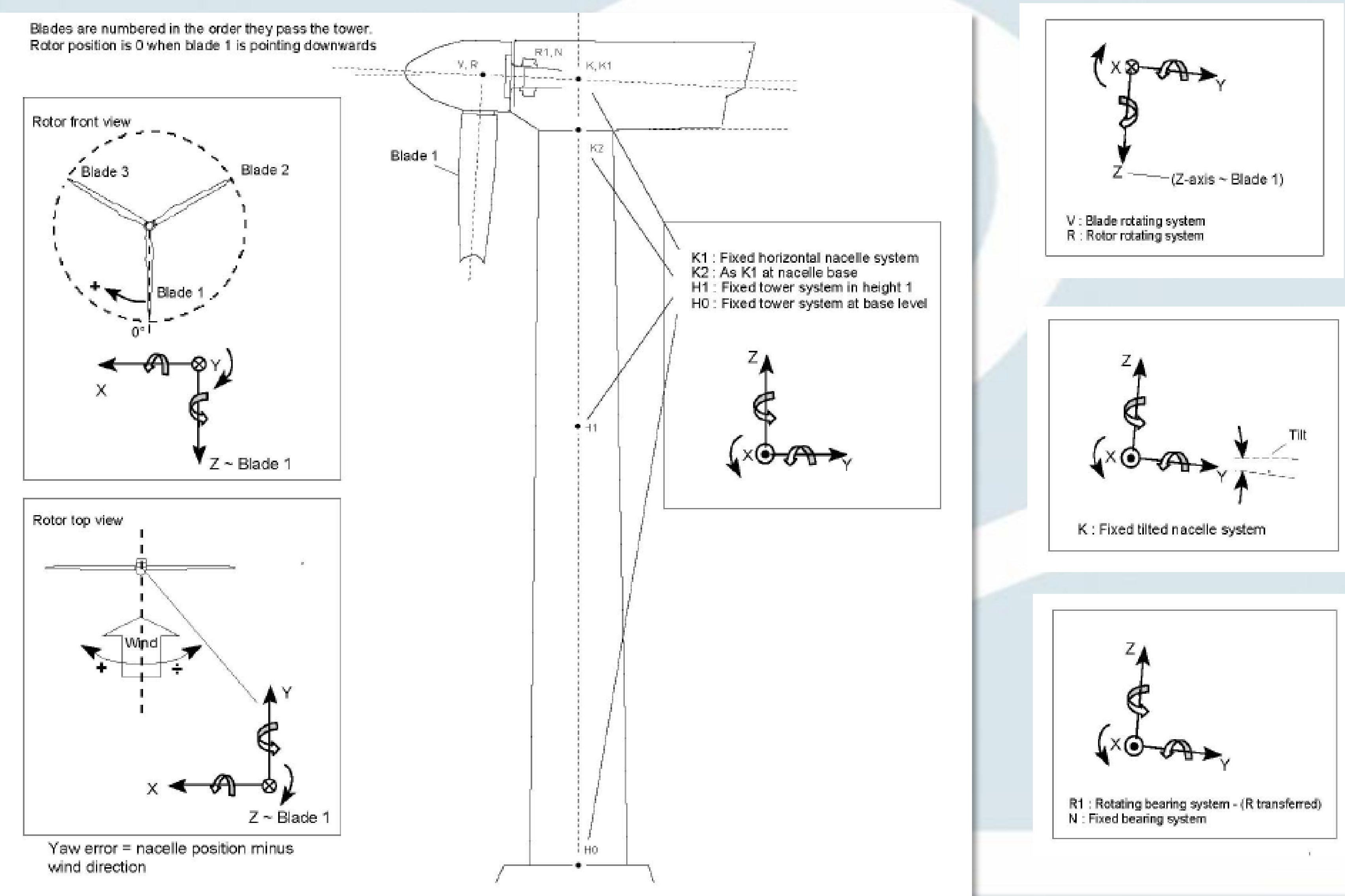


Wind turbine front view



… and lateral view

FORCES, MOMENTS, DISPLACEMENTS, ROTATIONS: DIRECTIONS

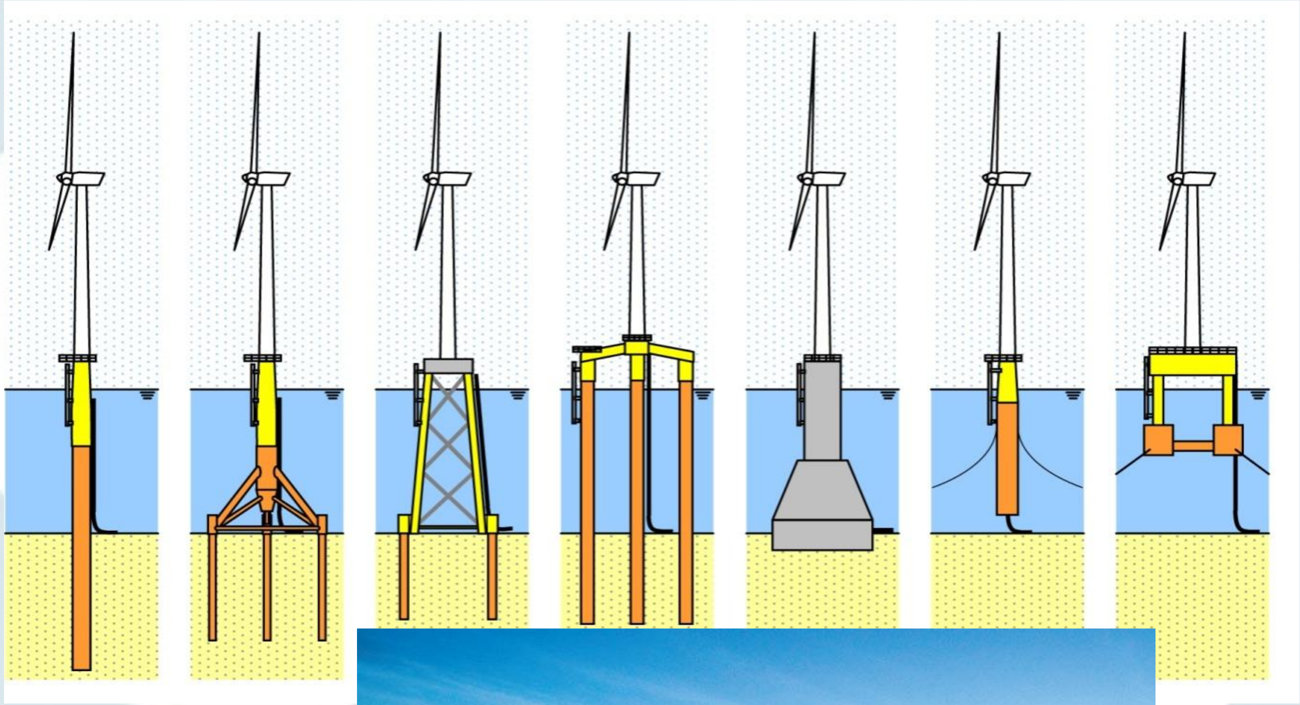


STRUCTURAL ANALYSIS & VERIFICATIONS

During the calculation steps of the structural analysis in support to the design have to be verified also theese following conditions

- *In service analysis*;
- *Dynamic modal response and fatigue analysis*;
- *Seismic analysis*;
- *Load out analysis of the structure on barges*;
- *Lift analysis at dock-yard and on site*;
- *Barge transportation analysis*;
- *On-bottom analysis*;
- *Free floating and upending analysis during the installation phases in the sea*;
- *Foundation pile driveability analysis*.

FUNCTIONS OF SUPPORT STRUCTURE



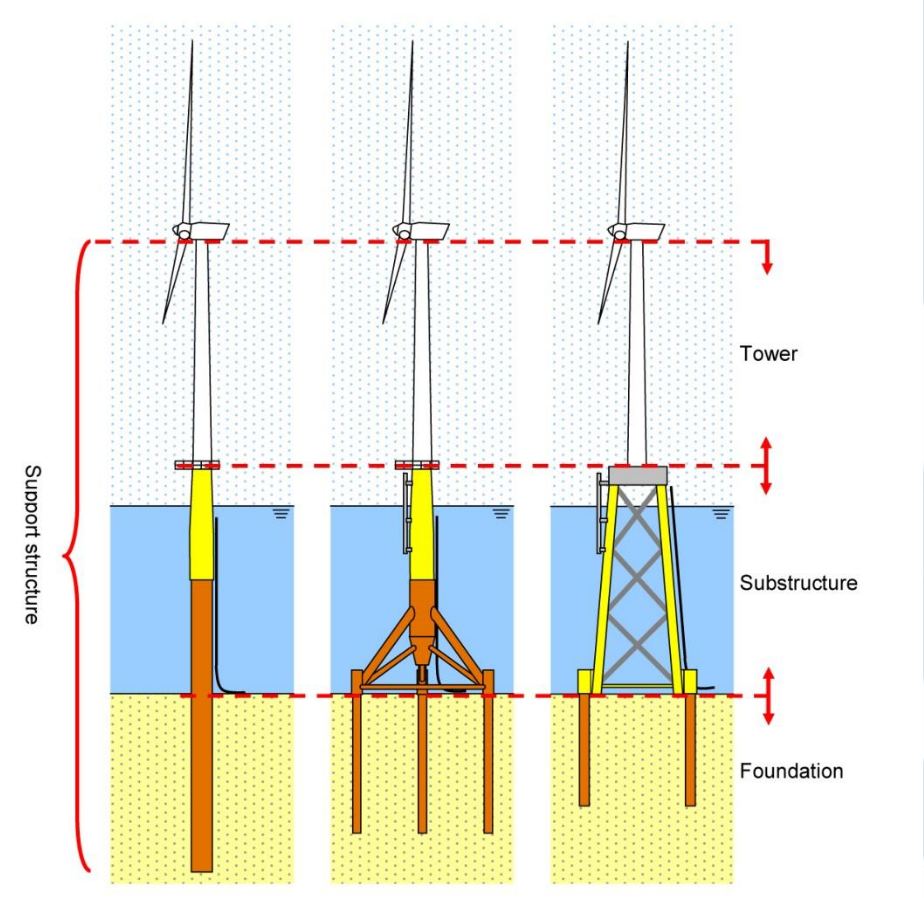
The functions of the structural bodies are

