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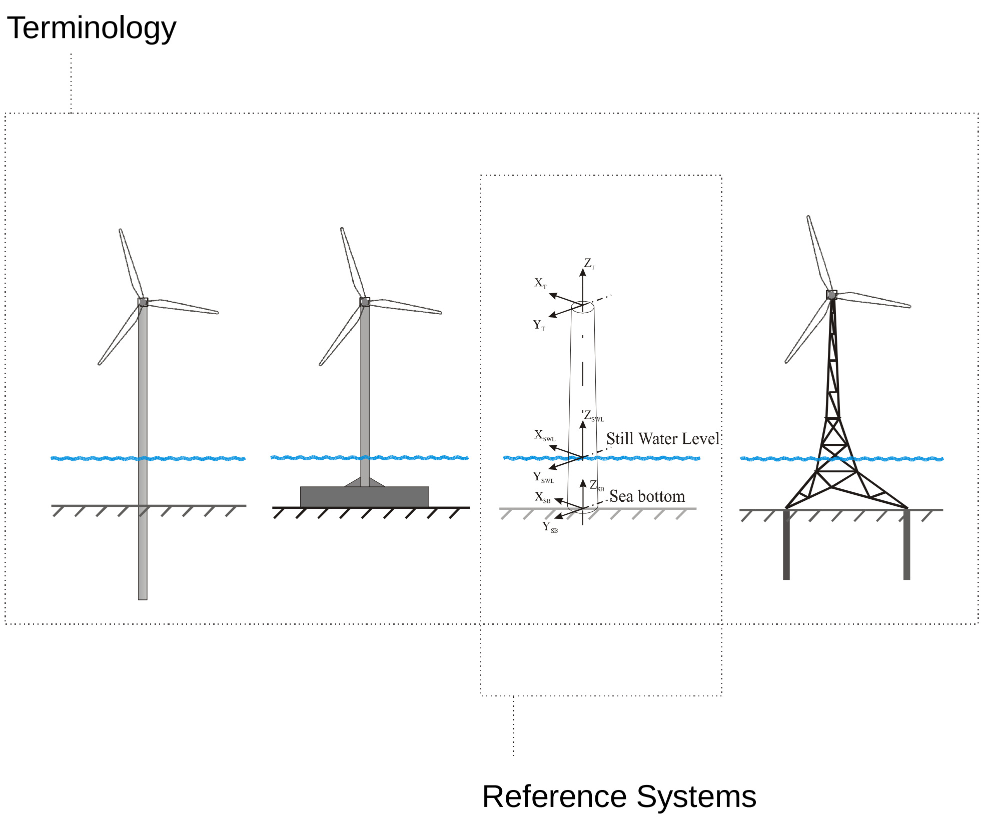
Terminology, Reference Systems and Conventions

R.van Rooij



Terminology, Reference Systems and Conventions

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Preface and background documents

This document provides guidelines for the communication within the European JOULE III project 'Design Methods for Offshore Wind Turbines at Exposed Sites' (OWTES). It is an update and review of the Terminology used in the Opti-OWECS project ('Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters, a European Joule III project [1]). M.Kühn is acknowledged for permission to use his document.

The document is intended to define the major components of the offshore wind farm in particular with respect to bottom mounted HAWT (Horizontal Axis Wind Turbines). Proposed are general notations and conventions, which have become common practice within the considered disciplines i.e. wind energy engineering, offshore technology and engineering economics.
Harmonisation in the description of the entire system and its components, the interfaces between sub-systems and the structural design, is required and this document will give a general overview as accepted by the participants of the OWTES project.

Concerning structural design, the 'Regulations for the Certification of Offshore Wind Energy Conversion Systems' of the Germanischer Lloyd [2] are recommended as main standard. Regarding wind turbine applications, assistance has been gained from the 'IEA 1400', International Energy Agency [3] and the 'Regulations for the Certification of Wind Energy Conversion Systems', Germanischer Lloyd [4].
In offshore technology the same holds for the DNV standard 'Rules for Classification - Rules for Fixed Offshore Structures' [5] and the HMSO Guidelines of the UK Department of Energy [6].
With respect to soil properties, the conditions and guidelines specified by the API [7] standards are recommended.

1 Terminology

1.1 Offshore wind farm (OWF)

1.1.1 Complete offshore wind farm

offshore wind farm (OWF)

Entire system, comprising (usually) several wind turbines, for conversion of wind into electrical power, infrastructure facilities necessary for operating the farm plus the electrical infrastructure within the farm and the transmission of the electrical energy to the utility grid connection point onshore.
Note that the environment i.e. air, water and soil as well as the utility grid are not considered as part of the wind farm.

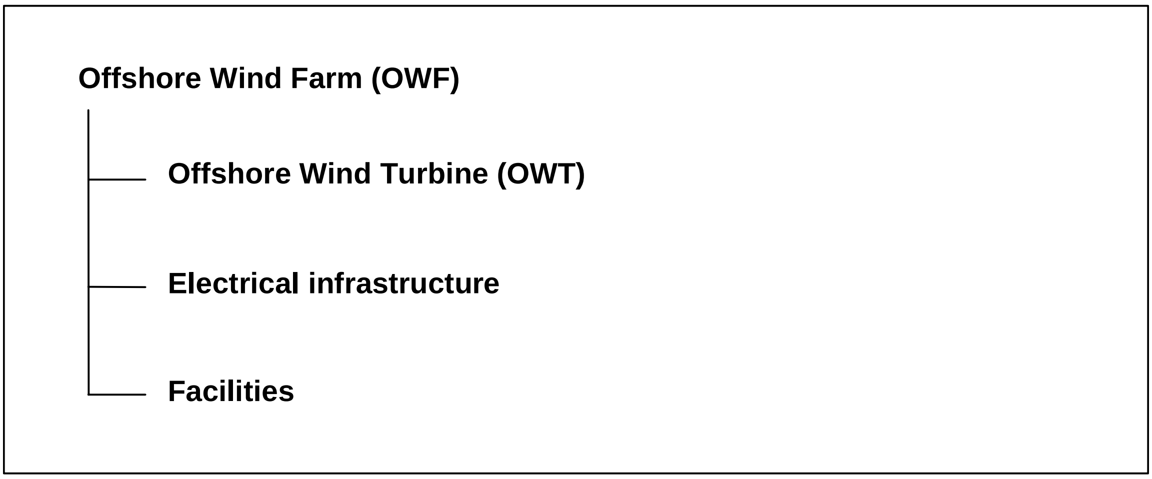

Figure 1 Components of the wind farm

offshore wind energy system (OWES)

synonym for offshore wind farm

1.1.2 Main components

offshore wind turbine (OWT)

single unit of the wind farm comprising energy conversion system and support structure

offshore wind energy conversion system (OWEC)

synonym for offshore wind turbine

electrical infrastructure

electrical system transmitting and collecting the power provided at the turbine connection point(s) and then passes on the power to the central cluster point(s). Transmission to shore by submarine cable up to the connection point to the public grid is included in this category.

facilities

auxiliary facilities required for operation, maintenance and administration of a wind farm.

1.1.3 Boundaries of the wind farm components

wind turbine and electrical infrastructure

The turbine main switch gear or circuit breaker in the tower is defined as boundary between electrical system of the turbine and farm infrastructure.

The voltage at the connection point corresponds to the generator or the inverter (if any). Although a transformer might be installed at the wind turbine unit, it is regarded as part of the electrical infrastructure.

The turbine control and safety system at the wind turbine is for proper operation of the individual turbine and is part of the wind turbine description, this despite the fact that its input parameters can also be fed by the (power) control system of the cluster(s) within/of the wind farm.

offshore wind farm and public grid

(is same division as between electrical infrastructure and public grid)

Electrical components required to convert and transform the farm electrical power to the frequency and voltage level required for the public grid is part of the wind farm (electrical infrastructure).

The physical connection itself is regarded as part of the utility grid meaning that the onshore connection point is the boundary between the wind farm and the utility grid.

1.1.4 Sub-components offshore wind farm

The components of an Offshore Wind Farm (OWF) are defined by **figure 2** to **figure 5**.

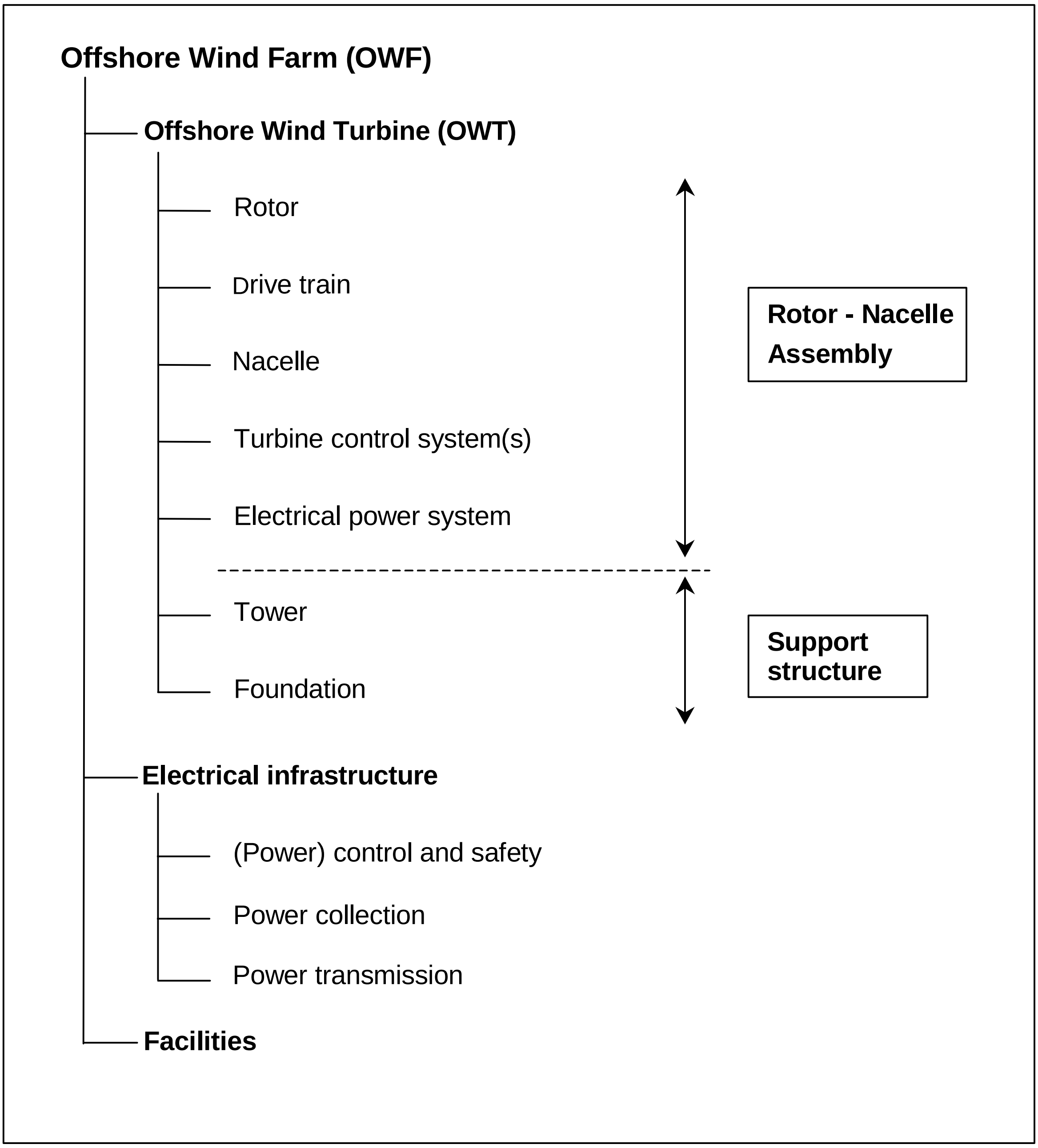

Figure 2 Components of the wind farm

Rotor - Nacelle assembly

Component of an offshore wind turbine that transforms wind energy into electric power comprising rotor, nacelle with entire interior, control system(s) and the electrical system (including when it is located in the tower base).

Components on and in the nacelle to facilitate maintenance (and installation) are also part of the rotor nacelle assembly.

rotor – nacelle assembly

- rotor
  - blades
  - hub
- drive train
  - primary shaft
  - brake(s)
  - coupling(s)
  - bearing(s)
  - gearbox (if any)
  - secondary shaft (if any)
- nacelle
  - bed plate
  - auxiliary equipment e.g. hydraulic
  - yaw mechanism
  - housing
- turbine control and safety system
- electrical power system
  - generator
  - converters and/or inverter (if any)
  - internal cables
  - switch gear, circuit breaker

Figure 3 Components of the rotor–nacelle assembly

Support structure

Structure that supports the rotor-nacelle assembly and transfers the loading to the seabed. The support structure comprises both the tower and the foundation.
Components on and in the support structure to facilitate maintenance (and installation) are also part of the support structure.

support structure

- tower
- foundation

Figure 4 Components of the support structure

Electrical infrastructure

The electrical infrastructure includes the (power) control and safety systems within and of the wind farm, and all electrical components between the electrical system at the wind turbine and the public grid connection onshore.

electrical infrastructure

- (power) control and safety
- power collection
  - transformers to collection voltage (usually at every turbine)
  - inverters (if any)
  - switch gears and circuit breakers
  - cables inside cluster(s)
- power transmission
  - electrical and electronic components (for connection to public grid)
  - submarine cable to shore

Figure 5 Components of the electrical infrastructure

Facilities

Auxiliary facilities for maintenance and administration which can be located offshore as well as onshore but are essential for (technical and economical) operation of the wind farm. The maintenance facilities may include a workshop, spare parts area, service equipment etc.

