OFFSHORE WIND ENERGY TECHNOLOGY

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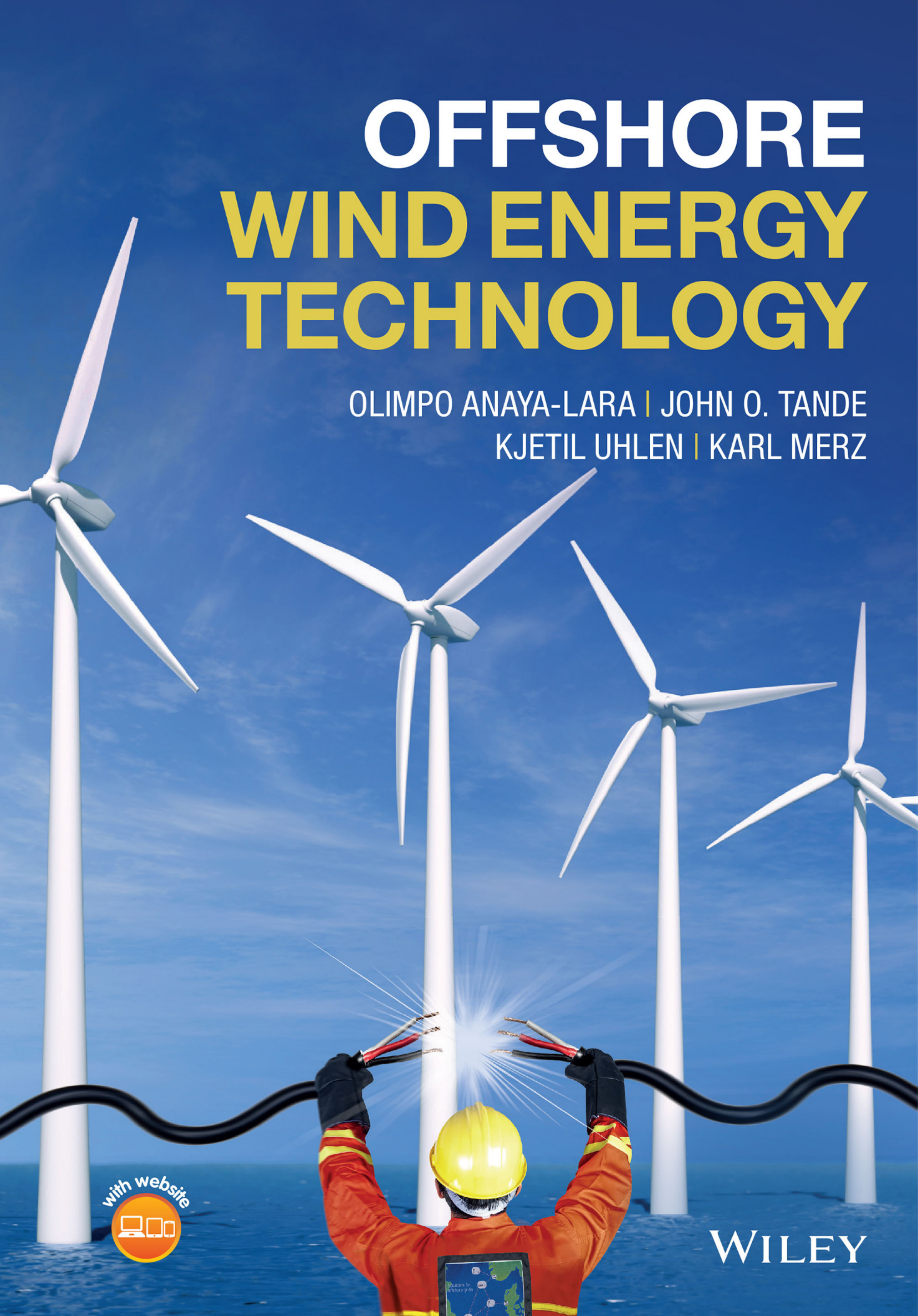

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Erin E. Bachynski has been an Associate Professor of marine structures in the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU) since 2016. She holds bachelor and masters degrees in naval architecture and marine engineering from the University of Michigan, and a PhD from NTNU, with a thesis titled 'Design and Dynamic Analysis of Tension Leg Platform Wind Turbines'. Associate Professor Bachynski's main research areas are numerical and experimental modelling of offshore wind turbine structures, including hydroelasticity, nonlinear wave loads and structural response modelling. Previous projects include development of numerical simulation tools for offshore wind turbines, including consideration of the faults, drivetrain responses, and higher-order hydrodynamic loads, as well as real-time hybrid testing of a semisubmersible wind turbine.