- to support the turbine;
- to hold up all the loads from normal/extreme conditions, meteorology/sea regimes, the turbine operation and to transfer them to the seabed;
- to respect the stiffness degree requested by dynamic regimes of the turbine;
- to hold a minimal surface of the seabed;
- to have the tower entrance over the maximum wave level in every moment;
- to reduce/annul its maintenance during the plant life.

MAIN COMPONENTS OF WIND TURBINE SUPPORT SYSTEM

Starting from the upper part the support structure consists

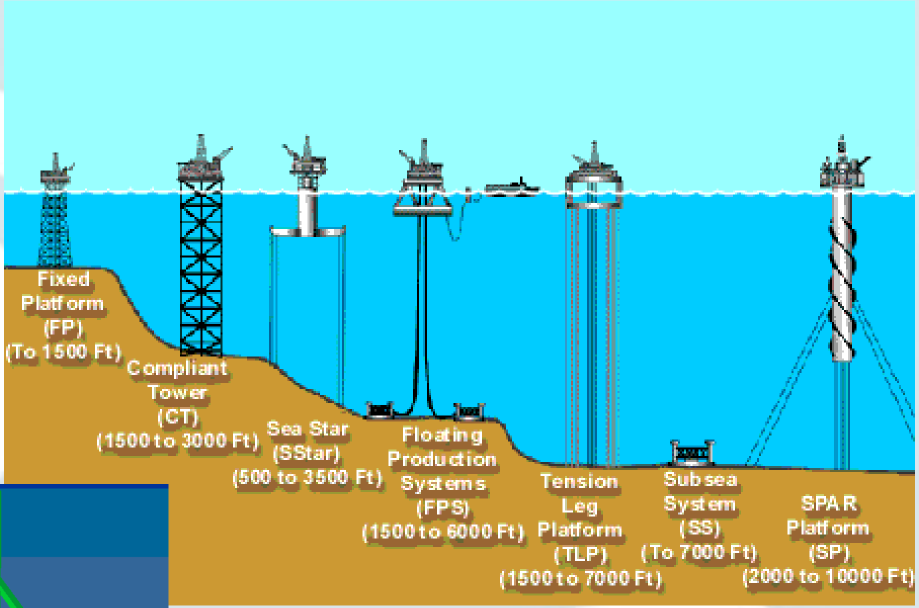
- of the *tower* usually made of two/three sections riveted each other supporting at the top the nacelle with rotor;
- of the *substructure* connecting the tower base with own root;
- of the *foundation* in strict contact with soil and able to transfer to it all the loads coming from the top for the solution in touch with seabed ;
- of anchoring elements in connection with dead mass on the seabed, acting as *foundation* for floating solution .

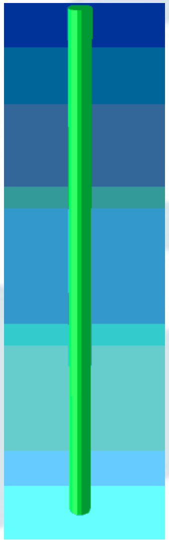


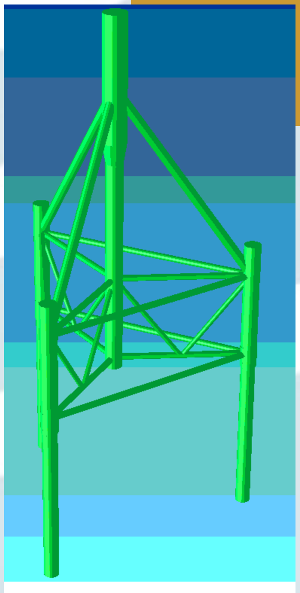
OFFSHORE SUBSTRUCTURES: ALTERNATIVES AND SOLUTIONS

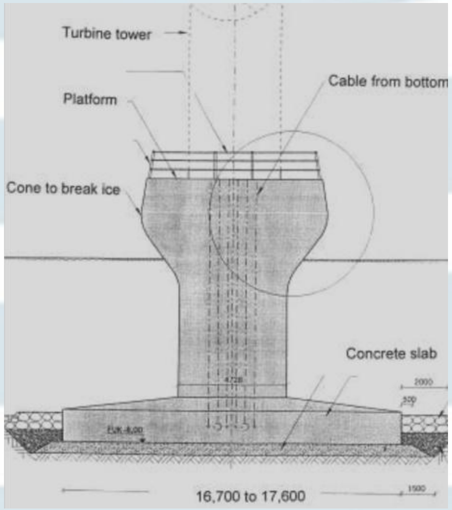
Foundations in direct contact with seabed
- *monopile/monopod substructure*;
- *tripod substructure*;
- *jacket substructure*;
- *gravity substructure*);

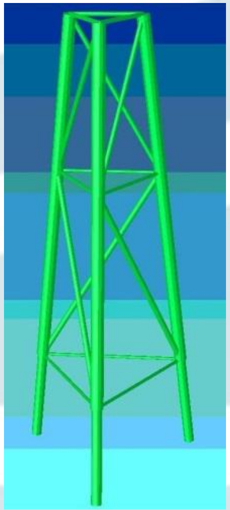
Foundations not in direct contact with seabed
- *floating substructure*.







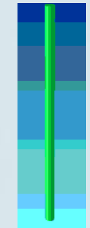


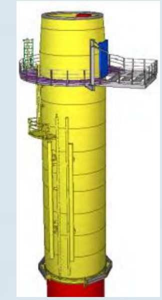


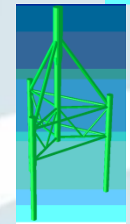
CHARACTERISTICS OF SUBSTRUCTURE SOLUTIONS

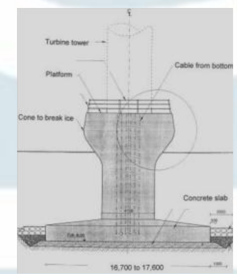
To describe a substructure type we have to consider these essential elements

Substructure solution	Main components
Monopile/monopode	**portion inserted in the seabed, transition piece (TP), upper terminal with main platform;**
Tripode/Tripile	**skirt pipes with foundation piles, central element supporting the platform, beams/tubes connecting central element with skirt pipes**
Jacket	**foundation piles, legs, beams/tubes connecting legs together, platform at terminal part or deck;**
Gravity mass	**preparation of seabed to host body and the anti-scour defense, basement, neck connecting base with the head equipped by the platform.**









MAIN COMPONENTS

In the substructure a certain number of parts have to correspond to specific functions of the wind turbine operation, as in particular

1. boat landing structure;

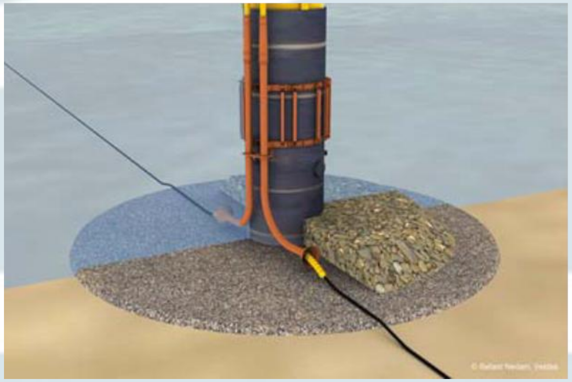
2. main/service platform;

3. starways, small secondary platforms, loading areas;

4. J-tube to guide electrical cables;

5. cathodic protections.



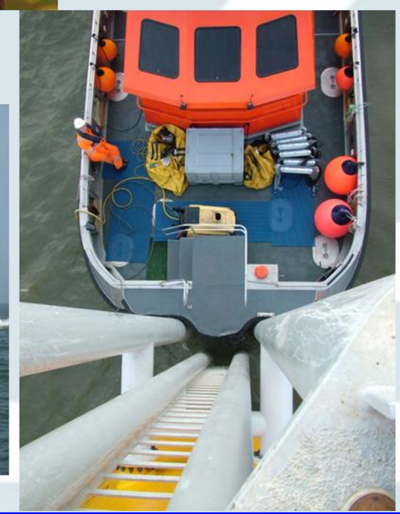



BOAT LANDING

The boatlanding is the structure to which a vessel can moor to transfer personnel and equipment to the substructure.