1.1.5 Boundaries of the offshore wind farm sub-components

rotor-nacelle assembly and support structure
The fixed end of the yaw mechanism of the nacelle is defined as the boundary between the rotor-nacelle assembly and the tower.

tower and foundation
The separation of the support structure into tower and foundation depends on the kind of foundation, for instances of piled, gravity or skirted types and might be influenced by manufacturing and installation considerations. For some integrated designs (e.g. an integrated monopile) a separation into tower and foundation might not be applicable.
As a general rule, for piled designs, only the actual piles are denoted as foundation. The gravity type foundation usually consists of structural part(s) (like caisson(s)) which transfer(s) the loading on to the soil.

offshore wind turbine and electrical infrastructure
In particular the boundary between the wind turbine control and wind farm control and safety systems are sometimes not obvious. When the control and safety system at the turbine(s) is only for proper operation of the individual turbine the system is regarded as being part of the offshore wind turbine. This can be with regard to load and/or individual power control.

electrical infrastructure sub-components
When the control and safety task accounts for the complete farm and is not specific for an individual wind turbine, the system is regarded as being part of the (main) electrical infrastructure.
The boundary between the power collection and power transmission is located at the point (could be more than one) where the total power of the wind farm is collected that will be transmitted by one (or more) transmission line(s) to shore. The voltage level between the connection point and the onshore connection to the public grid may be adjusted to reduce transmission losses and/or to connect to the public grid. If so, transformation to the public grid voltage becomes part of the wind farm transmission definition.

1.2 Wind and wave description and wind turbine orientation

1.2.1 Wind speeds

Wind speeds are generally measured in metres per seconds (m/s).
Without further remarks site related wind speeds are 10-min averaged ('mean wind speed' is indicated by an over-line) and related to hub height above still water level (SWL).

$$\bar{v}(z) = \overline{v_{ref}}\left(\frac{z}{z_{ref}}\right)^{\alpha}$$

where: $\bar{v}(z)$ mean wind speed at height z

$\bar{v}_{ref}$ mean wind speed at reference height

z_{ref} reference height e.g. 10.m

α wind shear component

Unless noted otherwise velocities for other heights are calculated by the power law.
A wind shear exponent of α = 0.11 according to [2] is used in absence of other confirmed data.

The mean wind speed, the extreme mean wind speed and the extreme 5 seconds gust with a probability of occurrence of once in 50 years (return period 50 years) are written as $\bar{v}$, $\bar{v}_E$ and v_E respectively. The same holds for the annual mean and annual gust wind speeds $\bar{v}_J$ and v_J respectively. Different averaging periods and different return periods should be indicated by indices e.g. $v_{E,1\min}$, $v_{J,1\min}$ for the 1-minute gust for extreme (50 years) and annual conditions respectively.
Moreover, heights different from the hub height have to be given explicitly e.g. $v_{E,10\mathrm{m}}$.
The wind direction is given w.r.t. true North (nautical reference system). When the wind comes from the East, the wind direction equals 90°, see figure 6.

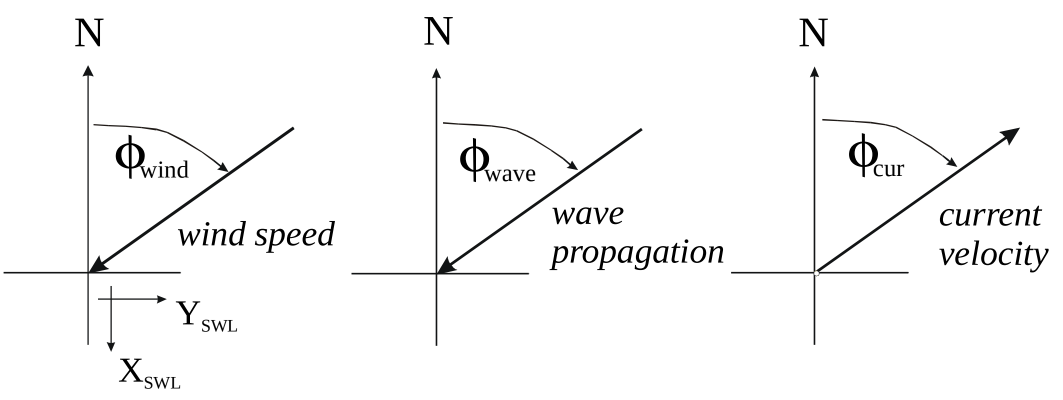

Figure 6: Wind, wave and current direction.

1.2.2 Water surface elevation and wave and current direction

The instantaneous water surface elevation *η(t)* is described in a fixed, non-rotating axis system ***(xyz)$_{SWL}$***, related to the support structure with origin at the undisturbed sea surface (i.e. at still water

level, SWL) on the tower centre line with the z-axis directed vertically upwards and the x-axis directed opposite to true (i.e. not magnetic) North (see chapter 2).
The directions of wind, waves and current are defined according to the nautical system i.e. clockwise from true North, which is at 0^o. Wind direction ϕ_{wind} and wave direction ϕ_{wave} are given as 'coming from'; in contrast to the current direction which refers to 'pointing towards'.

1.2.3 Turbine angle

For a clockwise rotating wind turbine the turbine angle ϕ_{turb} gives the angle of the nacelle w.r.t. the true North. When the turbine is oriented to the East (this means that the upstream direction is to the East) the turbine angle equals 90^o. See figure 7.

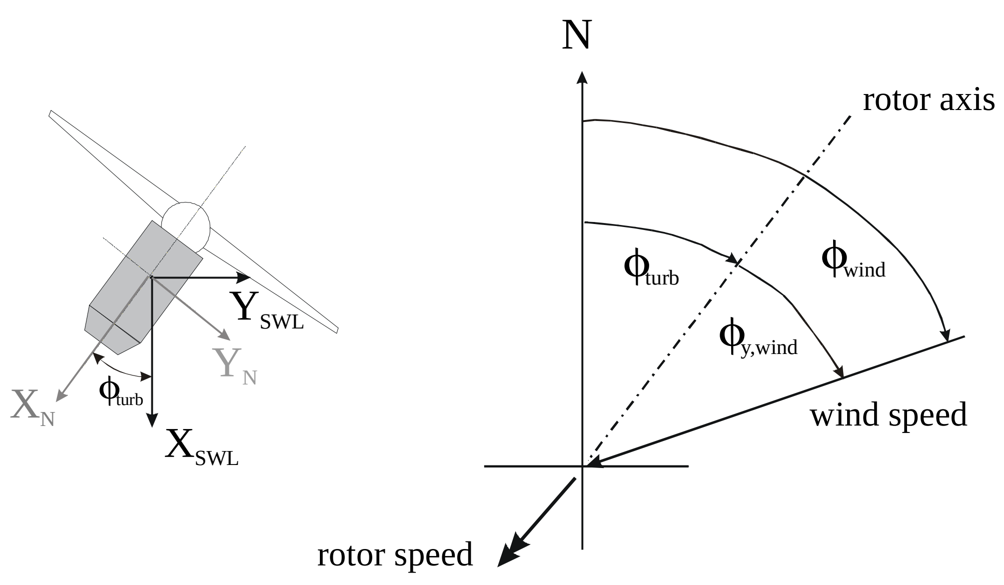

Figure 7: Turbine orientation and wind direction (clockwise rotating wind turbine)

1.2.4 Yaw misalignment with respect to wind and waves

The wind turbine yaw angle ϕ_y is generally given as the difference of the wind direction and the position of the nacelle, see figure 7. If both wind and wave loading are present the yaw misalignment w.r.t. wind (wind yaw angle) $\phi_{y,wind}$ and the yaw misalignment w.r.t. waves (wave yaw angle) $\phi_{y,wave}$ are distinguished.

$\phi_{y,wind} = \phi_{wind} - \phi_{turb}$ yaw misalignment w.r.t. wind direction

$\phi_{y,wave} = \phi_{wave} - \phi_{turb}$ yaw misalignment w.r.t. wave direction

1.3 Rotor-Nacelle assembly

This section applies to clockwise rotating wind turbines of the HAWT type with upwind or downwind orientation (see figure 8). For other turbine types the reader is referred to [9] which is largely quoted here in a shorted form.

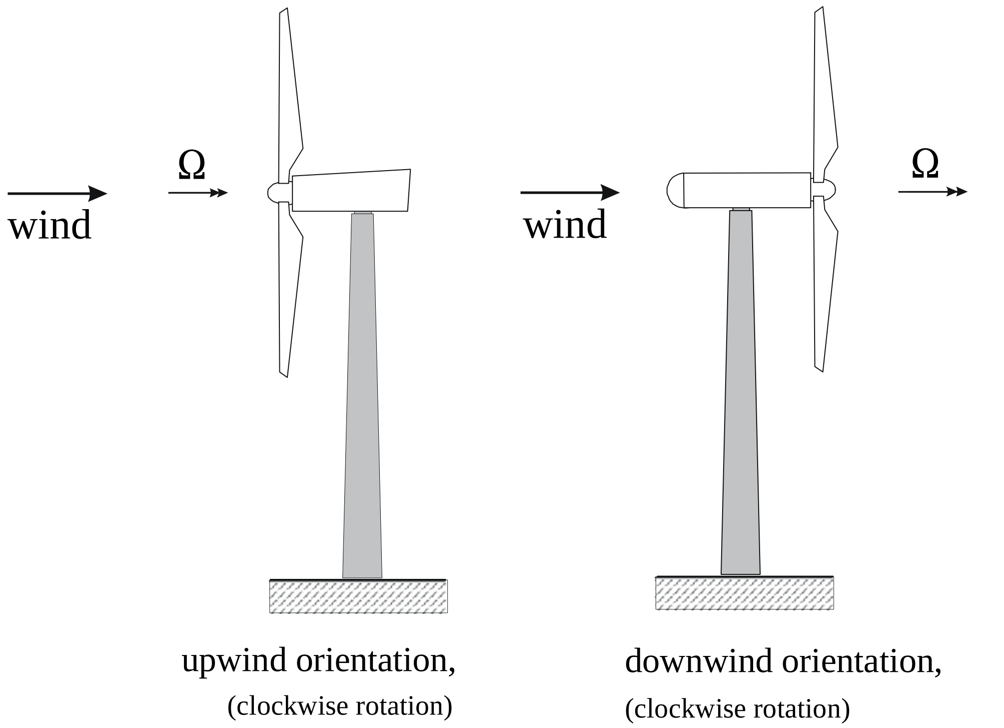

Figure 8: Rotor-Nacelle assembly Turbine orientation (upwind resp. downwind) and rotor rotation sense.

1.3.1 (Blade) azimuth angle and blade numbering

The blade azimuth angle $\phi_{r,B}$ is defined as azimuth angle of blade number 1; while the azimuth angle ϕ_r is the azimuth angle in the rotor plane, this not necessarily being the exact location of the blade. (See figure 9.)

The zero azimuth is in vertical upward direction. The azimuth angle is positive in clockwise direction looking downstream to the rotor.
The order in which the blades pass the tower is 1, 2 ,3 for a three bladed turbine.

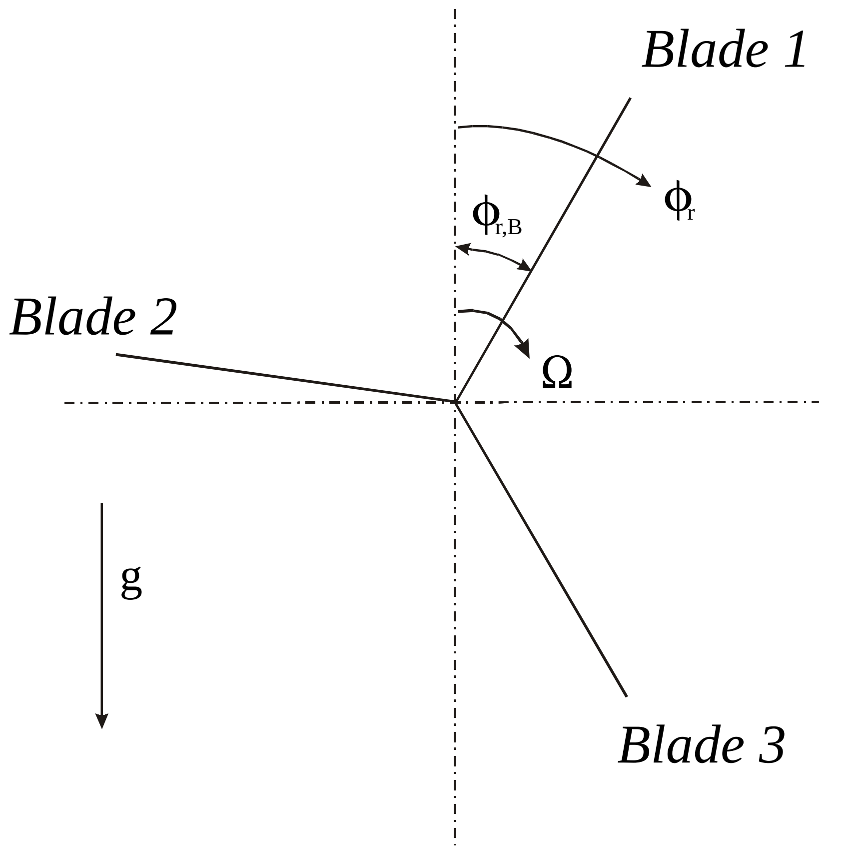

Figure 9: (Blade) azimuth angle and blade numbering for a clockwise rotating rotor.

1.3.2 Tilt angle, nacelle offset, rotor overhang and cone angle

The distance between tower top and nacelle coordinate system - whose position is determined by the intersection of the tower centre line with the rotor axis - is defined as nacelle offset d_{zN}.
The angle between the horizontal axis and the rotor shaft is defined as tilt angle α_t. A positive angle increases hub height and tower clearance.
The rotor overhang d_{xH} is the distance between the centre of the hub coordinate system $(xyz)_H$ and the intersection of the rotor axis with the tower centre line. For an upwind turbine the rotor overhang is positive.
The angle between the rotor plane and the blade axis is defined as cone angle (α_c). The blades are directed downwind for positive coning (figure 10).