David Campos-Gaona received his PhD degree in electrical engineering from Instituto Tecnológico de Morelia, Morelia, México, in 2012. From 2014–2016, he was a Postdoctoral Research Fellow with the Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada. Since August 2016, he has been a Research Associate with the University of Strathclyde, Glasgow, UK. His research interests include wind farm power integration, HVDC transmission systems and real-time digital control of power-electronic-based devices. Dr Campos-Gaona has been author/co-author of one book, seven journal papers and several conference papers in the area of electrical engineering and wind power systems.

Elin Espeland Halvorsen-Weare is a Research Scientist in the Maritime Transport Systems group at SINTEF Ocean, department of Maritime. She earned her MSc in Industrial Economics and Technology Management in 2007 and her PhD on Maritime Fleet Planning and Optimization under Uncertainty in 2012, both from the Norwegian University of Science and Technology (NTNU). Between 2011 and 2014 she held a position as postdoctoral fellow on the topic of discrete optimization methods for transportation problems at SINTEF ICT. Dr Halvorsen-Weare has mainly been working on optimization problems related to maritime logistics, but her interests also cover other related problems within transport and logistics. Her focus is on a broad range of solution methods, including exact optimization techniques, heuristics and multi-objective optimization and how to treat uncertainty in real-life logistic problems for the maritime industry.

Sung-ho Hur received a BEng degree in Electronics and Electrical Engineering (EEE) from the University of Glasgow in 2004 and an MSc (with Distinction) in EEE from the University of Strathclyde in 2005. He then worked as a research assistant in the Industrial Control Centre (ICC) within the Department of EEE at the University of Strathclyde before undertaking a PhD at the ICC in 2006. During his PhD, he conducted research on modelling, cross-directional control and fault monitoring of DuPont Teijin Films' plastic film manufacturing process. Since completing his PhD in 2010, he has been working as a Research Associate in the ICC, researching in control, modelling and anomaly detection of wind turbines and farms. Sung-ho Hur's primary research interests include control, modelling and condition monitoring, with particular interest in wind turbines and farms. Further interests include cross-directional processes, such as plastic film manufacturing processes.

William E. Leithead leads the wind energy research group and is the Director of the Industrial Control Centre at the University of Strathclyde. Professor Leithead is the Chair and Management Hub of the EPSRC Supergen Wind Energy Technologies Consortium. He is the Director of the EPSRC Centre for Doctoral Training in Wind Energy Systems and is also a member of the Executive Committee of the EPSRC Industrial Doctoral Centre in Offshore Renewable Energy. He is a member of the European Academy of Wind Energy Executive Committee, European Energy Research Alliance Joint Programme Wind Steering Committee, Scientific Advisory Board of the Norwegian Centre for Offshore Wind Technology (Trondheim), Scientific Advisory Board of the Norwegian Centre for Offshore Wind Energy (Bergen), Strategy Advisory Group of the Energy Technology Institute, Energy Technology Institute Wind Strategy Advisory Group and Wind Energy Coordinator of the Energy Technology Partnership. His research interests in wind energy include the dynamic analysis of wind turbines, their dynamic modelling and simulation, control system design and optimization of wind turbine design. Professor Leithead has strong links to all aspects of the wind energy industry and has been involved in many collaborative projects related to the design of controllers and wind turbines. He has been the recipient of more than 40 research grants and is the author of more than 200 academic publications.

Karl Merz has been a researcher in the field of offshore renewable energy since 2008. His PhD thesis was on the design of optimal stall-regulated rotors for offshore wind turbines. After joining SINTEF Energy in 2012, he has focused on the dynamics and control of offshore wind turbines and power plants. Highlights include the design of a control system for the Deepwind floating vertical-axis wind turbine and the development of the STAS wind power plant analysis program, which is a unified state–space model including aerodynamic, hydrodynamic, structural, electrical and control systems. Prior to his career in renewable energy, Karl Merz worked at Boeing Commercial Airplanes, where he developed analysis methods used to design and certify composite structures on the 787 aircraft.