The boatlanding consists of two mainly vertical fenders connected by stubs to the main structure.

Depending on the environmental conditions and on the maintenance strategy of the operator, there may be one or more boatlandings connected to a support structure.



PLATFORMS & MAIN PLATFORM

- Platforms are intended as safe working areas for personnel that need to work on the structure

- Different functions can be identified; there are access platforms, resting platforms, and depending on the type of structures service platforms and airtight platforms.

- Resting platforms are required for safety reasons, when the vertical distance from the initial access point along a ladder to the next safe point exceeds a certain value.

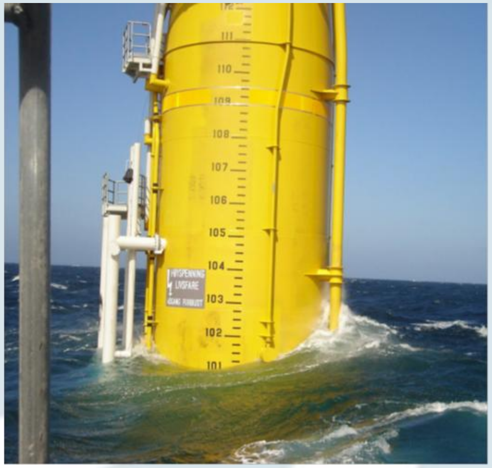
- Service platforms are included for instance in the transition piece to facilitate the tightening of bolts at the base of the tower.

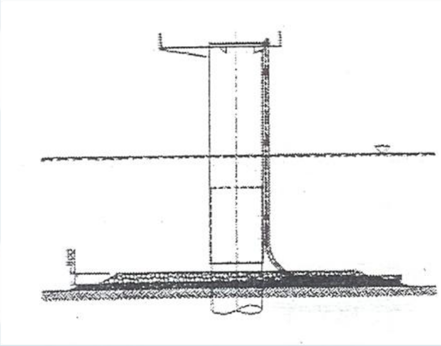
J-TUBES FOR ELECTRICAL CABLES

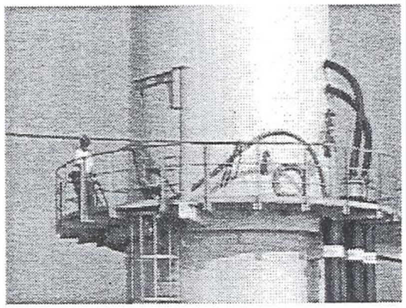
- To protect and guide the export cable into the support structure, a J-tube is installed on the structure.

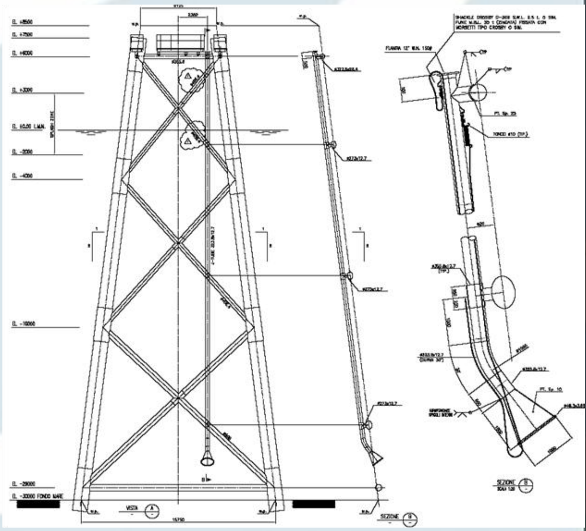
- The name derives from the shape that the tube makes as it curves to a horizontal orientation near the seabed.

- J-tubes can be either internal, only to protrude from the substructure at the seabed level, or external.





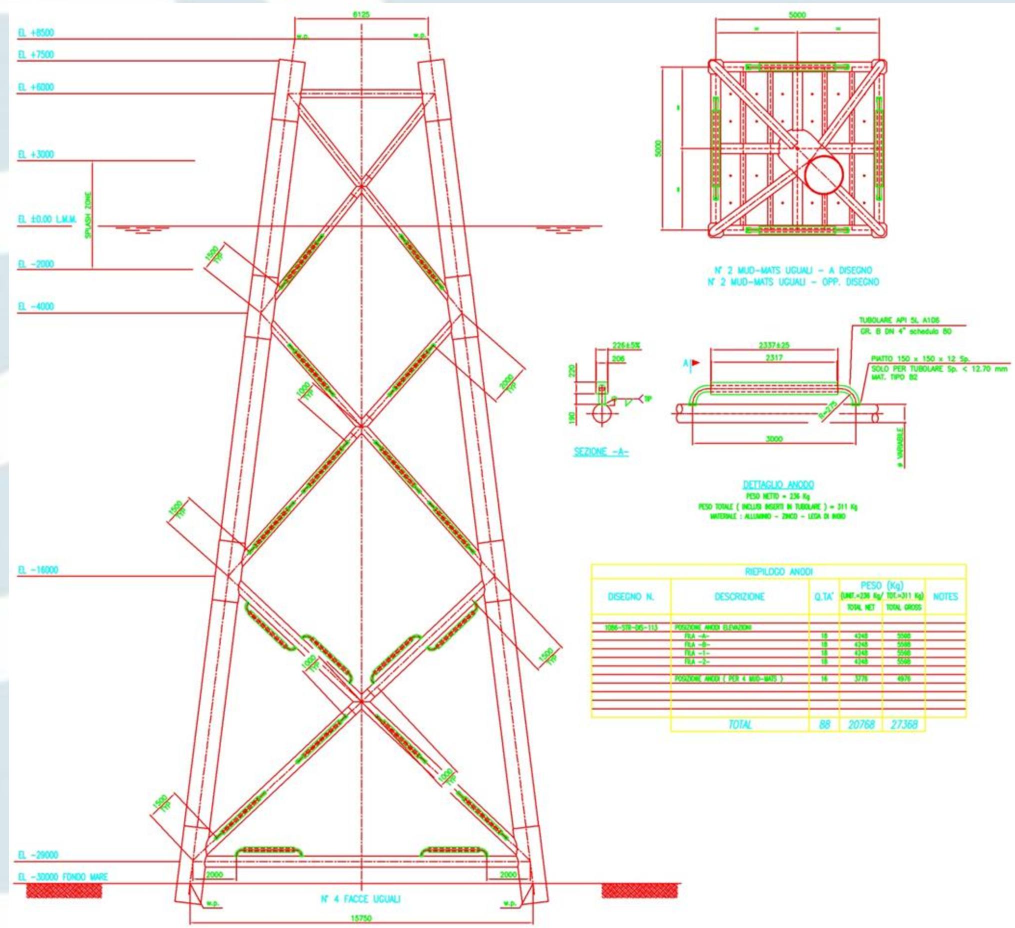




LAY-OUT OF CATHODIC PROTECTION

- To provide cathodic protection against corrosion, blocks of particular alloys (aluminium base, etc.) may be installed as sacrificial anodes;

- Provisions must be made on the substructure to fix the anodes.



MONOPILE SUBSTRUCTURES

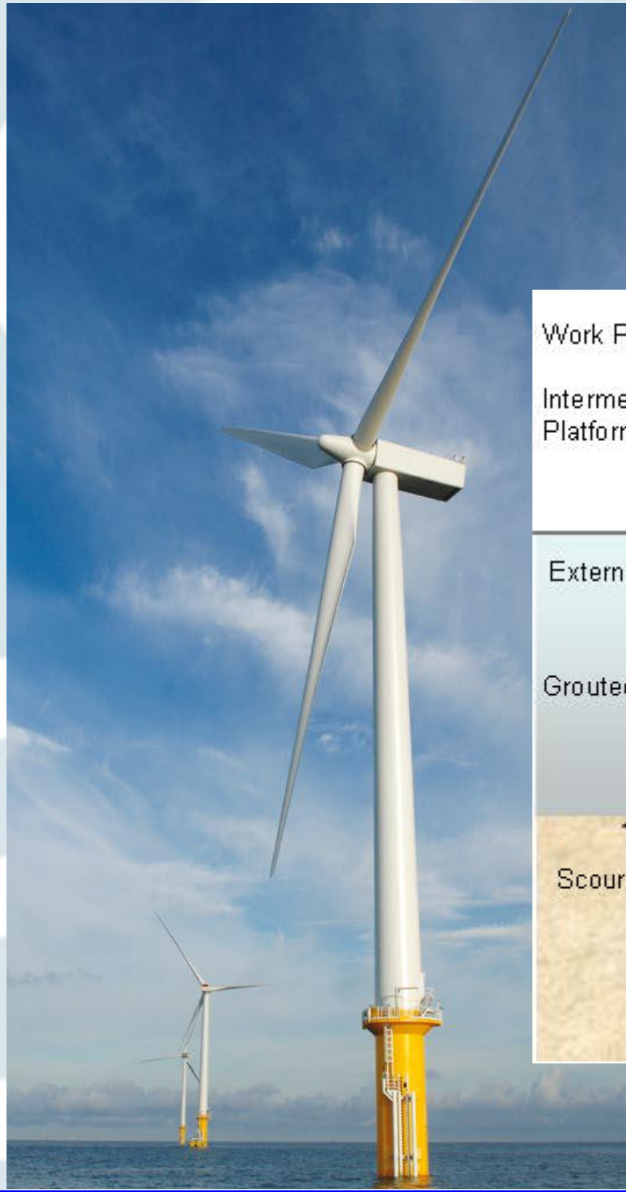
In a synthetic representation of wind turbines supported by a monopile substructure in the world we have to consider the following plants