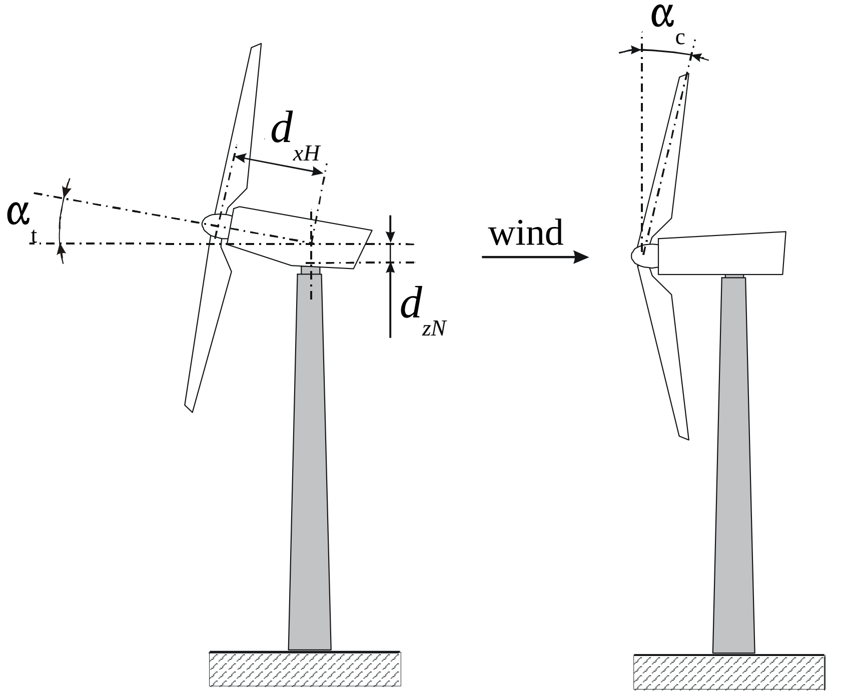

Figure 10: Tilt angle, nacelle offset, rotor overhang and cone angle.

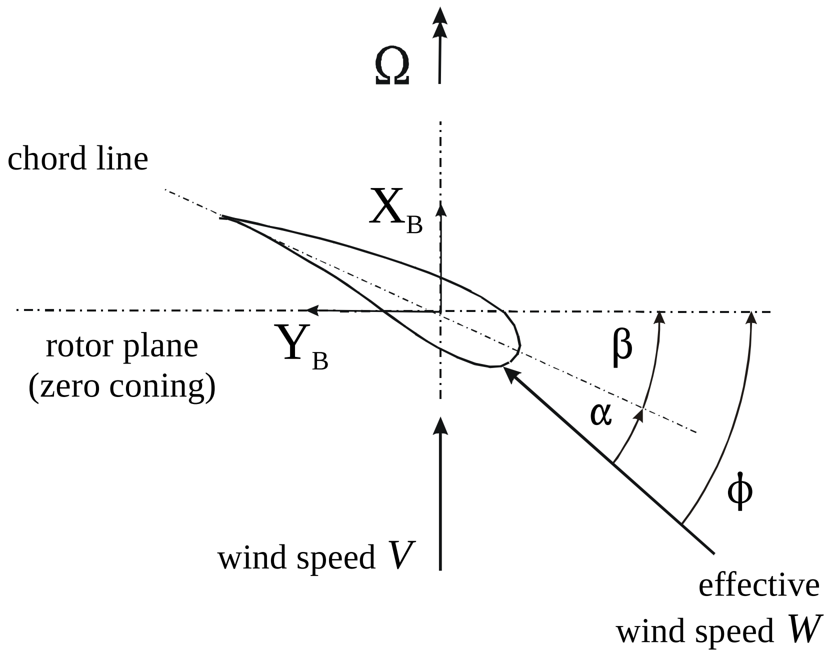

Figure 11: Local blade angle β, inflow angle ϕ and angle-of-attack α.
(Z-axis points towards tip (out of paper))

1.3.3 Pitch angle and twist

See figure 11, in which:

β = local blade angle is angle between chordline of the blade element and the rotor plane. Positive when airfoil trailing-edge points downwind, which is consistent with airfoil nose points upwind (feathering direction).
- full span pitch: $\beta = \theta + \epsilon$
- partial span pitch:
  inner part of the blade: $\beta = \epsilon$
  tip: $\beta = \theta_t + \epsilon$

θ = pitch angle. Positive when trailing edge points downwind.
θ_t = tip angle. In general the tip angle determines the default blade setting. By definition: $\theta_t = 0^o$, if chordline of tip-station stands in the rotor plane, see figure 12. (Sometimes extrapolation of the twist towards the tip is used as reference for the tip angle, because tip shapes complex the convention)
θ_0 = blade set angle. Pitch angle set at blade installation.

ϵ = local twist angle of the blade relative to the tip station

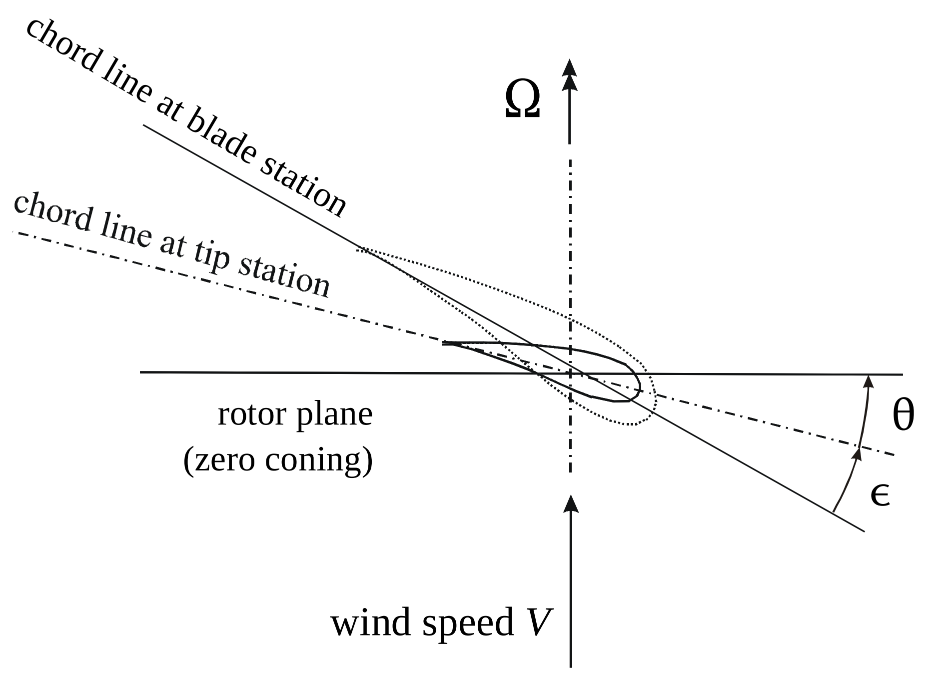

Figure 12 Blade pitch angle θ and twist ϵ
(clockwise rotating turbine, looking from the tip towards the root section)

1.4 Offshore technology

In the part related to offshore technology the DNV-Rules [5] and the HMSO-Guidelines [6] are used as reference for terminology and notation. **Appendix A** obtains a list of common definitions copied from both documents.

1.5 Periodic signals and dynamic characteristics of the support structure

Signals that vary periodically with the rotor revolution and its integer multiples are denoted as 1P, 2P, 3P, etc. and N_b P, where N_b is the number of blades.[1]

Support structures are characterised by the relation between the fundamental natural frequencies f_0 [2] and the rotor frequency f_R as well as the blade (passing) frequency $f_B = N_b f_R$.[3]

$f_0 < f_R$	or	$f_0 < 1P$	: *soft-soft* design
$f_R < f_0 < f_B$	or	$1P < f_0 < N_b P$	: *soft-stiff* design
$f_B < f_0$	or	$N_b P < f_0$	: *stiff-stiff* design

In case of a turbine with variable rotor frequency $f_{R,min}$. f_R . $f_{R,max}$ respectively with two constant rotational frequencies $f_{R,1} < f_{R,2}$ the following definitions are valid.

$f_0 < f_{R,min}$	or	$f_0 < f_{R,1}$	: *soft-soft* design
$f_{R,max} < f_0 < f_{B,min}$	or	$f_{R,2} < f_0 < f_{B,1}$	: *soft-stiff* design
$f_{B,max} < f_0$	or	$f_{B,2} < f_0$	: *stiff-stiff* design

A *very soft* support structure design is synonym with a *soft-soft* design.
A *soft* support structure design is synonym with a *soft-stiff* design.
A *stiff* support structure design is synonym with a *stiff-stiff* design.

1.6 Cyclic and circular frequency, definition of spectra

By convention:
Cyclic frequency *f* in unit Hz as well as circular frequency (angular velocity) ω can be used in equations. In figures and tables, however, the frequency axis should be written as cyclic frequency *f* in unit Hz, in order to avoid confusion.

According to the definition of spectra given in **Appendix B** the following relation is valid between spectra expressed as function of cyclic and circular frequency.

$$S_{\bar{x}\bar{x}}(f) = 2\pi\, S_{\bar{x}\bar{x}}(\omega)$$

[1] The symbol P is used with respect to 'per revolution'.

[2] Usually these are the fundamental fore-aft and the lateral bending mode.

[3] Instead of the applied notations *soft-soft* and *stiff-stiff,* in literature respectively *soft* and *stiff* are in general mentioned. This is confusing because *soft* and *stiff* has another general understanding.

1.7 External and operating conditions

External and operating conditions are described in figure 13 and figure 14.

external conditions

- normal
  i.e. in general events which have a probability of being once a year or more often
- extreme
  i.e. conditions with a probability of being exceeded (typically) once in fifty years

External conditions are all external influences on the wind turbines resulting from oceanographic or meteorological conditions or other external sources (e.g. grid connection, mechanical powered machinery)

Figure 13: External conditions of an offshore wind turbine.

operational conditions

- normal conditions
  - stand-by
    i.e. no fault or other shut-down condition,
    wind speed $v < v_i$ or $v > v_o$, turbine standstill or idling
  - start-up
    i.e. transition between stand-by and power production,
    or between different conditions during productive operation
  - power production
    i.e. wind speed range $v_i \leq v \leq v_o$
  - normal shut-down
    i.e. transition between power production and stand-by,
    or between different conditions during productive operation
- fault conditions
  i.e. state arising if defects occur in the wind turbine
- condition after occurrence of a fault
- erection
  i.e. transport, erection , maintenance and (de-)commissioning

v_i cut-in wind speed, v_o cut-out wind speed

Figure 14: Operational conditions of an offshore wind turbine.

1.8 Economic terminology

In this section the use of the 'IEA Recommended Practices for Wind Turbine Testing and Evaluation. Vol. 2: Estimation of Cost of Energy from Wind Energy Conversion Systems' [8] is advised. **Appendix C** obtains a list of common definitions copied from [5] and [6].

2 Reference systems

Nine Cartesian, right-handed reference systems are introduced, see **figure 15 - 17**.

Installation:

- A fixed, non-rotating axis system ***(xyz)$_{LAT}$*** (LAT = Lowest Astronomical Tide) related to the offshore wind turbine with origin at **lowest astronomical tide**.
  Offshore wind turbine dimensions and construction at sea are expressed in this frame by preference.

Loads:

- A fixed, non-rotating axis system ***(xyz)$_{SB}$*** (*SB* = Sea Bottom or Mudline) for the determination of structural loads related to the offshore wind turbine with origin on the **sea bottom**.
  Structural loads are expressed in this frame, by preference.

- A fixed, non-rotating axis system ***(xyz)$_{SWL}$*** (SWL = Still Water Level) related to the support structure with origin on the **undisturbed sea surface** (i.e. at sea level SWL).
  Hydrodynamics are expressed in this frame, by preference.

- A fixed, non-rotating axis system ***(xyz)$_{T}$*** (*T* = top) related to the tower with origin in the **centre of the yaw bearing system**.
  Quantities at the nacelle/tower interface are expressed in this frame, by preference.

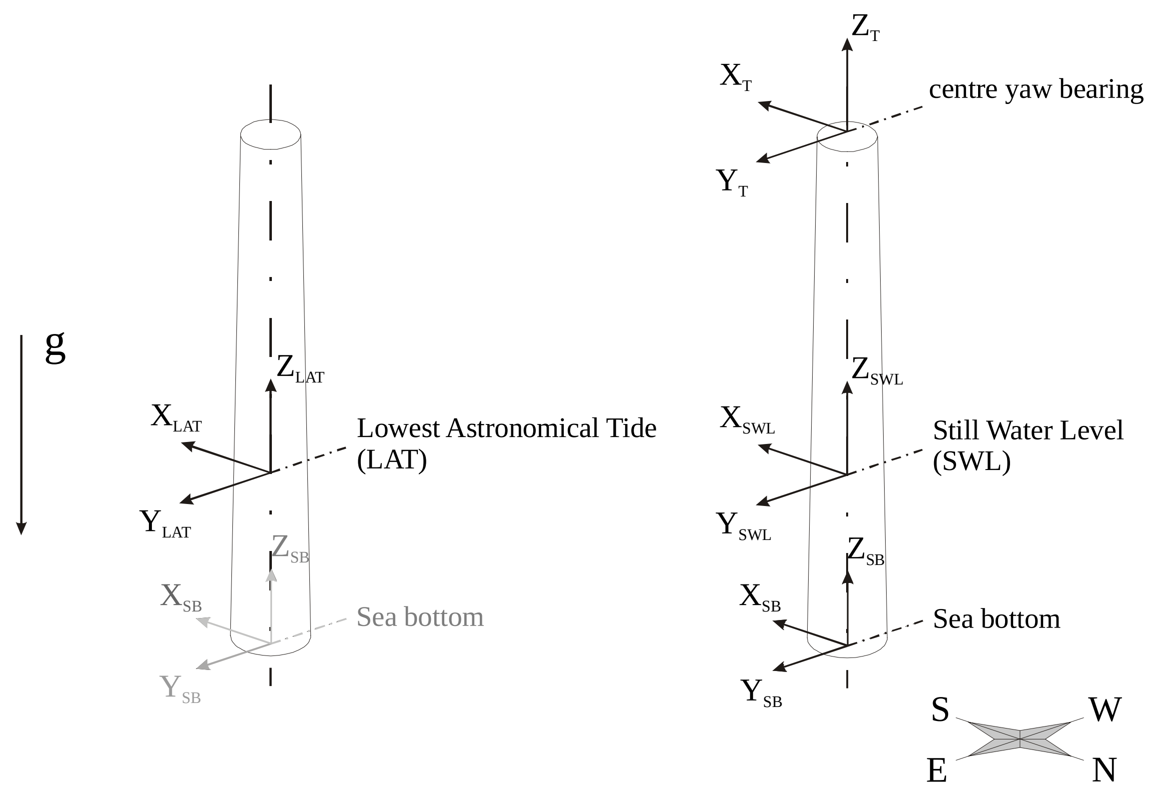

Figure 15: Reference systems for installation and loads description.

Components:
These coordinate systems are allowed to move with respect to the inertia reference systems described in the installation and load paragraph.

- An axis system ***(xyz)$_N$*** (*N* = nacelle), related to and rotated with the **nacelle** with origin in the centre of the yaw bearing.

- An axis system ***(xyz)$_H$*** (*H* = hub) related to and rotated with the nacelle with origin in the **rotor hub centre**. Note this system does *not* rotate with the rotor.

- An axis system ***(xyz)$_{HR}$*** (*HR* = hub, rotating) related to and rotated with the rotor axis with origin in the **rotor hub centre**. This axis system rotates with nacelle and with the blades.

- An axis system ***(xyz)$_B$*** *(B* = blade) with origin at the blade root of **blade *i***. Note this system is rotating with the azimuth angle, but not with the pitch angle.

- An axis system ***(xyz)$_{rot}$*** with origin at the leading edge of *i* th blade section, rotated with the nacelle, tilt, cone and local blade angle and rotating with the blade azimuth angle.

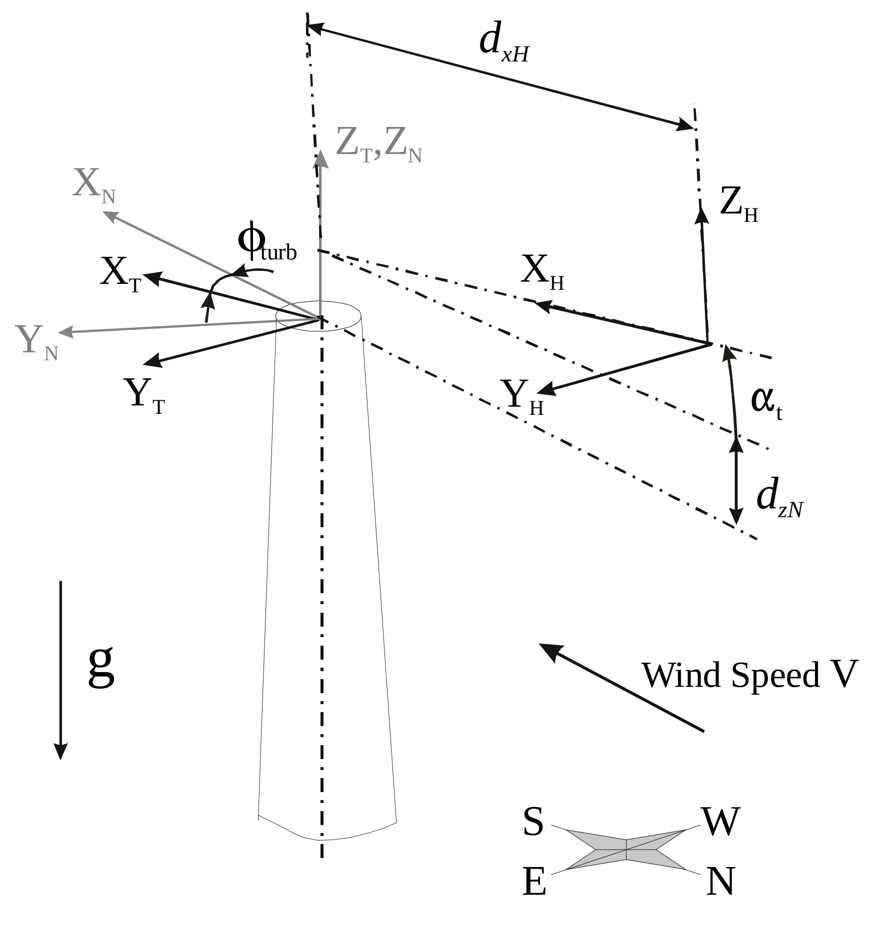

Figure 16: Tower top (T), nacelle (N) and hub (H) reference system.

2.1 Construction reference system

x_{LAT} , y_{LAT} , z_{LAT} : right handed coordinate system, origin at the lowest astronomical tide (LAT) and on the tower centre line of an unloaded tower. Is parallel to $(xyz)_{SB}$ coordinate system.

x_{LAT} -axis: directed to the South (opposite to true (i.e. not magnetic) North),
y_{LAT} -axis: directed to the East,
z_{LAT} -axis: along the support structure centre line, positive in vertical upwards direction.

2.2 Structural loads reference system

x_{SB} , y_{SB} , z_{SB} : right handed coordinate system, origin on the unscoured seabed and at the centre line of an unloaded tower.

x_{SB} -axis: directed opposite to true (i.e. not magnetic) North,
y_{SB} -axis: directed to the East,
z_{SB} -axis: along the support structure centre line, positive in vertical upwards direction.

2.3 Hydrodynamic loads reference system

x_{SWL} , y_{SWL} , z_{SWL} : right handed coordinate system, origin on the undisturbed sea surface (SWL) and on the tower centre line of an unloaded tower. Is parallel to $(xyz)_{SB}$ coordinate system.

x_{SWL} -axis: directed opposite to true (i.e. not magnetic) North,
y_{SWL} -axis: directed to the East,
z_{SWL} -axis: along the support structure centre line, positive in vertical upwards direction.

2.4 Tower top reference system

x_T , y_T , z_T : right handed coordinate system, origin in the tower top centre; parallel to $(xyz)_{SB}$ coordinate system. The tower top centre is defined as the intersection of the tower centre line and the interface plane between tower and nacelle.

x_T -axis: directed opposite to true (i.e. not magnetic) North,
y_T -axis: directed to the East,
z_T -axis: along the support structure centre line, positive in vertical upwards direction.

Support structure top loading:

x_T : $F_{x,T}$ = horizontal force on top of the support structure, directed opposite to true (i.e. not magnetic) North,
y_T : $F_{y,T}$ = horizontal force on support structure top, directed to the East,
z_T : $F_{z,T}$ = vertical force on support structure top, positive in vertical upwards direction.
x_T : $M_{x,T}$ = moment on support structure top, bending the tower top to the West,
y_T : $M_{y,T}$ = moment on support structure top, bending the tower top to the South,
z_T : $M_{z,T}$ = torsion moment on support structure top, positive in anti-clockwise direction.

2.5 Nacelle reference system

x_N , y_N , z_N : right handed coordinate system, origin in the centre of the yaw bearing system; rotated by the turbine angle with respect to the tower top system.

Origin and orientation of this coordinate system move with the movements of the tower top centre in its six degrees of freedom.

x_N -axis: horizontal along the rotor shaft (assuming zero tilt angle) in downwind direction in the plane of the interface between tower and nacelle.
The turbine angle (ϕ_{turb}) gives the angle of the x_N-axis w.r.t. to South i.e. the x_T-axis.
y_N -axis: directed to the left, looking downstream to the rotor,
z_N -axis: along the (local) vertical tower and support structure axis, positive in vertical upward direction.

Note in [9] the $(xyz)_N$ coordinate system is rotated by an azimuth angle of 90^o i.e. the y_N-axis is directed upward.

Nacelle loading:

x_N : $F_{x,N}$ = axial force on nacelle, positive in downstream direction,
y_N : $F_{y,N}$ = lateral force on nacelle, positive if the force acts to the left, standing in front of the rotor,
z_N : $F_{z,N}$ = vertical force on nacelle, positive in vertical upward direction.
x_N : $M_{x,N} = M_{torq,N}$ = moment around x_N-axis, torque on nacelle,
y_N : $M_{y,N} = M_{tilt,N}$ = tilt moment, positive if it increases the tilt angle,
z_N : $M_{z,N} = M_{yaw,N}$ = yaw moment, the turbine angle $(\phi_{y,turb})$ is decreased by a positive yaw moment.

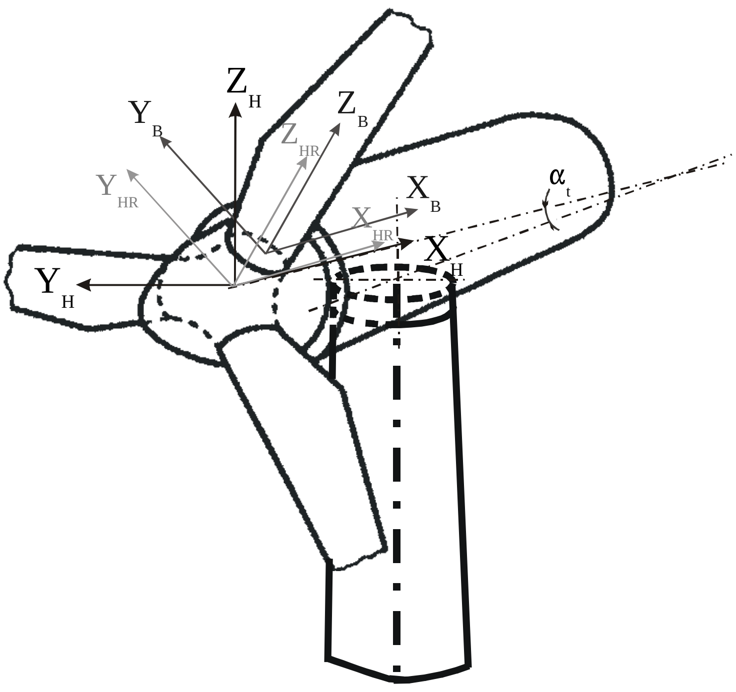

Figure 17: Hub, hub-rotating and blade root reference system.

2.6 Hub reference system not rotating with the rotor

x_H, y_H, z_H : right handed coordinate system, origin in the rotor centre; Origin and orientation of this coordinate system move with the movements of the tower top centre in its six degrees of freedom.

x_H -axis: along the rotor shaft, positive in downstream direction,
y_H -axis: directed to the left, looking downstream to the rotor,
z_H -axis: along the vertical upward direction (assuming zero tilt angle). The tilt angle (α_t) gives the angle between the x_H -axis and the x_N -axis.

Note in [9] the $(xyz)_H$ coordinate system is rotated by an azimuth angle of 90^o i.e. the y_H -axis is directed upward.

Hub loading:

x_H : $F_{x,H} = F_{ax}$ = axial force on hub, positive in downstream direction,
y_H : $F_{y,H} = F_{lat,H}$ = lateral force on hub, positive if the force acts to the left, standing in front of the rotor,
z_H : $F_{z,H} = F_{vert,H}$ = 'vertical' force on hub, positive in vertical upward direction (assuming zero tilt angle).
x_H : $M_{x,H} = M_{torq,H}$ = rotor shaft torque,
y_H : $M_{y,H} = M_{tilt,H}$ = tilt moment, positive if it increases the tilt angle,
z_H : $M_{z,H} = M_{yaw,H}$ = 'yaw' moment, (assuming zero tilt angle).

2.7 Hub reference system rotating with the rotor

x_{HR}, y_{HR}, z_{HR} : right handed coordinate system, origin in the rotor centre; Origin and orientation of this coordinate system move with the movements of the tower top centre in its six degrees of freedom.

x_{HR} -axis: along the rotor shaft, positive in downstream direction and coinciding with x_H ,
y_{HR} -axis: perpendicular to the X_{HR} and Z_{HR} axis,
z_{HR} -axis: in radial direction towards blade tip, parallel with the axis Z_B of one blade.

Hub loading:

x_H : $F_{x,HR} = F_{ax}$ = axial force on hub, positive in downstream direction,
y_H : $F_{y,HR}$ = traverse load on hub and rotor (shaft),
z_H : $F_{z,HR}$ = traverse load on hub and rotor (shaft).
x_H : $M_{x,HR}$ = torsion in rotor shaft,
y_H : $M_{y,HR}$ = bending moment on rotor shaft,
z_H : $M_{z,HR}$ = bending moment on rotor shaft.

2.8 Blade root reference system

x_B , y_B , z_B : right handed coordinate system, origin at the blade root centre, rotated by the turbine, tilt and cone angle and rotating with the blade azimuth angle. Origin and orientation of this coordinate system move with the movements of the tower top centre in its six degrees of freedom.

x_B -axis: in downwind direction (assuming zero turbine, tilt and cone angle),
y_B -axis: in tangential direction from the leading to the trailing edge for zero local blade angle of a clockwise rotating wind turbine,

z_B -axis: in radial direction towards blade tip.

Blade root loading:

x_B : $F_{x,B} = F_{flap}$ = flap shear (out-of-plane) force, positive in downwind direction,
y_B : $F_{y,B} = F_{lead\text{-}lag}$ = lead-lag shear (in-plane) force, positive from the leading to the trailing edge for zero pitch of a clockwise rotating wind turbine,
z_B : $F_{z,B} = F_{radial,B}$ = radial force, positive towards blade tip.
x_B : $M_{x,B} = M_{lead\text{-}lag}$ = lead-lag (in-plane) moment, positive w.r.t. the rotor torque for a clockwise rotating wind turbine,
y_B : $M_{y,B} = M_{flap}$ = flap (in-plane) moment, positive if bending the blade in downwind direction,
z_B : $M_{z,B} = M_{pitch}$ = torsion (pitch) moment, positive if reducing the blade pitch.

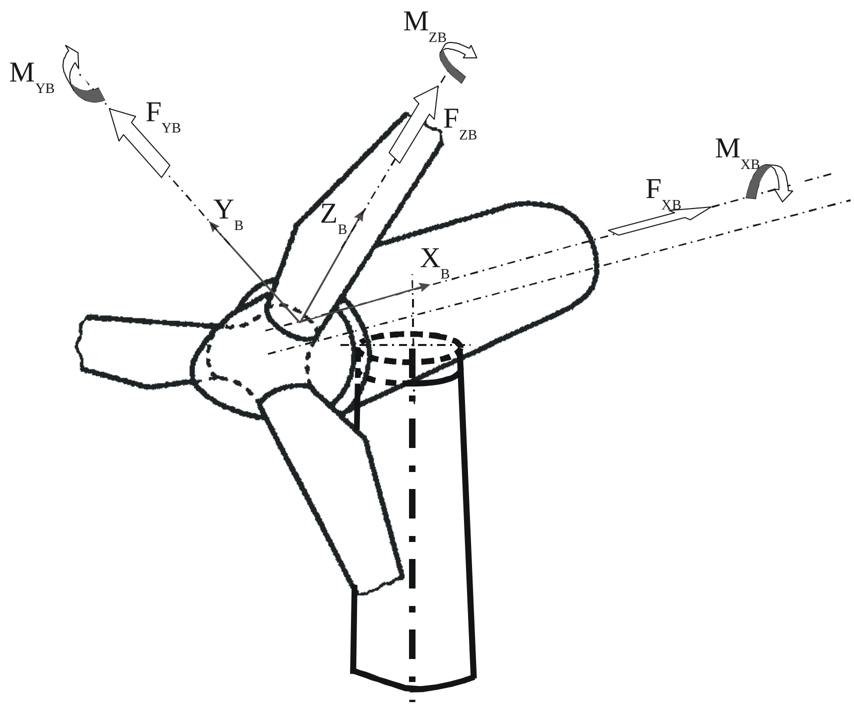

Figure 18: Blade root reference system [4].