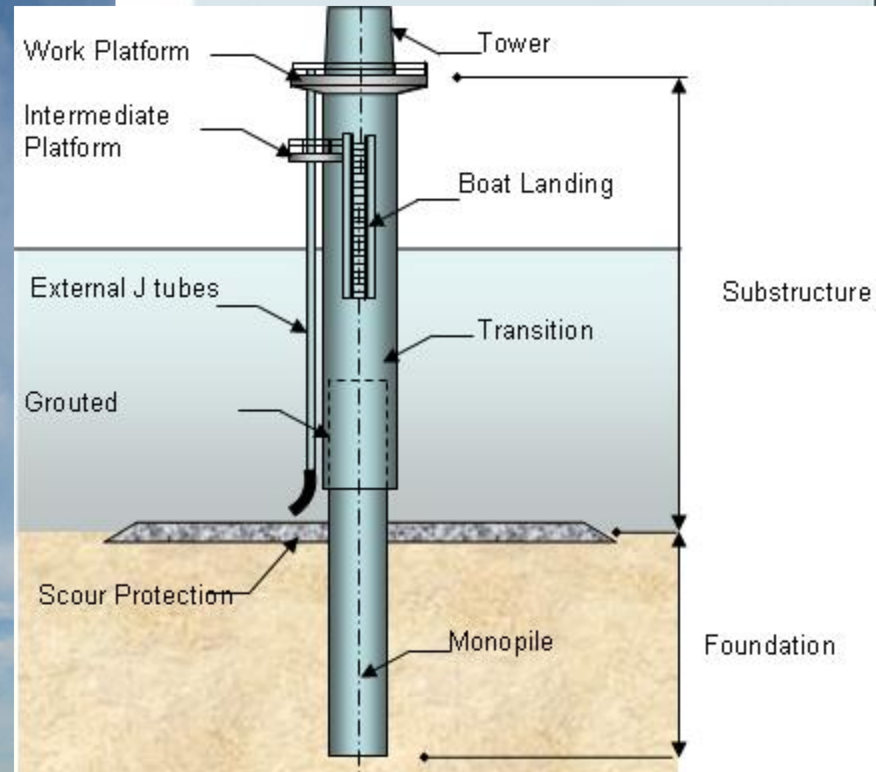
Arklow Bank (7, 25, 2007, Ireland); Barrow (30, 90, 2005, UK);
Blyth (2, 4, 2000, UK); Egmond aan Zee (36, 108, 2006, NL);
EnBW Baltic 2 (39 turbines over 80, 288, 2013/5, DE);
Greater Gabbard (140, 504, 2012, UK);
Gunfleet Sands (48, 172, 2010, UK); Horns Rev 1&2 (80/91, 160/209, 2002/2009, DK);
Kentish Flats (30. 90. 2005, UK); Lely (4, 2, 1994, NL);
London Array (340, 1224, 2014, UK); Lynn & Inner Dowsing (54, 194, 2008, UK);
North Hoyle (30, 60, 2003, UK); Princess Amalia/Q7 (60, 120, NL, 2008);
Rhyl Flats (25, 90, 2009, UK); Robin Rigg (60, 180, 2010, UK);
Scroby Sands (30, 60, 2004, UK);
Utgrunden (7, 10, 2000, SE); Walney 1 (51, 183, 2011, UK),

in the round brackets the number of units, the total power, the year for beginning of electrical generation and the country.

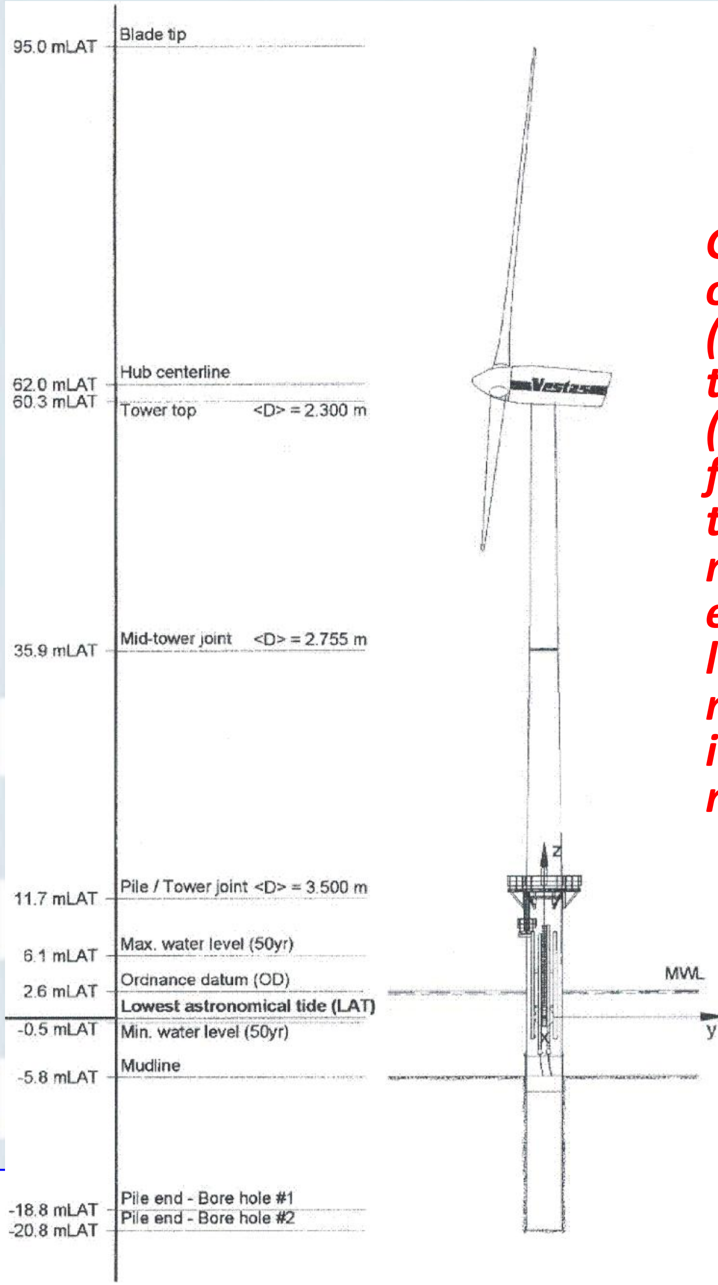
MONOPILE SUBSTRUCTURE: CHARACTERISTICS

- Geometrical continuation of the tower ;
- Steel for all structural materials;
- Diameter range from 4 to 8 m (in function of turbine data and seabed height), thickness over 140 mm;
- Hydrodynamic loads increasing with outside diameter;
- Vertical loads transferred to the soil through the resistance of soil-tube and of the pile tip;
- Horizontal forces transferred to foundation through the bending moment;
- Stiffness improvement by increasing diameter and thickness with consequent difficulties in inserting the tube by pile-driver;
- Installation through driving or vibrating or seabed drilling;
- Transition Piece connected to monopile by grouting;
- Preparation of the area around the pile to avoid the strong effects of scour;
- Solution for seabed height range up to 30/35 m.





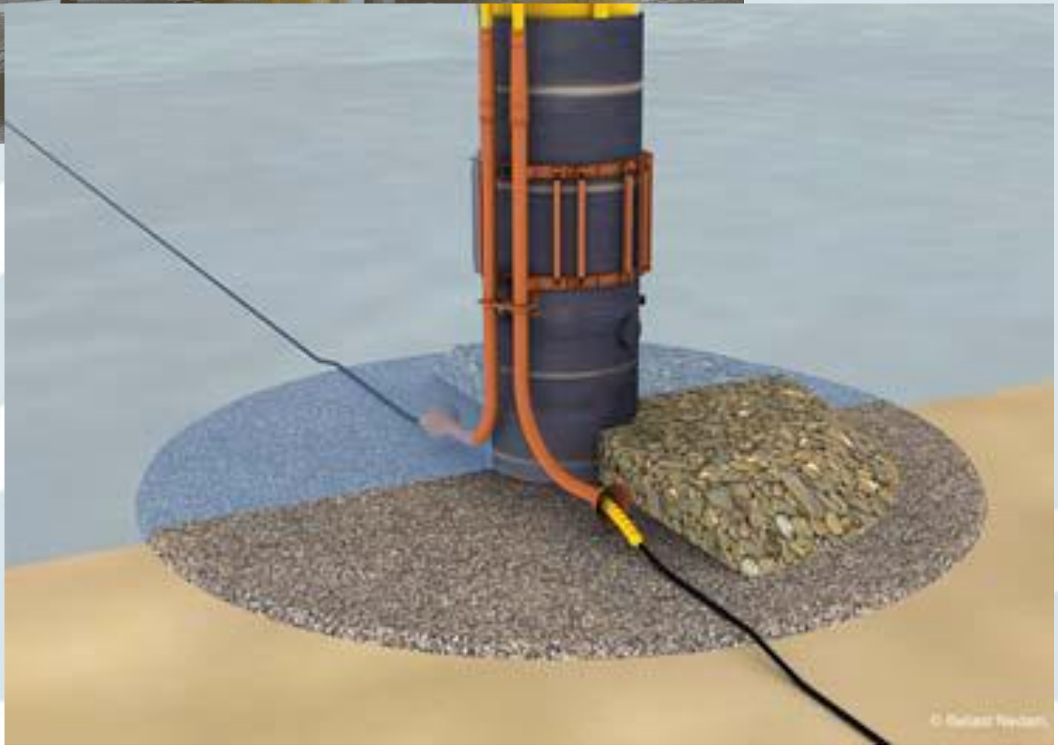
MONOPILE GENERAL ARRANGEMENT



General arrangement of turbine on onopile (left) and transition piece (right) between foundation and tower during the mounting (in evidence J-tubes, landing structure, mean platform and in perspective the nacelle)