2.9 Local blade reference system

x_{rot} , y_{rot} , z_{rot} : right handed coordinate system, origin at the leading edge of **blade section i**, rotated by the turbine, tilt, cone and local blade angle and rotating with the blade azimuth angle.
Origin and orientation of this coordinate system move due to blade bending and torsion.

x_{rot} -axis: perpendicular to the chord line; positive in downwind direction for zero local blade angle,
y_{rot} -axis: along chord line, positive from leading edge (y = 0) to trailing edge (y = c),
z_{rot} -axis: along rotor blade axis directed to the tip.

Blade section loading:

x_{rot} : $F_{x,rot}$ = F_{flat}	= flat shear force, positive in downwind direction for zero local blade angle,
y_{rot} : $F_{y,rot}$ = F_{edge}	= edge shear force, positive towards the trailing edge,
z_{rot} : $F_{z,rot}$ = $F_{radial,rot}$	= radial force, positive towards blade tip.
x_{rot} : $M_{x,rot}$ = M_{edge}	= edge moment, positive w.r.t. to rotor torque (for clockwise rotating turbine),
y_{rot} : $M_{y,rot}$ = M_{flat}	= flat moment, positive if the blade is bended in downwind direction (for zero local blade angle),
z_{rot} : $M_{z,rot}$ = $M_{pitch,rot}$	= torsion (pitch) moment, positive if reducing the blade pitch.

Flatwise vs. flapwise moment

The flatwise moment is defined w.r.t. the local blade reference system. It is the moment in direction y_{rot}, standing parallel to the local chord.
In contrast, the flapwise moment is defined in the blade root reference system, but it is parallel to the rotor plane, i.e. for local blade angle $\beta = 0$ the flatwise and flapwise moments are similar.

Edgewise vs. lead(-lag)wise moment

The edgewise moment is defined w.r.t. the local blade reference system. It is the moment in direction x_{rot}, standing perpendicular to the local chord.
In contrast, the lead(-lag)wise moment is defined in the blade root reference system, but it is parallel to the rotor axis, i.e. for local blade angle $\beta = 0$ the edgewise and lead(-lag)wise moments are similar.

3 Abbreviations and symbols

3.1 Abbreviations

DNV	Det Norske Veritas	OT
DIBt	Deutsches Institut für Bautechnik	WT
GL	Germanischer Lloyd	
HAT	highest astronomical tide	OT
HAWT	horizontal axis wind turbine	WT
HMSO	Her Majesty Shipbuilding Organisation	OT
IEA	International Energy Agency	
MSL	mean sea level	OT
LAT	lowest astronomical tide	OT
LPC	levelized production costs	
OT	offshore technology	
Opti-OWECS	Structural and Economic Optimization of Bottom-Mounted Offshore Wind Energy Converters	
OWEC	offshore wind energy converter (synonym for OWT)	
OWES	offshore wind energy system (synonym for OWF)	
OWF	offshore wind turbine farm	
OWT	offshore wind turbine	
RP	return period	OT
STA	spring tidal amplitude	OT
SWL	still water level	OT
VAWT	vertical axis wind turbine	WT
WT	wind turbine	WT

3.2 Symbols

Symbols and units

a	[-]	axial induction factor	WT
$C_{D,ax}$	[-]	axial force coefficient: $C_{D,ax} = F_{ax} / (0.5\, \rho\, v^2\, \pi R^2)$	WT
C_P	[-]	power coefficient: $C_P = P_{shaft} / (0.5\, \rho\, v^3\, \pi R^2)$	WT
$C_{\bar{x}\bar{x}}$	[ ]	auto covariance function	
c	[m]	chord length at rotor blade	WT
c_d	[-]	aerodynamic drag coefficient	WT
c_D	[-]	hydrodynamic drag coefficient	OT
c_l	[-]	aerodynamic lift coefficient	WT
$c_{l,}$	[rad^{-1}]	slope (derivative) of the aerodynamic lift coefficient $dc_l / d\alpha$	WT
c_M	[-]	hydrodynamic inertia coefficient	OT
D_R	[m]	rotor diameter	WT
D	[-]	fatigue damage	
d	[m]	generally: diameter	
d_w	[m]	water depth	OT
d_{xH}	[m]	rotor overhang (along rotor axis)	WT
d_{zN}	[m]	nacelle offset	WT
E	[N/m^2]	Young's modulus	
F_{ax}	[N]	axial rotor force	WT
F_{edge}	[N]	edge shear force	WT
F_{flat}	[N]	flat shear force	WT
F_{flap}	[N]	flap shear (out-of-plane) force	WT
F_{lat}	[N]	lateral force	WT
$F_{lead\text{-}lag}$	[N]	lead-lag shear (in-plane) force	WT
F_{radial}	[N]	radial force, positive towards blade tip	WT
f	[Hz]	frequency (general)	

f_0	[Hz]	fundamental eigenfrequency (general)	
f_B	[Hz]	blade passing frequency = $N_b \cdot f_R$	WT
$f_{B,1}$, $f_{B,2}$	[Hz]	lower (upper) blade passing frequency (double speed wind turbine)	WT
$f_{B,min}$, $f_{B,max}$	[Hz]	minimum (maximum) blade passing frequency (var. speed wind turbine)	
f_R	[Hz]	rotor frequency	WT
$f_{R,1}$, $f_{R,2}$	[Hz]	lower (upper) rotor frequency (double speed wind turbine)	WT
$f_{R,min}$, $f_{R,max}$	[Hz]	minimum (maximum) rotor frequency (variable speed wind turbine)	WT
G	[-]	gust reaction factor	WT
G_s	[-]	modified gust reaction factor	WT
g	[m/s^2]	gravitational acceleration	
H	[m]	generally wave height (crest to through)	OT
H_B	[m]	breaking wave height	OT
$H_{red,50}$	[m]	reduced extreme wave height	OT
H_{sN}	[m]	significant wave height with return period N (e.g. H_{s50})	OT
H_s	[m]	significant wave height	OT
H_N	[m]	individual wave height with return period N (e.g. H_{50})	OT
h	[m]	height	
I	[-]	turbulence intensity	WT
I	[m^4]	moment of inertia	
k	[m^{-1}]	wave number	OT
k	[N/m, Nm/rad]	generally: translation or rotational stiffness (preferably with subscript)	
M_b	[Nm]	generally: bending moment	
M_{edge}	[Nm]	edgewise blade bending moment	WT
M_{flap}	[Nm]	flapwise (out-of-plane) blade bending moment	WT
M_{flat}	[Nm]	flatwise blade bending moment	WT
$M_{lead\text{-}lag}$	[Nm]	lead-lag (in-plane) blade bending moment	WT
M_{tilt}	[Nm]	tilting moment	WT
M_{torq}	[Nm]	rotor shaft torque	WT
M_{pitch}	[Nm]	pitching blade (torsion) moment	WT
M_{yaw}	[Nm]	yawing moment	WT
N_b	[-]	number of blades	WT
P	[Hz]	rotational frequency	WT
P	[W]	power	WT
R	[m]	outer rotor radius	WT
Re	[-]	Reynolds number	
r	[m]	radial position, r = 0 at rotor shaft	WT
$S_{\bar{x}\bar{x}}$	[ ]	auto power spectral density function (of stochastic variable $\bar{x}$)	
T	[s]	period (esp. wave period or structural eigenperiod)	
T_z	[s]	mean zero-up-crossing wave period	OT
t	[s]	time	
t_w	[m]	wall thickness	
V	[m/s]	horizontal incoming (undisturbed) wind speed at blade element	WT
v	[m/s]	generally: wind speed	
$\bar{v}$	[m/s]	mean wind speed (10 min averaged, at hub height)	WT
$\bar{v}_M$	[m/s]	averaged mean wind speed (10 min averaged for many years, at hub height)	WT
$\bar{v}_E$	[m/s]	extreme mean wind speed (10 min averaged, at hub height, return period 50)	WT
$v_{E,1min}$	[m/s]	reduced extreme gust (1 min averaged, at hub height, return period 50)	WT
v_E	[m/s]	extreme mean wind speed (10 min averaged, at hub height, return period 50)	WT
v_i	[m/s]	cut-in wind speed (at hub height)	WT
$\bar{v}_J$	[m/s]	maximum annual mean wind speed (10 min averaged, at hub height)	WT
v_J	[m/s]	annual gust wind speed (5s averaged, at hub height, return period 1)	WT
$v_{J,1min}$	[m/s]	reduced annual gust (1 min averaged, at hub height, return period 1)	WT
v_o	[m/s]	cut-out wind speed (at hub height)	WT
v_r	[m/s]	rated wind speed (at hub height)	WT
W	[m/s]	effective wind speed seen by blade	WT

W	[m^3]	section modulus	
x	[m]	generally: coordinate in horizontal, axial direction towards North or along rotor axis in downwind direction	
y	[m]	generally: coordinate in horizontal, lateral direction towards West or lateral to rotor axis to the left looking downwind	
z	[m]	generally: coordinate in vertical, upwards direction or along the rotor blade towards the tip	
α	[°]	angle of attack	WT
α	[ ]	wind shear coefficient	WT
α_c	[°]	cone angle	WT
α_t	[°]	tilt angle	WT
β	[°]	local blade angle	WT
γ_F	[-]	partial safety factor for loads	
γ_M	[-]	partial safety factor for material	
ϵ	[°]	local twist angle relative to tip station	WT
η	[m]	water elevation w.r.t. SWL	OT
θ	[°]	pitch angle	WT
θ_t	[°]	tip angle	WT
λ	[ ]	tip speed ratio: $\lambda = (\Omega R) / V$	WT
μ	[kg/m]	mass per unit length	
σ_x	[ ]	standard deviation	
σ_x^2	[ ]	variance	
ξ, ξ_i	[ ]	modal damping (of i th eigenmode) as fraction of critical damping	
π	[ ]	3.1416	
ρ	[kg/m^3]	mass density	
ϕ	[°]	inflow angle at blade element	WT
ϕ_{cur}	[°]	current direction	OT
$\phi_{y,wind}$	[°]	yaw misalignment angle w.r.t. wind direction	WT
$\phi_{y,wave}$	[°]	yaw misalignment angle w.r.t. wave direction	WT
ϕ_r	[°]	azimuth angle	WT
$\phi_{r,b}$	[°]	blade azimuth angle	WT
ϕ_{turb}	[°]	turbine angle	WT
ϕ_{wave}	[°]	wave direction	OT
ϕ_{wind}	[°]	wind direction	
ω	[rad/s]	rotational frequency of the rotor	WT
Ω	[rad/s]	angular frequency (esp. circular wave frequency)	

Subscripts

B	blade root reference system	
b	blade WT	
D	design value (e.g. H_D design wave height)	
F	foundation reference system	
el	electrical	
H	non-rotating hub reference system	
hub	hub height	
N	nacelle reference system	
ref	reference e.g. associated with reference height	
rot	rotating blade root reference system	
SB	sea bottom or mudline	
T	tower top reference system, which coincides with centre of the yaw bearing system	
w	water, wave	OT

Diacritical Marks

_mean value e.g. 10 min averaged wind speed

4 Units

4.1 Units system

Generally SI units (metric system) are to be used.

4.2 Unit of frequencies

Structural eigenfrequencies are generally written as cyclic frequencies in Hz.
Other frequencies are given as cyclic frequencies in Hz, by preference. However, circular frequencies in radians per seconds or periods in seconds can be used if this is common practice and meaningful.
In general, both frequency f (**Hz**) and the angular frequency ω (**rad/s**) can be used in **equations**. In **figures** and **tables**, however it is recommended to use the unit **Hz** for the frequency axis in order to avoid confusion.

References

[1] Kühn, M
Terminology, Reference Systems and Conventions to be used within the Opti-OWECS Project.
Report IW 96.097R 1996

[2] Germanisher Lloyd
Regulations for the Certification of Offshore Wind Energy Conversion Systems
Germanischer Lloyd, Hamburg 1995

[3] International Energy Agency (IEA)
IEA 1400 Safety of Wind Energy Generator Systems 1994

[4] Germanischer Lloyd
Regulations for the Certification of Wind Energy Conversion Systems
Germanischer Lloyd, Hamburg Edition 1993, modified 1995

[5] Det Norske Veritas
Rules for Classification - Rules for Fixed Offshore Structures (DNV Rules)
Det Norske Veritas Classification A/S. Høvik. July 1995

[6] Department of Energy.
Offshore Installations: Guidance on Design, Construction and Certification
London, HMSO 4th edition, 1990.

[7] American Petroleum Institute
Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design
Washington DC 20005, USA 20th edition, July 1, 1993

[8] Tande, O.J. , Hunter R. (editors)
Recommended Practices for Wind Turbine Testing and Evaluation. Vol. 2: Estimation of Cost of Energy from Wind Energy Conversion Systems. Risø National Laboratory, Denmark and Renewable Energy Unit, UK. 1994

[9] Schepers, G.J., Reference Systems, Terminology and Conventions IEA Annex XIV.
ECN. The Netherlands 1994

Appendix A Offshore technology terminology

(The pages A1-A6 and page A7 are reproduced from [6] and [5], respectively.)

11.1.5 FURTHER INFORMATION

These sections should be read in close association with the sections dealing with Hydrostatic and Hydrodynamic Loads and Site Investigations.

11.1.6 DEFINITIONS

The following definitions apply specifically to this section of Guidance.
Note: Italic words are cross references to other definitions in the list.

Average spring tidal current : See *tides.*

Chart datum, CD : The *datum* adopted by the Admiralty for tidal predictions and depth soundings as plotted on navigation charts. Since 1975, Chart Datum has been defined as *lowest astronomical tide*; on earlier Admiralty charts, a different definition applied. Chart Datum varies from chart to chart. (This revision of the Guidance Notes uses *mean sea level* as the *datum* for sea level variations.)

Circulation : See *residual currents.*

Cumulative frequency distribution : See *wave exceedance diagram.*

Current : Unless otherwise specified, a flow of water past a fixed location - more precisely described as an Eulerian current. (A Lagrangian current is measured by following the movement of a water particle.) Currents are usually described with a *current speed* and direction; measurements are usually analysed in terms of the *tidal current* and *residual currents.*

Current ellipse : See *tides - tidal current.*

Current speed : Unless otherwise indicated, taken to be the horizontal speed of the *current* (independent of direction). The speed varies throughout the water column.
Depth-averaged current speed is the speed of the current averaged throughout the water column.

Datum : In this revision of the Guidance Notes the datum for measuring changes in *still water level* is the local *mean sea level.* See also *Chart Datum.*

Depth-averaged current speed : See *current speed.*

Design value : In the design of offshore installations, the *extreme value* of a metocean variable whose exceedance has a *return period* that satisfies the criteria specified in SI 1974/289.

Design wave :
Extreme amplitude design wave is the periodic *wave* having the same *height* as the *extreme* wave with the *return period* required by the specification. Used as the initial design condition for a non-compliant offshore structure. It may have a range of *wave periods* associated with it and its expected *direction* may be specified.
Extreme response design wave or waves may be smaller than the extreme amplitude design wave but produce a greater loading on the structure.

Extreme value : An estimate of the value of a metocean variable with a stated *return period.*

Highest astronomical tide, HAT : The highest *tidal level* the undisturbed *tide* will ever reach above a *datum.* Usually obtained from measurements or predictions covering several decades where these are available. Alternatively, it can be estimated from predictions covering a period when the astronomical positions of the moon and sun are known to be favourable in producing high tidal ranges. See also *lowest astronomical tide, LAT*

Indicative values (of a metocean parameter) : Values of a metocean parameter to be used when reliable values based on *site-specific measurements* or other studies are not available. In the Guidance Notes they are generally presented as contours on maps; the contours are based on those reliable long-term data sets that are available, supplemented by mathematical modelling techniques. They do not take account of small-scale local features.

Joint probability : When two or more metocean variables interact in producing forces on a structure, it may be necessary to determine the probabilities with which various combinations of them occur, ie their joint probability of occurrence.

Lowest astronomical tide, LAT : The lowest *tidal level* the undisturbed *tide* will ever reach below *datum.* Because of shallow water effects around the coast of the UK, LAT and HAT are not generally symmetrical about *mean sea level.* See also *highest astronomical tide, HAT.*

Mean sea level, MSL : The average level of the sea over a period of time long enough to remove variations in level due to *waves, tides* and *storm surges.* Used as a *datum* from which to measure or estimate changes in *still water level* due to *tides* and *storm surges.*

Mean water depth : See *water depth.*

Mean zero-up-crossing period : See *wave period.*

Metocean : Abbreviation of 'meteorological and oceanographic'.

Neap tide : See *tides.*

Peak frequency : See *wave energy spectrum.*

Probability of joint occurrence : See *joint probability.*

Refraction : The process by which *wave* energy is redistributed as a result of changes in the wave propagation velocity due to variations in water depth.

Residual currents : The components of a *current* other than *tidal current.* The most important is often the *storm surge current.*

Mean flow or circulation is the residual averaged over a period greater than 10 days.

Return period : The average period of time between exceedances of a stated value of a metocean variable. See also *extreme value.*

Sea state : A general term for the wave conditions at a particular time and place. Parameters such as significant *wave height* and mean zero-up-crossing *wave period* are often referred to as 'sea-state parameters'. A sea state is usually assumed to stay statistically stationary for a period of 3 hours. See also *wave sampling period.*

Sea surface variance : The mean-square elevation of the sea surface (with respect to *still water level*) due to *waves.* Proportional to the energy density per unit area of sea surface. See also *wave energy spectrum.*

Significant wave height : See *wave height.*

Significant wave steepness : See *wave steepness.*

Site-specific measurements : In the context of these Guidance Notes, measurements of a *metocean* variable made at the location or proposed location of an offshore installation.

Spectrum : See *wave energy spectrum.*

Spring tidal amplitude : See *tides.*

Spring tidal current : See *tides.*

Spring tide : See *tides.*

Still water level : The level of the surface of the sea in the absence of surface *waves* generated by the wind. Variations in still water level are principally due to *tides* and *storm surges.* See also *wave crest elevation.*

Storm surge : Irregular movement of the sea brought about by wind and atmospheric pressure variations. In UK waters, storm surges are usually generated by depressions passing from the Atlantic into Europe.

Storm surge elevation is the change from the predicted *tidal level* as a result of a storm surge. It can be positive or negative and, for design purposes, is defined as an *extreme value.*

Storm surge current is the *current* resulting from a storm surge. An *extreme value* is required for design purposes.

Surface wind drift : The *current,* in the top few metres of the water column, generated in direct response to the local wind blowing over the surface of the sea.

Thermocline : The relatively steep vertical temperature gradient sometimes present over part of the water column. Solar heating of the surface layers of the sea in summer generates seasonal thermoclines that disappear in winter. Permanent thermoclines can also be present at greater depths, usually indicating a boundary between different water masses.

Tides : Regular and predictable movements of the sea generated by astronomical forces. They can be represented as the sum of a number of harmonic constituents, each with different but known periods. In UK waters, the largest constituents are the lunar and solar semi-diurnal components (designated M_2 and S_2) with periods of 12.4 and 12.0 hours respectively.

Average spring tidal current is the *tidal current* corresponding to *spring tidal amplitude* (see below).

Spring tidal amplitude, STA is an indicator of the variation in still water level due to a typical spring tide. Defined as the change due to M_2 and S_2 only (see above). Amplitude is half the range.

Spring tides occur when M_2 and S_2 (see above) are in phase, and **Neap tides** when they are out of phase.

Tidal current is the *current* resulting from the tides. During a characteristic tidal current period, the current vector describes an ellipse with a maximum *current speed* and associated direction and a minimum speed and direction. The size of the ellipse changes with the progression of spring and neap tides.
Tidal level is the change in *still water level* brought about by tides. Measured relative to a *datum.*

Voluntary observing fleet, VOF : The ships of passage that transmit basic *metocean* data to the Meteorological Office.

Water depth : The vertical distance between the sea bed and a defined *datum* near the sea surface, eg *mean sea level* in this revision of the Guidance Notes (giving 'mean water depth').

Waves : Taken in the Guidance Notes to refer to movements on the sea surface generated by wind and with *wave periods* of less than about 25 seconds.

Wave crest elevation, C : The vertical distance between the crest of a *wave* and *still water level.*

Wave direction : The mean direction from which wave energy is travelling.

Wave energy spectrum : A frequency-domain description of the whole *wave* system (or *sea state*). The wave system is assumed to consist of a large number of long-crested sinusoidal wave trains travelling independently but superimposed on each other. The omnidirectional spectral density function $S(f)$ is defined such that $S(f)\delta f =$ the sum of the *sea surface variances* (proportional to energy per unit area) of the wave trains with frequencies between f and $f + \delta f$, where δf is a small frequency interval.
Peak frequency of a spectrum is the *wave frequency* corresponding to the maximum value of the omnidirectional spectral density function.

Wave exceedance diagram : A plot of the proportion of time for which the *wave height* is less than the value specified on the abscissa. Can be presented on a seasonal or all-year basis. Also called the 'cumulative frequency distribution of wave height'.

Wave frequency : The number of waves passing a fixed point in unit time. See also *wave period.*

Wave height, H : In general, the vertical distance between the crest of one wave and the preceding trough. Only in unusual circumstances is it exactly twice the *wave crest elevation.*
Height of a zero-up-crossing wave is the vertical distance between the highest and lowest points on the water surface of a particular *zero-up-crossing wave.*
Significant wave height, H_s is $4\sqrt{m_0}$ where m_0 is the *sea surface variance.*
In sea states with only a narrow band of *wave frequencies*, H_s is approximately equal to $H_{1/3}$ (the mean height of the largest third of the *zero-up-crossing waves*).
Extreme significant wave height, H_{sN} is the *significant wave height* (see above) with a *return period* of N years (eg 50 years for H_{s50}).
Extreme wave height, H_N is the individual wave height (generally the *zero-up-crossing wave* height) with a *return period* of N years (eg 50 years for H_{50}).

Wave hindcasting : Estimating the wave characteristics at a specified time in the past using historic meteorological data.

Wave period, T : The time interval between successive waves. The period of a *zero-up-crossing wave* is the time interval between the two zero up-crossings which bound it. See also *wave frequency*.

Mean zero-up-crossing period, T_z, is calculated for a random sea by dividing the *wave sampling period* by the number of *zero-up-crossing* waves in the sampling period.

Wave sampling period : The relatively short period of time (usually 1000 seconds) for which wave elevation and/or other wave variables are measured in order to define the *sea state*.

Wave scatter diagram or plot : The bivariate probability distribution (or joint frequency distribution) of *significant wave height, H_s,* and *mean zero-up-crossing wave period, T_z,* of the measured sea states at a location. Other height and period parameters are occasionally used.

Wave spectrum : See *wave energy spectrum*.

Wave steepness : The ratio of the *wave height* to the wave length.

Significant wave steepness in deep water is the ratio of the *significant wave height* to the wave length of a periodic wave whose period is the *mean zero-up-crossing wave period*.

Zero-up-crossing wave : The portion of a wave record (the time history of wave elevation) between adjacent zero-up-crossings. A zero-up-crossing occurs when the sea surface rises (rather than falls) through the *still water level*. Wave records are conventionally analysed on the basis of the zero-up-crossing waves they contain.

Height of a zero-up-crossing wave See *wave height*.

Zero-up-crossing period See *wave period*.

Table 11.1

Metocean design parameters for offshore installations

Parameter value required	Influences on values*
Winds	
Extreme wind speed and direction	Averaging time
Vertical profile	Height above sea level
Gust speeds and spectra	
Waves	
Extreme wave crest elevation	Water depth
Extreme wave height, direction and range of associated periods	Currents Averaging time
Cumulative frequency distribution of individual wave heights	
Joint probability of significant wave height and period	
Wave spectra and directional spreading	
Water depths and sea level variations	
Water depth below mean sea level	Long-term changes in water depth
Extreme still water level variations	Tide and storm surge
Currents	
Extreme current speed and direction	Tidal and residual currents
Variation through the water depth	
Fatigue-design current speed	Averaging time
Temperatures	
Extreme air temperatures, maximum and minimum	
Extreme sea temperatures, maximum and minimum	Depth below sea surface
Snow and ice	
Maximum thickness of snow	Part of the structure
Maximum thickness of ice	
Densities of snow and ice	
Marine growths	
Type of growth	Water depth
Permitted thickness	Growth rate
Terminal thickness profile	

** Note that geographical location and the season of the year influence the majority of the parameters*

SECTION 3
ENVIRONMENTAL CONDITIONS

A. General

A 200 Definitions

201 *Hindcasting:* Re-construction of environmental conditions based on barometric pressure measurements and/or wind field charts.

202 *Short-term:* A period of time sufficiently short to ensure that environmental conditions may be considered as stationary in a statistical sense.

203 *Long-term:* A period of time during which the environmental conditions are non-stationary.

204 *Sustained wind speed:* The average wind speed during a specified time interval equal to, or greater than, one minute.

205 *Gust wind speed:* The average wind speed during a specified time interval of less than one minute.

206 *Most probable largest:* The value of a parameter corresponding to the peak of the probability density function for the extreme value of the parameter, over specified time interval.

207 *Recurrence period:* The average time period between two consecutive exceedances of a given value of an environmental parameter.

208 *Significant wave height:* Is defined as $4\sqrt{m_o}$ where m_o is the zero order spectral moment of the wave spectrum.

A 300 Notations

301 The following notations are used throughout this section:

H = crest-to-trough wave height (m)
H_s = significant wave height (m)
T = period of a regular wave (s)
T_p = period of peak spectral density (s)
T_z = average zero-up-crossing period (s).

E. Tide

E 100 General

101 The tidal range is defined as the range between the highest astronomical tide (HAT) and the lowest astronomical tide (LAT), see Fig. 2.

102 The mean water level (MWL) is defined as the mean level between the highest astronomical tide and the lowest astronomical tide, see Fig. 2.

103 The design maximum still water level (SWL) is to include astronomical tidal influences as well as wind and pressure induced storm surge, see Fig. 2. The SWL to be used together with extreme waves for design purposes are given in C 100.

104 Lowest design tide levels are normally to be based on the astronomical part of the tide, only. Lowest tide levels to be used together with extreme waves for design purposes are given in C 100.

105 If data for the specific location in question is not available, the best estimate based on data for nearby locations may be accepted.

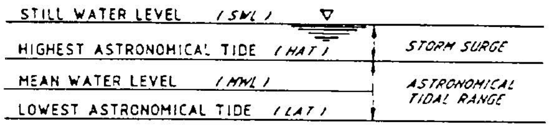

Fig. 2
Definition of Water Levels

SECTION 5
DESIGN LOADS

A 300 Definitions

301 The following definitions are to apply to design load considerations (see also Sec.1 B100 and Sec.3 A200):

— *Expected value:* First order statistical moment of the probability distribution function for the considered variable during a specified time period.

Guidance note:

In practice the expected value may normally be taken as the mean value, or best estimate value during the period considered.

---e-n-d---o-f---G-u-i-d-a-n-c-e---n-o-t-e---

— *Specified value:* Minimum or maximum value during the period considered. This value may take into account operational requirements, limitations and measures taken such that the required safety level is obtained.

— *Expected load history:* Expected load history for a specified time period, taking into account the number of load cycles and the resulting load levels for each cycle.

— *Abnormal load effect:* A load effect with an annual probability of being exceeded equal to, or less than 10^{-4}.

Appendix B Definition of spectra

Notation

$S_{\bar{x}\bar{x}}$: auto power spectral density function (of stochastic variable $\bar{x}$)
$C_{\bar{x}\bar{x}}$: auto covariance function

$\sigma_{\bar{x}}$: standard deviation

$\sigma_{\bar{x}}^2$: variance

f: frequency (Hz)
ω: angular frequency (rad/s)

We will use the convention of one-sided spectra (positive frequencies only).