MONOPILE SUBSTRUCTURE

- *Transition pieces (TP) ready to site transportation and complete of landing structure & main platform;*
- *Monopile equipped by cathodic defence, J-Tubes with the in/out submarine cables and anti-scouring area;*
- *Monopile in place with upper conical guide for the insertion of the TP.*



MONOPILE SUBSTRUCTURE: SOME TECHNOLOGICAL ASPECTS

- *Sheetes, whose edges are prepared as required for welding, are subjected to calandra, leaving with some small extension to test the longitudinal welding cords;*

- *The rings, aligned in a particular order to increase the general resistance, are automatically welded before a preliminary preheating;*

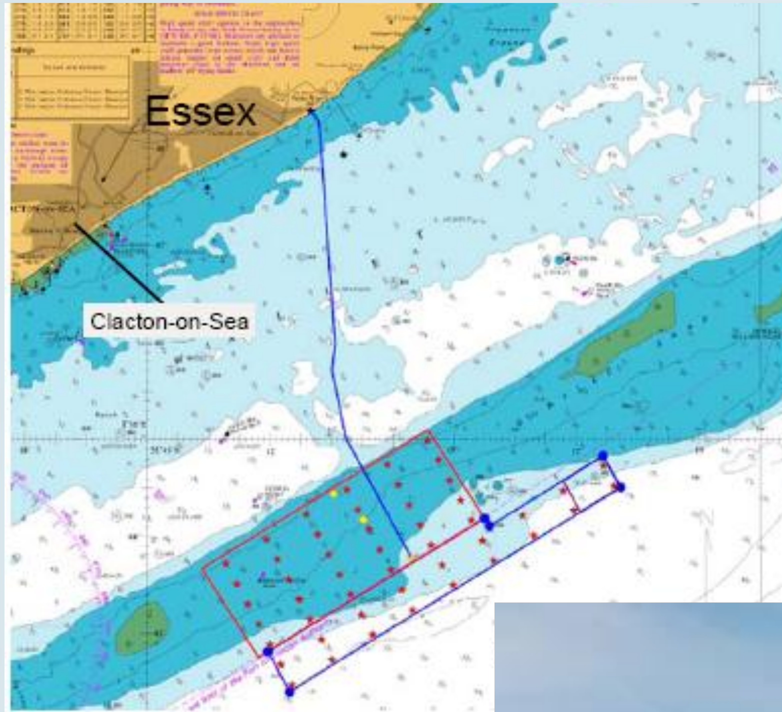
- *Tolerances on ovalization and eccentricity have to be respected costantly;*

- *To move the piece some device (like ear, bees or so on) have to be welded to each extremity;*

- *Openings have to be prepared in particular positions (for example, for J-Tube, if they are located inside the monopile).*

GUNFLEET SANDS WINDFARM (GB)

- *Gunfleet Sands windfarm at 7 km from Northern coast of Thames estuary on shallow waters (from -0.5 m to -10 m);*
- *48 Siemens turbines of 3.6 MW (SWT-3.6-107) supported by monopile substructures (5 m outside diameter, 40 m of inside lehgth in the soil);*
- *172 MW total power with one SSE offshore; first electrical generation from 2010;*
- *distance: 435 m between two turbines of the same row and 839 m between adjacent rows;*
- *total sea surface of windfarm 15 kmq.*



TRIPOD SUBSTRUCTURE

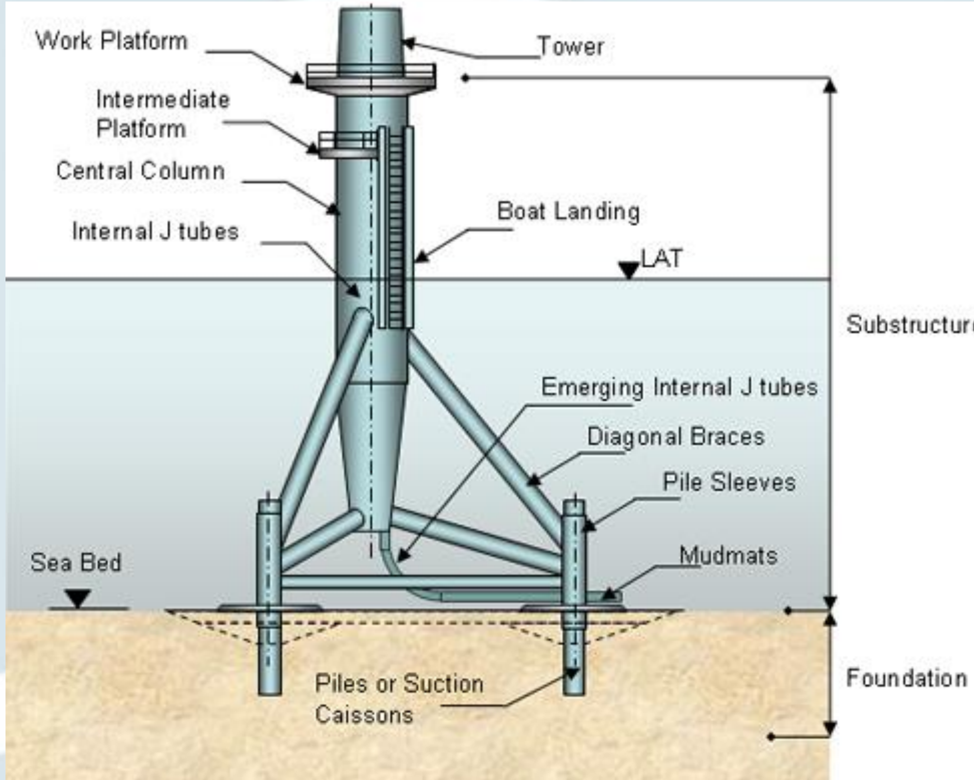
In a synthetic representation of wind turbines supported by tripod/tripile substructure we have to consider the following plant

Alpha Ventus (6 Multibrid turbines over 12, 60, 2010, DE);
Bard Offshore 1 (80, 400, 2013, DE),

in round brackets the number of units, the total power, the year of beginning of electrical generation and the country.

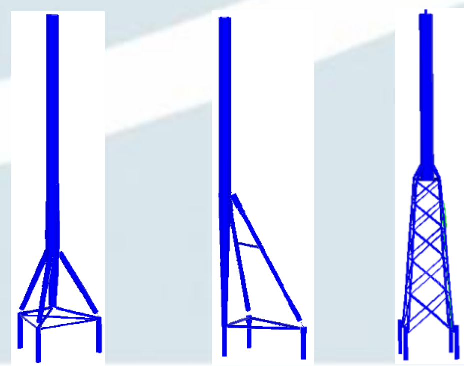
TRIPOD SUBSTRUCTURE: CHARACTERISTICS

- A three-legged steel frame which supports the main pile under water;
- Pinned to the seabed with three small piles, which have to be hammered;
- Diameter of piles smaller than the monopile;
- Suitable in a water depth of up to 30 metres or more;
- Good scour protection (another advantage of the tripod);
- Because of the need to drive piles, tripods not usable on a stony seabed.



TRIPOD SUBSTRUCTURE: CHARACTERISTICS

- Three short legs directly connected to the central element (column or chandle) supporting the main platform;
- Foundation piles (Φ = 0,8-2,5 m) guided by the pile sleeves, which are the leg of the substructure;
- All the tructure in steel pipes (Φ = 1.5-5 m) welded togheter;
- transition piece insert in the central column;
- structure less flexible than monopile thank the large base.



Schemes of different configurations of tripod

ALPHA VENTUS TRIPOD: CONSTRUCTION

The sheets wih edges bevelled are rolled and welded into large diameter tubular and conical sections for the main column, legs and lower braces.
For the connections of the legs and braces to the main column and to the pile sleeves, the ends of these sections must be cut into the exact predefined shape and welded.
A flange is fitted to the top of the main column.
Several sections of the main column are lifted into alignment and welded together. Also the leg sections and the brace elements are assembled.
Subsequently welds are ground and tested.
The pile sleeves are preassembled and welded to the braces.
When all elements have been tested and match specifications, they have assembled in the final arrangement of the structure.