The spectrum and the covariance function forms a Fourier Transform pair:

$$S_{\bar{x}\bar{x}}(f) = 2\int_{\infty}^{\infty} C_{\bar{x}\bar{x}}(\tau)\, e^{-j2\pi f\tau}\, d\tau \;\; ; \;\; f \geq 0$$

and

$$C_{\bar{x}\bar{x}}(\tau) = \int_{0}^{\infty} S_{\bar{x}\bar{x}}(f)\, e^{j2\pi f\tau}\, df$$

The variance equals the area below the curve of the spectrum:

$$\sigma_{\bar{x}}^2 = C_{\bar{x}\bar{x}}(0) = \int_{0}^{\infty} S_{\bar{x}\bar{x}}(f).df$$

It is also possible to use as variable the angular frequency ω=2π.f with unit rad/s.
In that case the Fourier Transform pair becomes:

$$S_{\bar{x}\bar{x}}(\omega) = \frac{1}{\pi}\int_{\infty}^{\infty} C_{\bar{x}\bar{x}}(\tau)\, e^{j\omega\tau}\, d\tau \;\; ; \;\; \omega \geq 0$$

and

$$C_{\bar{x}\bar{x}}(\tau) = \int_{0}^{\infty} S_{\bar{x}\bar{x}}(\omega)\, e^{j\omega\tau}\, d\omega$$

The variance equals the area below the curve again:

$$\sigma_{\bar{x}}^2 = C_{\bar{x}\bar{x}}(0) = \int_0^\infty S_{\bar{x}\bar{x}}(\omega).d\omega$$

In the OWTES project the frequency f (Hz) or the angular frequency ω (rad/s) may be used in equations. In figures and tables only the unit Hz is applied.

Conventions

1) In literature about wind turbulence it is common to use the frequency expressed in Hz. In case of waves both convention are possible, but the angular frequency (rad/s) has the preference.

2) According to the definitions given above the following relation is valid between the spectra expressed in units Hz and rad/s:

$$S_{\bar{x}\bar{x}}(f) = 2\pi\ S_{\bar{x}\bar{x}}(\omega)$$

Appendix C Economic terminology

(This part is reproduced from [6].)

RECOMMENDED PRACTICES FOR
WIND TURBINE TESTING

2. ESTIMATION OF COST OF ENERGY FROM WIND ENERGY CONVERSION SYSTEMS

2. EDITION 1994

Contents

Estimation of cost of energy from WECS

1 Applications of the levelised cost concept

In this document a standard method for estimating the cost of energy from wind energy conversion systems is recommended. The cost of energy is expressed as the *levelised production cost* (LPC) which is the cost of production of one unit (kWh) levelised over the wind power station's entire lifetime.

The derived cost of energy figure is most suitable for making cost comparison between wind turbines and other sources of energy having similar functional and operational characteristics. Cost comparison with any other energy technologies may be appropriate for a market assessment and as an indication of the economic feasibility of installing the assessed wind turbine. The application of the LPC is further illustrated in examples 1 to 4.

Example 1:
A choice between two or more wind turbines for installation at a specific site is to be made. Basing the choice solely on cost efficiency, the wind turbine with the lowest LPC should be selected.

Example 2:
A choice is to be made between a wind energy, a solar and a wave power system. Basing the choice on cost efficiency, the system with the lowest LPC should be selected.

Example 3:
A specific wind turbine is to be installed at one of several possible sites. Basing the choice on cost efficiency, the site yielding the lowest LPC should be selected.

Example 4:
The economic feasibility of installing wind turbines in an electric power supply system is to be estimated. An initial indication is provided by comparing the LPC of the wind turbines with the short run marginal cost ($SRMC$, i.e. operation cost) of the existing system. A LPC of the wind turbines lower than the $SRMC$ for the existing system indicates economic soundness for small wind energy penetration levels. Higher wind energy penetration levels may modify the power system operation, and in such cases the cost of wind energy calculation should be supported by total power system modelling for deriving all costs and benefits. It should also be noted that if expanding a power supply system with wind turbines, it can be shown statistically that the loss of load probability is reduced. The wind turbines will have a capacity value equivalent to the capacity of a conventional plant which would have to be installed to attain the same level of power supply reliability.

It is stressed that cost comparisons are meaningfull only if the cost of energy figures are estimated on the same basis and with the appropriate level of accuracy. Furthermore, cost calculations of energy technologies are not a substitute for full system analyses deriving the total system cost of energy for adopting different energy generating technologies.

2 Cost components and energy production

The cost components are assumed to be the investment cost (including possible interest during construction), operation and maintenance cost, repair cost, salvage value and social cost. Apart from the social costs, only the costs which relate to the wind turbine system up to the point of interconnection with the public transmission or distribution network are considered.

In some cases it may be necessary to reinforce the public transmission or distribution system (or to include special control devices, etc.) due to the introduction of wind power. In such cases, depending on the scope of the analysis, these extra costs (or a part thereof) may be included in the analysis.

The wind energy output considered could be a) the annual net energy (ANE_t) as *available* at the wind turbine terminals, or b) the annual energy as *utilized* in the connected power system i.e. the annual utilized energy (AUE_t). The relation between the annual utilized energy and the annual net energy can be described by:

$$AUE_t = ANE_t \cdot K_{los,t} \cdot K_{util,t}$$

Here, $K_{los,t}$ is a factor relating to the electric losses which occur between the wind turbine terminals and the electric grid where the energy is utilized, and $K_{util,t}$ is a factor which depends on how the transmitted wind energy is utilized in the power system, see figure 1.

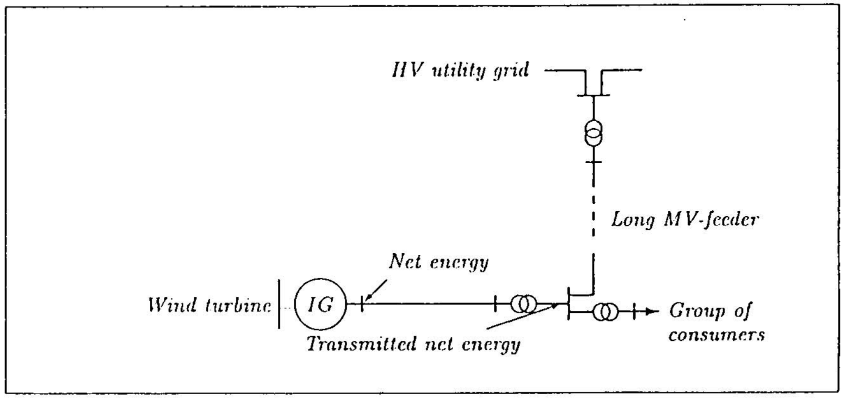

Figure 1: *Example of an electrical system where the energy losses in the long medium voltage feeder are reduced due to the wind power production so that the utilized wind energy becomes higher than the transmitted net energy and* $K_{util,t} > 1$.

Depending on the scope and field of application, both the annual net energy output and the annual utilized energy output are recognized as adequate energy measures, and the assessor must judge which to use in each case.

3 Cost calculation methodology

3.1 General approach

The measure of the estimated cost of energy adopted in this document is *the levelised production cost.* The levelised cost method is thoroughly described and discussed in NEA 1983, [2]. The method will only be described briefly in the following text.

The levelised production cost (LPC) is the cost of one production unit (kWh) averaged over the wind power station's entire expected lifetime. The total utilized energy output and the total costs over the lifetime of the wind turbine are both discounted to the start of operation by means of the chosen discount rate, and the LPC is derived as the ratio of the discounted total cost and utilized energy output.

It is assumed that all costs are given in a fixed currency for a specified year. The currency and cost level year should be decided and clearly declared by the assessor when reporting the estimated cost of energy. In the calculations all costs are discounted to the present value, i.e. the first date of commercial operation of the wind turbine. The discounted present value of the total cost (TC) is given as:

$$\boxed{TC = I + \sum_{t=1}^{n}(OM_t + SC_t + RC_t) \cdot (1+r)^{-t} - SV \cdot (1+r)^{-n}}$$

The levelised production cost (LPC) is given as the ratio of the total discounted cost and the total discounted utilized energy, i.e.:

$$\boxed{LPC = TC / \sum_{t=1}^{n} AUE_t \cdot (1+r)^{-t}}$$

The annual utilized energy, AUE_t, should be specified for each year by adjusting the annual potential energy output, E_{pot}, with a number of correction factors:

$$\boxed{AUE_t = ANE_t \cdot K_{los,t} \cdot K_{util,t} = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t} \cdot K_{los,t} \cdot K_{util,t}}$$

The parameters required for estimating the LPC are further specified and discussed in section 4, whereas section 5 suggests a method for estimating the uncertainty in the cost of energy.

3.2 Simplified approach

In many cases it may be appropriate to assume the annual utilized energy to be constant from year to year (i.e. $AUE_t = AUE$ for $t = 1$ to n). In such cases, the LPC can be calculated as:

$$LPC = I/(a \cdot AUE) + TOM/AUE$$

a is the annuity factor as defined in the table below. I/a is the capital to be paid annually during the assumed period in order to cover both the depreciation and the assumed interest.

TOM is the total levelised annual "downline costs", i.e. all costs other than the initial investment. TOM may for simplicity be estimated as a certain percentage of the investment. The exact definition of TOM is given in table 1 below.

Table 1: *Summary specification of symbols used in this document for calculating the levelised production cost.*

Symbol	Unit	Definition
TC	currency	Discounted present value of total cost of energy production.
I	currency	Investment including possible interest during construction.
OM_t	currency	Operation and maintenance cost during year t.
SC_t	currency	Social cost during year t.
RC_t	currency	Retrofit cost during year t.
SV	currency	Salvage value after n years.
LPC	currency/kWh	Levelised production cost.
ANE_t	kWh	Net energy output during year t.
AUE_t	kWh	Utilized energy during year t.
$K_{per,t}$		Performance factor (rain, dirt, etc.).
$K_{site,t}$		Site factor (obstacles).
$K_{ava,t}$		Technical availability factor (failure, service).
$K_{los,t}$		Electric transmission losses factor.
$K_{util,t}$		Utilization factor.
E_{pot}	kWh	Annual potential energy output.
r		Discount rate.
n	year	Economic lifetime.
t		Year index.
a		Annuity factor, $a = 1/\sum_{t=1}^{n}(1+r)^{-t} = (1-(1+r)^{-n})/r$
TOM	currency	Total levelised annual "downline cost", $TOM = a^{-1} \cdot \sum_{t=1}^{n}(OM_t + SC_t + RC_t)(1+r)^{-t} - SV(1+r)^{-n}$

4 Estimation and specification of input parameters

In this section the input parameters are specified further and guidance is given for their estimation. In many cases one or more of the input parameters will be known explicitly, and of course, the known figures should be used whenever possible.

4.1 Economic parameters

This document considers the cost of energy from wind turbines excluding all possible taxes and subsidies.

4.1.1 Investment

The investment should include all the costs of constructing the WECS. Although only the total investment is included in the formula for calculating the levelised production cost, the analysis report should include a break-down of the investment as indicated in table 2.

In some cases, e.g. for very large wind farms, the construction time may be of substantial length, and the interest on the investment, during the time from when the payment is made until the start of commercial operation, should be calculated and included in the total investment:

$$I = \sum_{i=1}^{j} I_i \cdot (1+r)^{t_i}$$

Here, j is the number of investment payments, r is the discount rate, and I_i is the investment part paid t_i years before the start of commercial operation of the wind power installation.

It is important to notice that bank interest for financing the investment is not considered, since in this document the *project* is being assessed, not how it will be financed.

4.1.2 Operation & maintenance

The O&M costs will depend on the number of wind turbines, the wind turbine type, the site conditions and the connected system. Accordingly, this document recommends project specific estimates of the O&M costs to be specified for each year of the scheme's lifetime. Although only the total annual O&M cost for each year is included in the formula for calculating the levelised production cost, the analysis report should include a break-down as indicated in table 3.

Table 2: *List and specification of investment cost components for grid connected wind turbines. The cost components may be further divided into parts and labour costs. The table is partly based on Nielsen (1990) ref. [5].*

- Wind turbine ex factory cost.
- Special certification or other external test procedure costs if procured.
- Transportation costs, i.e. loading and unloading and other costs associated with transporting the wind turbine from the manufacturer to the site.
- Site preparation costs, i.e. civil works for preparing access road(s), leveling the site, and other actions depending on the specific landscape and ground conditions.
- Foundation costs, i.e. civil works for preparing the wind turbine foundation.
- Erection costs, i.e. costs for erecting the wind turbine at the foundation.
- Internal electrical connections, i.e. costs associated with the low voltage (< 1000 V) electrical works.
- Grid connection costs, i.e. costs associated with the high voltage (> 1000 V) electrical works.
- External monitoring and control system costs. Such external systems are typically associated with large wind farms monitored and operated from a remote utility central.
- Consultancy services and other costs for design and supervision of the installation works.
- General site costs, i.e. costs associated with possible temporary installations such as sanitary installations, work-shops, etc. at the site while installing the wind turbine.
- Land costs, i.e. the cost of buying or renting land for the wind power installation. The use of land near a wind turbine may be restricted by regulations concerning safety and noise aspects as well as restrictions for avoiding construction of buildings or other obstacles which would reduce the wind turbine output. The costs should be discounted to the first date of commercial operation using the discount rate as specified in section 4.1.7. In cases where the land is also used for farming or other activities, the land investment cost should be reduced by the discounted income of these activities.

Table 3: *List of operation and maintenance cost components for grid connected wind turbines. The cost components may be further divided into parts and labour costs.*

- Normal liability and property insurance costs covering sudden wind turbine damage and operational losses due to such damage.
- Special insurance for an annual energy output guarantee.
- Service costs may include the man-power costs of the scheduled services. Service costs during the first years are sometimes included in the wind turbine price.
- Consumable spare parts for wear and tear as well as lubrication grease and oil.
- Repair costs, i.e. minor repairs outside the scheduled service and not covered by any insurance or guarantee surveillance.
- Management costs, i.e. costs connected to the construction and operation management of the wind turbine(s). Management costs may be substantial for large wind farms.

4.1.3 Social costs

The social (or external) costs of energy production are those which are borne by third parties and are not reflected in the market price of energy. Social costs may be associated with environmental damage, nuisance to people, etc.

Consensus on specific methods for estimation of social costs has yet to be established. However, it is accepted that social costs exist and that they should be included when calculating the cost of energy production. It is also widely accepted that social costs of wind energy production are small or negligible, especially when compared to those associated with energy generation from non-renewable sources.

4.1.4 Retrofit cost

The need and costs for replacements or major repairs during the adopted lifetime (see section 4.1.6) should be evaluated. These are dependent on numerous factors, and it is recommended that project specific estimates are made of the timing and cost of possible major repairs.

4.1.5 Salvage value

The salvage value is defined as the difference between the scrap value and the decommissioning cost of the entire scheme at the end of the lifetime adopted for the economic analysis.

If the adopted economic lifetime, n, is less than the assumed technical lifetime of the wind turbine, the salvage value should be a positive value reflecting the capital value of the total wind power installation after n year of operation.

Note that even if the adopted economic lifetime (see section 4.1.6) is set equal to the assumed technical lifetime of the wind turbine, the salvage value of the total investment may not be zero as land, electrical cables, etc. may have a significant capital value.

4.1.6 Economic lifetime

The actual technical lifetime of a wind power installation depends on numerous factors, and it may in fact be very difficult to predict.

Modern electricity producing wind turbines are commonly designed to have a life of 20 years, and normally a 20 year economic life can also be assumed.

The economic life should not be set to a value which exceeds the technical life of the wind turbine.

It should be noted that the economic life as described in this document is a parameter that can be set by the analyst. It should not be confused with other parameters such as the possible loan payback period.

4.1.7 Discount rate

The discount rate, r, given in real terms may be defined as the rate at which the nominal rate, i, exceeds the inflation rate, v, i.e.:

$$1 + r = \frac{1 + i}{1 + v}$$

The choice of the numerical value for the discount rate must be decided by the relevant country, utility, developer etc. and may reflect the cost of financing the project, the possible earned return of an alternative investment or the opportunity cost of capital, the project risks, or any policy objective or constraint.

The following points should be noted:

- The levelised production cost of energy will be higher for a higher discount rate and lower for a lower discount rate.
- If the energy is sold at the calculated levelised production cost, the project costs and income will balance each other and the internal rate of return will be equal to the assumed discount rate.
- An increased discount rate will reduce the economic attractiveness of projects with high investments and low running costs compared to less capital intensive projects.

International studies of electricity generation costs often adopt 5 to 7 % as the annual discount rate in real terms, whereas private investors investigating commercial projects may adopt higher values. In general, it is recommended that an analysis is carried out to determine the the cost of energy sensitivity to the discount rate.

4.2 Wind energy output

The following discussion on estimating the annual utilized energy highlights the most important factors to be considered and reported. It is not meant to give strict directions and thus the appropriate calculation methods may vary considerably from system to system. This document recommends that the assessor uses the best available information for estimation of the annual utilized wind energy output.

Measured values give actual achieved operational statistics and production costs per kWh. Single "spot" measurements (e.g. one year of production figures) should however be used with care for calculation of the levelised production cost, as they can be significantly biased compared to the levelised lifetime figures.

The subsequent sections 4.2.1 – 4.2.8 consider single wind turbines only. The utilized energy output of a wind power plant consisting of more wind turbines can be estimated either by treating the plant as a single large wind turbine, or it can be found by summing the individual utilized energy output estimates of all the wind turbines in the wind power plant.

4.2.1 Potential energy output

The annual potential energy output, E_{pot}, of a wind turbine experiencing specific meteorological conditions is given as:

$$E_{pot} = 8766 \cdot \int_0^\infty p(u) \cdot f(u) du$$

Here, 8766 is the average number of hours in a year, $p(u)$ is the power curve of the wind turbine, and $f(u)$ is the normalised wind speed probability distribution at the hub height of the wind turbine. Often, the wind speed probability distribution is expressed by a Weibull or Rayleigh distribution.

The wind speed distribution should ideally be based on many years of on-site wind speed measurements, but in practice it will often be necessary to extrapolate long term wind data from nearby high quality measurement stations, using for instance the wind atlas method as embodied in the European Wind Atlas, ref. [1], or by applying the statistical "measure-correlate-predict" approach, see for instance Derrick (1992) [7].

The power curve normally gives (as recommended in ref. [3]) the net power output for standard air density conditions (i.e. 15°C and 1013.3 mbar) and for carefully selected weather conditions (e.g. absence of precipitation). When calculating $E_{pot,i}$, corrections must be made for actual atmospheric conditions at the specific site.

For a stall regulated wind turbine, the power curve can be approximately adapted to the actual site by applying the formula:

$$p(u) = p(u)_{std} \cdot \frac{\rho}{1.225}$$

Here $p(u)_{std}$ is the power curve for standard conditions and ρ is the actual annual average air density in kg/m^3. The standard air density is 1.225kg/m^3.

4.2.2 Wind turbine performance factor

The performance of a wind turbine may be reduced dramatically due to dirt, rain or ice on the blades. If the site conditions are likely to give such problems, then either cleaning of the blades must be included in the O&M costs or a reduction in the annual energy output relative to the potential output must be assumed. This reduction in the annual energy output, $\Delta E_{per,t}$, can be expressed by the performance factor, $K_{per,t}$, defined as the ratio of the reduced annual energy output and the annual potential output:

$$K_{per,t} = 1 - \frac{\Delta E_{per,t}}{E_{pot}}$$

The performance factor may change over time due to turbine wear, and changing seasonal climatic conditions.

4.2.3 Site factor

The wind speed distribution assumed for calculating the potential energy output should be the wind speed distribution at the hub height of the wind turbine. In some cases however, the site surroundings may change with time due to erection of new wind turbines, tree planting, construction of new houses, etc. thus influencing the wind speed distribution and the energy output from the wind turbine. In such cases, it may be adequate to take the assumed annual potential energy output, E_{pot}, and then apply a site factor to take account of the reduction in annual energy output, $\Delta E_{site,t}$, due to the changed surroundings. The annual reduction may be expressed by means of the site factor, $K_{site,t}$:

$$K_{site,t} = 1 - \frac{\Delta E_{site,t}}{E_{pot} \cdot K_{per,t}}$$

4.2.4 Technical availability factor

The technical availability, $C_{ava,t}$, of a wind turbine is defined as the fraction of the year the wind turbine is ready for operation:

$$C_{ava,t} = \frac{8766 - T_{out,t}}{8766}$$

Here, 8766 is the number of hours in an average year, $T_{out,t}$ is the total annual scheduled and forced outage time of the wind turbine.

The resulting technical availability, $C_{ava,t}$, may in general depend both on the wind power installation and on the connected system, e.g. a grid connected wind turbine will shut down in the event of an external grid failure. In such cases, it is often adequate to specify the technical availability of the wind turbine and the connected system separately, and to estimate the resulting technical availability, $C_{ava,t}$, as the product of these two availability factors. It should be noted that for large modern power systems, the grid availability may be very close to 1, whereas for smaller rural grids, the availability will typically be lower.

The *technical availability factor*, $K_{ava,t}$, assumed by this document is defined by the energy loss, $\Delta E_{ava,t}$, due to the wind turbine availability:

$$K_{ava,t} = 1 - \frac{\Delta E_{ava,t}}{E_{pot} \cdot K_{per,t} \cdot K_{site,t}}$$

$K_{ava,t}$ may be different from $C_{ava,t}$, e.g. if the wind turbine servicing is scheduled during calm periods, $K_{ava,t}$ will probably be higher than $C_{ava,t}$.

4.2.5 Net energy output

The annual net energy output (ANE_t) is the annual energy output at the wind turbine terminals:

$$ANE_t = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t}$$

4.2.6 Electric transmission losses factor

The annual electrical transmission loss, $\Delta E_{los,t}$, is the difference between the wind turbine net energy output and the transmitted net energy fed into the point of public utilization.

The annual electrical transmission losses may be expressed as a factor, $K_{los,t}$:

$$K_{los,t} = 1 - \frac{\Delta E_{los,t}}{ANE_t}$$

An estimate of the annual electric transmission losses may be based on the annual net wind power distribution and specifications of the site transmission system. It is important to know the actual net wind power distribution as the transmission losses will be a function of the square of the net wind turbine output power.

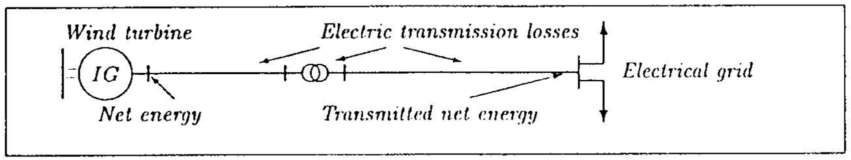

Figure 2: *Example of the electrical grid connection of a wind turbine. The wind energy electric transmission losses occur between the wind turbine and the grid where the wind energy is utilized.*

4.2.7 Utilization factor

In most cases, the transmitted wind energy ($ANE_t \cdot K_{los,t}$) will be very close both geographically and numerically to the wind energy utilized in the connected system (AUE_t), see also figure 2. However, in certain cases (see example 5 and 6) there may be a substantial difference, and the utilization factor is defined to take account for such cases:

$$K_{util,t} = 1 - \frac{\Delta E_{util,t}}{ANE_t \cdot K_{los,t}}$$

Example 5:
In an electrical system with high wind energy penetration, the power production may be higher than the load during high wind and low load periods. Thus, the excess energy has to be dissipated during these periods, and the utilized wind energy will be lower than the transmitted net wind energy output.

Example 6:
In an electrical system where the wind turbines are connected to the grid at a point close to a large group of consumers and far from any other power plant, the grid losses (in the grid between the power plant and the consumers in question) may be reduced, and the utilized wind energy will be higher than the transmitted net wind energy output. See figure 1 for illustration.

4.2.8 Utilized energy

The annual utilized energy, AUE_t is the wind energy output utilized in the connected system. The AUE_t may be estimated for each year of the wind turbine's lifetime by assuming the potential output, E_{pot}, and the year specific factors $K_{per,t}$, $K_{site,t}$, $K_{ava,t}$, $K_{los,t}$ and $K_{util,t}$.

$$AUE_t = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t} \cdot K_{los,t} \cdot K_{util,t}$$

A Summary of input parameters

Input parameter	Range & Comment
Total initial capital investment, I	Wind turbine and system specific.
O&M cost, OM_t	Wind turbine and system specific; average annual O&M costs of $\sim$ 2% of ex factory wind turbine investment can be assumed.
Social cost, SC_t	Wind turbine and system specific; commonly accepted as being negligible for wind turbines.
Retrofit cost, RC_t	Wind turbine and system specific; a retrofit after 10 years costing approx. 10-15% of the ex factory wind turbine investment is often assumed for proven grid connected wind turbines.
Salvage value, SV	Wind turbine and system specific; depends also on the adopted economic lifetime.
Economic lifetime, n	Decision parameter; should be equal to or shorter than the technical lifetime, 20 year is commonly assumed for proven grid connected wind turbines.
Discount rate, r	Decision parameter, 5-7% is commonly assumed in international studies of electricity generation costs.
Power curve, $p(u)$	Wind turbine specific, should be corrected to air density at site.
Air density, ρ	Site specific, 1.225 kg/m^3 at 15°C, 1013.3mbar.
Wind speed distribution, $f(u)$	Site specific; commonly expressed by a Weibull or Rayleigh distribution.
Annual potential production, E_{pot}	$E_{pot} = 8766 \int_0^\infty p(u) \cdot f(u)du$
Performance factor, $K_{per,t}$	Wind turbine and site specific; the factor may range from 0.7 to $\sim$ 1.0 depending on dirt, rain and ice conditions and on wind turbine maintenance, $\sim$ 1.0 is typical.
Site factor, $K_{site,t}$	Site specific; factors from 0.6 to $\sim$ 1.0 are experienced for wind turbines in wind farms, 0.95 is typical.
Technical availability factor, $K_{ava,t}$	Wind turbine and system specific; 0.9 to $\sim$ 1.0 is a typical range for proven grid connected WECS.
Annual net energy, ANE_t	$ANE_t = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t}$
Electric transmission losses factor, $K_{los,t}$	Dependent on site transmission system and power production distribution; 0.9 to $\sim$ 1.0 is a typical range for proven grid connected wind turbines.
Utilization factor, $K_{util,t}$	Dependent on system configuration, load and power production distribution; $\sim$ 1.0 is typical for electrical power systems with low penetration of wind power; values much below 1.0 may be experienced if the installed wind power capacity is higher than the minimum consumer load.
Annual utilized energy, AUE_t	$AUE_t = E_{pot} \cdot K_{per,t} \cdot K_{site,t} \cdot K_{ava,t} \cdot K_{los,t} \cdot K_{util,t}$

B Summary of uncertainty parameters

Sample parameter	confidence interval*	Comments
Total investment, I	5	Assuming short term (less than 2 years) forecast for specified proven technology at specific site.
O&M cost, OM_t	5-10	Assuming the forecast is for specified proven technology at a specific site; uncertainty depends on forecast length.
Social cost, SC_t	??	The uncertainty may be neglected as the social cost of wind power is commonly assumed to be very low.
Retrofit cost, RC_t	??	Uncertainty may be neglected as having very little impact on the *LPC*.
Salvage value, SV	??	Uncertainty may be neglected as having very little impact on the *LPC*.
Power curve, $p(u)$	10-15	Dependent on average wind speed; thoroughly discussed in ref. [3].
Wind speed distribution, $f(u)$	10-15	Dependent on quality and amount of historical wind speed data, complexity of terrain and on wind speed data analysis method; see ref. [4].
Air density, ρ	1	Uncertainty due to instrument bias error; see ref. [3].
Performance factor, $K_{per,t}$	5	Estimated uncertainty on forecasted performance factor assuming no extreme operation conditions; see ref. [4].
Site factor, $K_{site,t}$	4-6	Estimated as 1/3 of observed total variability range of wake factor; see ref. [4].
Technical availability, $K_{ava,t}$	1-2	Assuming proven technology; uncertainty depends on forecast length; see ref. [4].
Electric transmission losses, $K_{los,t}$	3	Estimated as 1/3 of typical range of transmission efficiency, actual uncertainty depends strongly on method used for estimating the parameter.
Utilization factor, $K_{util,t}$	6	Estimated as 1/3 of typical range of utilization factor, actual uncertainty depends strongly on method used for estimating the parameter.

* The confidence interval, $\frac{\Delta}{E(X_t)}$, is in % of the expectation value of the input parameter, X_t. The numbers are samples for the 95 % confidence level, and the given numbers should not be regarded as a substitute for the recommended project specific analysis.