TRIPILE SUBSTRUCTURE: CHARACTERISTICS

- Tripile consists of three steel piles which sit on a three-legged structure above the water level;

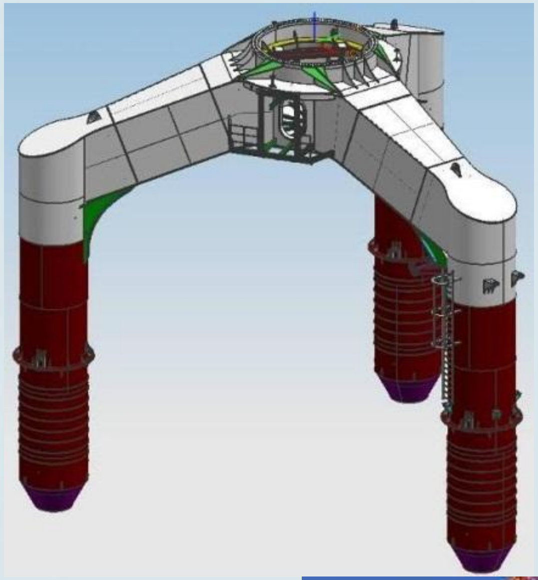
- Pinned to the seabed , as for the jacket and tripod;

- Tripile production relatively cost-effective due to its compact construction;

- First tripiles in operation in Bard Offshore I wind farm;

- According to the manufacturer, tripiles usable in a water depth of 25-50 meters.

ALPHA VENTUS & BARD OFFSHORE I SUBSTRUCTURES



JACKET SUBSTRUCTURES

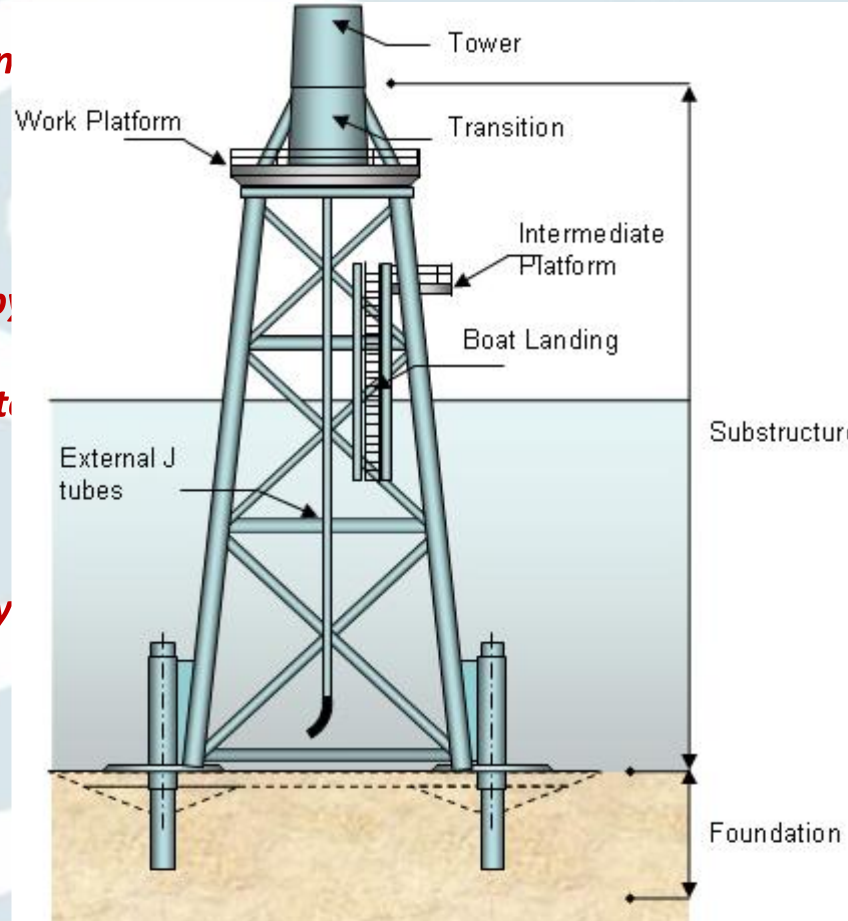
In a synthetic representation of wind turbines supported by a jacket substructures we have to consider the following plants

Alpha Ventus (6 REpower turbines over 12, 60, 2012, DE);
Beatrice Windfarm (Moray Firth, 2, 10, 2007, UK);
EnBW Baltic 2 (41 turbines over 80, 288, 2013/5, DE);
Ormonde (30, 150, 2013, UK);
Thornton Bank II (30, 185, 2013, BE) & III (18, 110, 2014, BE),

in round brackets the number of units, the total power, the year of beginning of electrical generation and the country.

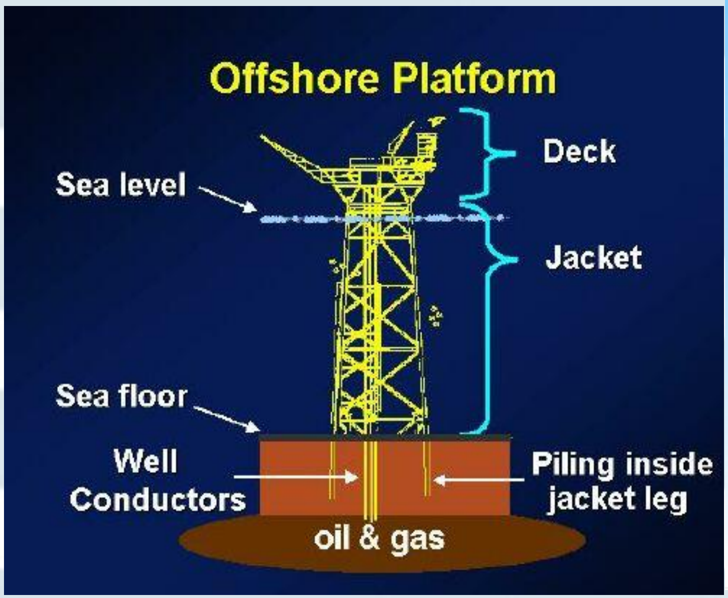
JACKET SUBSTRUCTURE: CHARACTERISTICS

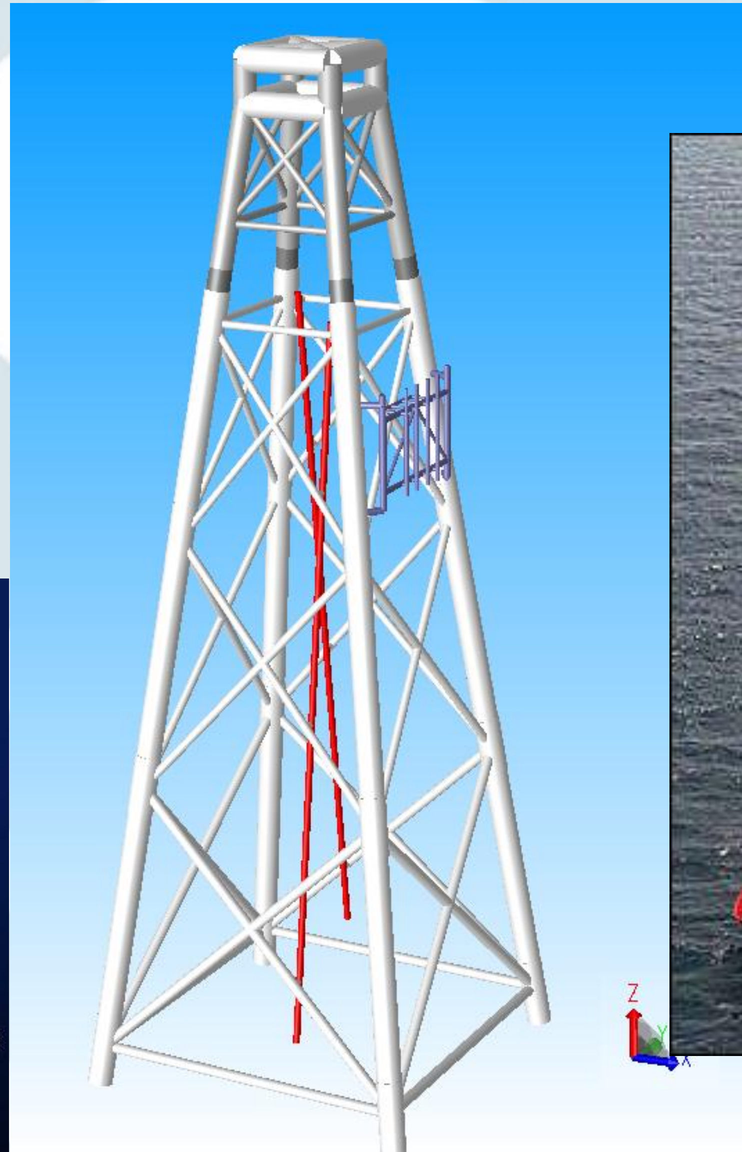
- *Frame construction made of steel in the forn of a lattice with 3-4 legs (Φ = 0.8-2.5 m) of reduced slope (8°-10°) and connected together by diagonal or horizontal tubes ;*
- *Pinned to the seabed with pile foundations (Φ = 0,8-1,5 m) guided by the legs itself or b extra piles;*
- *Offshore installation period quite long due t the time needed for pile driving;*
- *Used in the oil industry and appropriate for heavy, large-scale turbines;*
- *Due to the piling not to be usable on a stony seabed;*
- *Structure not subjected to hydrodynamic loads due to its transparancy to waves;*
- *No anti-scour preparation of seabed;*
- *Easely designed in agreement to stiffness degree requested by turbine, modifying leg slope, distance among legs, dianeter & thickness of pipes, number/position diagonal (X-braces), etc.;*
- *Suitable for medium and deep waters.*



JACKET SUBSTRUCTURE: INDUSTRIAL APPLICATIONS

- *Schematic view of typical oil field production rig for exploitation in the Gulf of Mexico (USA)*
- *Platform of mexican Pernex damaged by an explosion during rough sea (October 2007)*
- *Jacket for supporting structure of offshore wind turbine to be installed on a 30 m deep seabed*





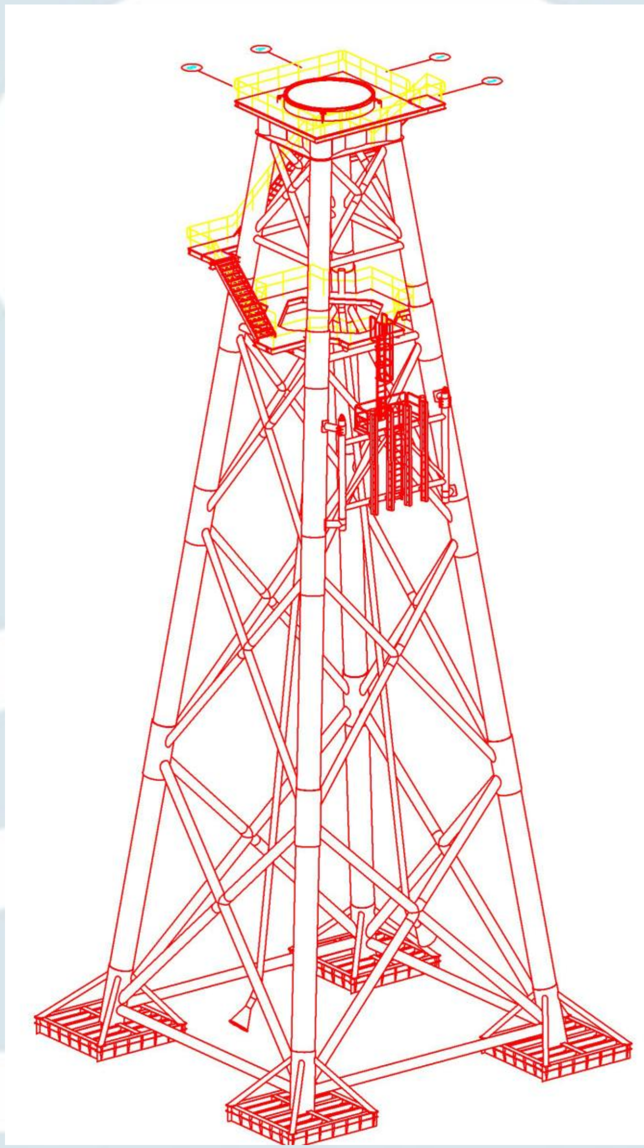
JACKET SUBSTRUCTURE: CONSTRUCTION

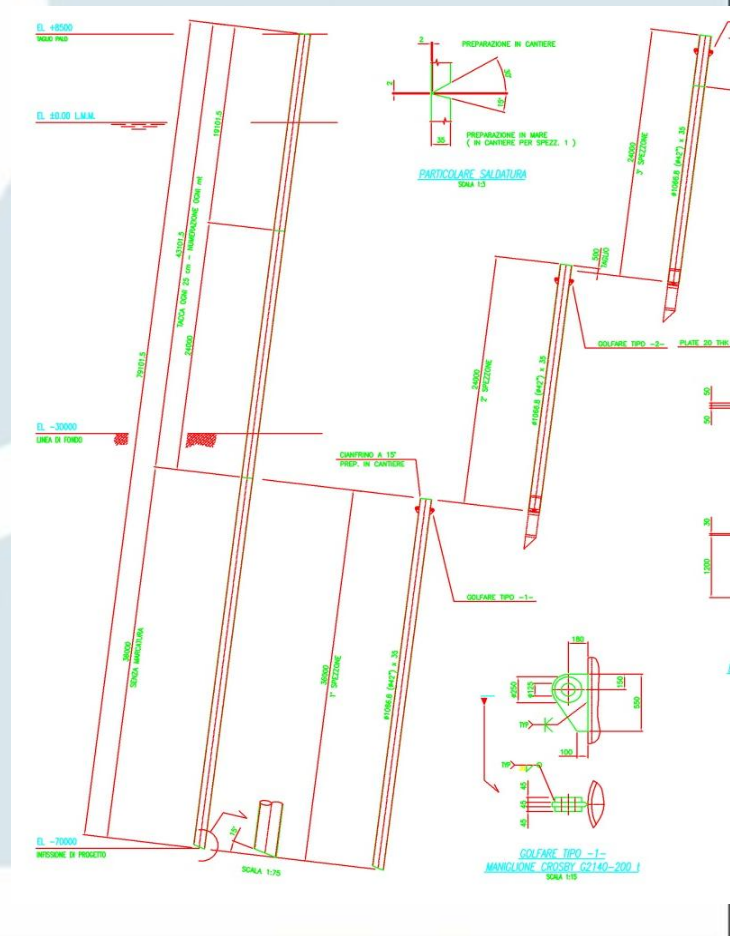
- ***Peparation the jacket joints from tubular elements delivered at the fabrication yard and assembling then in legs by welding;***
- ***Connecting two legs before coated through the X-brace sections to obtain a frame after having placed the legs on elevated supports in a horizontal position;***
- ***Welding the X-braces to the legs in manner to connect them to the second leg;***

- ***Preparation of the mudmats and the pipe sleeves by calender in the case they are necessary;***
- ***Pile sleeves lifted into position to allow the attachment onto the jacket legs foot applying finally the protection by coating;***
- ***Manufacturing the transition joint and welding it to the jacket already copleted through these four legs.***

JACKET SUBSTRUCTURE: CONSTRUCTION

- ***Legs of the jacket setting on the seabed;***
- ***Foundation piles driven in at each leg to secure the structure;***
- ***A wider cross section than the monopile, strengthening it against momentary loads from the wind and waves;***
- ***Because of its geometry, the jacket foundation able to be relatively lightweight for the strength that it offers;***
- ***Weighing approximately 400-600 tons;***
- ***Design more complex than that of a monopile;***
- ***Manufacturing and deployment practices scaled up to economical meeting with large project needs.***





TRANSPORTATION TO SITE AND INSTALLATION

- **Transportation of some jacket support structures and the corresponding foundation piles to the offshore location on barge;**

- **Lifting by heavy vessel in condition to host cranes (crane barge, pontoon equipped with crane or jack up) and tilting the structure until it was in an upright position;**

- **Lowering the support structure onto the seabed and levelling;**

- **Driving the piles in seabed.**

JACKET SUBSTRUCTURE: INSTALLATION

The sequence of installation is listed as follows
- Transport to site, lifting & landing of substructure;
- Foundation piles;
- Turbine installation (tower, nacelle, rotor & blades).

The piles can be driven through pile sleeves at the bottom of the structure a so-called ‘tower’ structure or the piles can be driven through the legs thrmselves of the structure. In this case the connection is made at the top of the structure. Such a structure is called a ‘jacket’ structure.

Although there is a difference in the way forces are directed to the foundation, in practice often no distinction is made between these two terms.

Ormonde Windfarm

- Offshore windfarm equipped by 30 turbines of 5 MW (REpower 5M) located at about 10 km from the coast of Barrow-in-Furness (Irland Sea);
- Turbines supported by jacket substructures with lower extention to be fitted in the fondation piles;
- Seabed heigth of 17/21 m di profondità and surface for all the windfarm covers 8,7 kmq.
- One offshore SSE for collecting electrical energy and to trasnform the voltage from 33 kV to 130 kV to connect the network.

GRAVITY BASE STRUCTURE (GBS)

In a synthetic representation of wind turbines supported by a gravity base substructures we have to consider the following plants

Ayos Kemi (10, 30, 2008, FI); Lillgrund (48, 110, 2007, SE); Middelgrunden (20, 40, 2007, DK); Nysted (72, 166, 2003, DK); Thornton Bank Phase 1 (6, 30, 2008, BE); Tunø Knob (10, 5, 1995, DK); Vindeby (11, 5, 1991, DK),

in round brackets the number of units, the total power, the year of beginning of electrical generation and the country.

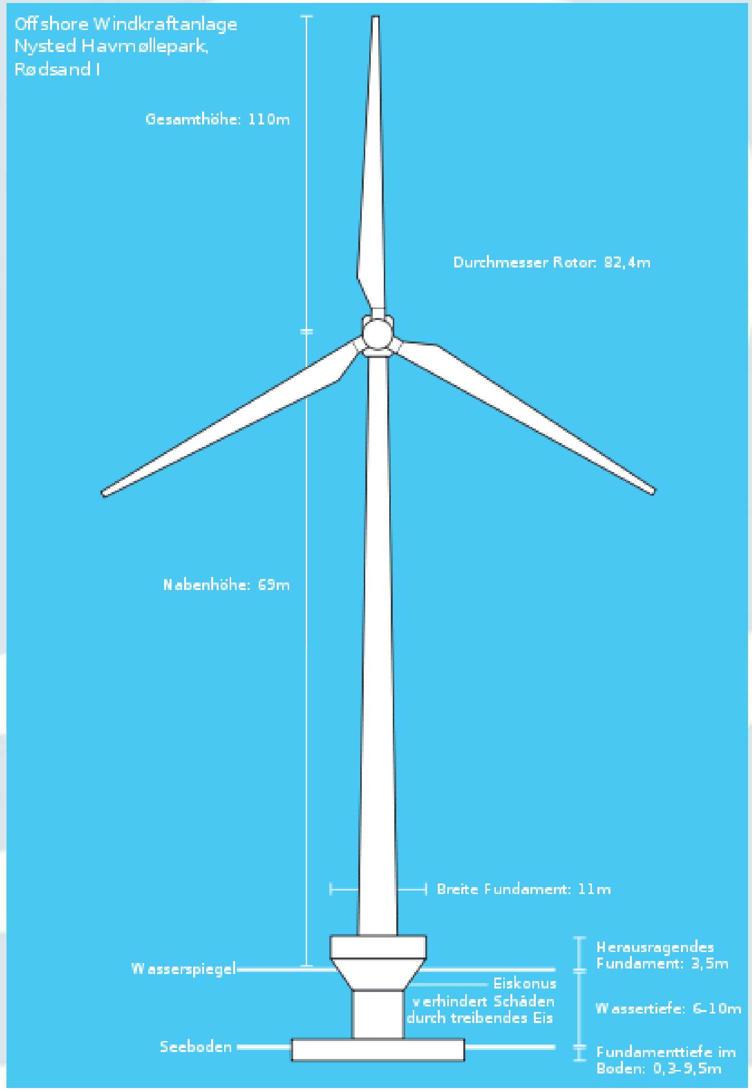
GRAVITY BASE SUBSTRUCTURE: CHARACTERISTICS

- *Structure made of a large base, circular o conical neck, a head or a body particularly shaped;*

- *Placed directely on the seabed already prepared through a large and thick area (around and under the structure) to reduce or eliminate the effects of scour along certain portion of the basement body;*

- *Generally made of concrete -for the big sizes of the body- which is cheaper than steel;*

- *Low centre of gravity thank to the great base which has to be in condition to oppose to the bending moment of wind action;*
- *Suitable for shallow or medium waters.*



GRAVITY BASE SUBSTRUCTURE: CHARACTERISTICS

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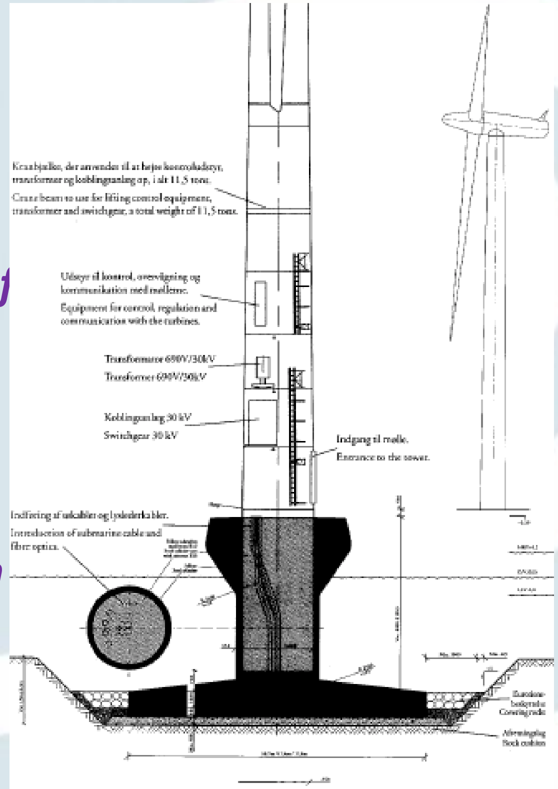
Applied in some European wind farms in a water depth of up to 10 meters (now possible to install them in deeper water);

Held in place by gravity, which is why no piling is needed;

High initial costs reduced by changing their shape;

Transportation problem for their sheer weight.

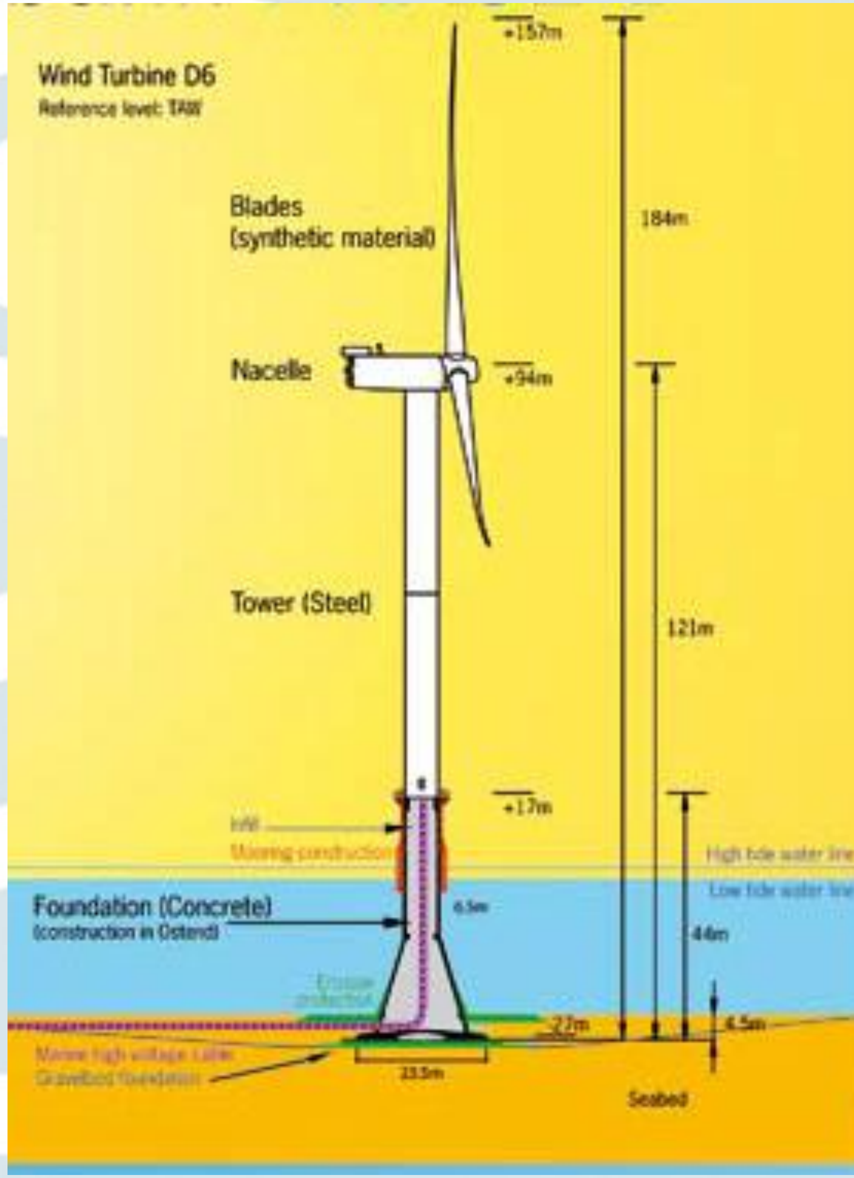


GRAVITY BASE SUBSTRUCTURE: CHARACTERISTICS

- *As the GBS requires a large mass it generally made of concrete as it is much cheaper than steel;*
- *The GBS can be equipped with vertical walls that protrude from below the actual base, called skirts, which penetrate into the soil below the base. These skirts increase resistance to base shear and help to avoid scour below thebase.*
- *Liquefaction of the soil beneath the base due to cyclic loading is an issue that must be addressed when assessing the stability of the foundation.*
- *The GBS can be extended to the platform level, thereby reducing the number of offshore installation activities, as no separate transition piece needs to be installed.*

THORNTON BANK GBS

- **General and dimensional plan of substructure for installation on the site (seabed depth 23 m at 30 km from Ostende coast);**
- **Three of six units during the construction phase at ground.**



THORNTON BANK GBS

- Dock-yard with six substructures for REpower 5M turbines at different stage of construction;
- Substructure displacement in the dock-yard area to the charge basin;
- Trasport to the site in partial buoyancy conditions.

MIDDELGRUNDEN GBS

- 20 Bonus turbine of 2 MW in a site at 3,5 km from Copenhagen on seabed of -4/-8 m height;
- Configuration at circunference arc following the site solution voted and approved by town population;
- View of the windfarm from the Christianshavn quarter houses.

CHARACTERISTICS OF DIFFERENT SUBSTRUCTURE CONCEPTS

Type	Depth	Example of application	Advantages	Disadvantages
Gravity base	up to 40 m	Nysted, Lillgrund	Needs little steel, no pile driving	Expensive if used at great depths
Monopile	20-30 m	Horns Rev	Can withstand scour	Large pile hammer
Tripod	20-50 m	Alpha Ventus	Dimension of piles is small	Cannot be used in a stony seabed
Jacket	20-50 m	Alpha Ventus & other	Already in use in the oil industry	Needs large quantities of steel
Tripile	25-50 m	BARD Offshore I	Quite lightweight construction	Only one test facility to date
Suction Bucket	up to 30 m	Test phase	No pile driving	Little experience
Floating	80 -700 m	Test phase, Hywind, Tricase	Suitable for deep water	Little experience