Amir Rasekhi Nejad is an associate professor at the Marine Technology Department, Norwegian University of Science and Technology (NTNU). He lectures 'Machinery and Maintenance', 'Wind Energy' and 'mechatronics' courses at NTNU. Prior to joining NTNU, he worked in different industries, such as industrial machinery design, mechanical power transmission systems, gear industry, offshore oil and gas and third party design verification, for more than ten years. He has carried out extensive research on drivetrains in offshore wind turbines, both fixed and floating ones. His current research interests include design, dynamic modelling, reliability analysis, fault detection and condition monitoring of mechanical systems in marine and renewable applications. Dr Nejad holds a PhD in Marine Engineering, MSc in Subsea Engineering and BSc in Mechanical Engineering. He is a member of the 'Norwegian Standard committee on vibration and shock' and 'ISO committee on condition monitoring and diagnostics of wind turbines'.

Øyvind Netland has an MSc and a PhD, both from the Department of Engineering Cybernetics at the Norwegian University of Science and Technology (NTNU), Trondheim, Norway. The PhD was funded through the Norwegian Research Centre for Offshore Wind Technology (NOWITECH). He is currently working with Norsk Automatisering AS (NAAS), which is a participant in the LEANWIND project, and as a postdoctoral researcher at the Department of Mechanical and Industrial Engineering at NTNU. His research interests include embedded systems, real-time systems and robotics.

Lars Magne Nonås is a Senior Research Scientist in the Maritime Transport Systems group at SINTEF Ocean, department of Maritime. He holds an MSc in Optimization from the Department of Informatics, University of Bergen (2002), and gained his PhD in Operational Research at the Department of Finance and Management Science at the Norwegian School of Business (NHH). Lars Magne Nonås has over 10 years of national and international research experience within maritime transport and logistics problems (shipping, oil and gas, and offshore wind), and nine years within the offshore wind industry. His research interests and expertize include heuristics and optimization methods applied towards practical decision problems.

Morten D. Pedersen is Assistant Professor at the Department of Engineering Cybernetics in the Norwegian University of Science and Technology (NTNU). He has held this position since 2013 and teaches a range of courses on control theoretical subjects. Morten holds an MSc in Engineering Cybernetics from NTNU, received in 2009. He has also earned a PhD at the same university in 2017 with a thesis named 'Stabilization of Floating Wind Turbines'. His main research interests include efficient modelling of wind energy systems, stabilization of floating wind turbines, navigation problems and linear systems theory.

Iver Bakken Sperstad is a Research Scientist in the Power System Asset Management group at SINTEF Energy Research, department of Energy Systems. He holds a PhD in theoretical and numerical physics from the Norwegian University of Science and Technology. Since joining SINTEF in 2012, he has been working on simulation modelling of operation and maintenance and logistics of offshore wind farms, and he has been the lead developer of the strategic decision support tool NOWIcob since 2014. He has also been involved in international collaborations on LCOE calculation (through IEA Wind Task 26 Cost of Wind Energy) and comparison, verification and validation of strategic operation and maintenance decision support tools. Other research interests include power system reliability, vulnerability and optimization of energy storage systems.

Magnus Stålhane is Associate Professor at the Department of Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU). He has an MSc in Industrial engineering from NTNU. He worked at the MARINTEK as a research scientist while writing his PhD thesis at NTNU, Department of Industrial Economics and Technology Management, between 2008 and 2012. His areas of interest include optimization of transport and logistics problems, especially within the field of maritime logistics.

John O. Tande is Chief Scientist with SINTEF Energy Research and Director of NOWITECH, a EUR 40 million (2009–2017) research cooperation on Offshore Wind Technology (www.nowitech.no). He is also heading the subprogramme on offshore wind energy within the European Energy Research Alliance and is a Steering Committee member of the European Technology and Innovation Platform ETIP wind. He has more than 20 years experience within the field of wind energy research, with a focus on grid integration and offshore technology. He graduated from the Norwegian University of Science and Technology in 1988 and has since worked in Denmark and Norway. He has been with SINTEF Energy Research since 1997.

Kjetil Uhlen is Professor in Power Systems at the Norwegian University of Science and Technology (NTNU), Trondheim, and a Special Adviser at STATNETT (the Norwegian TSO). He has an MSc (1986) and PhD degree (1994) in control engineering. His PhD work was on design and control of autonomous wind–diesel systems with battery energy storage. Research on wind power integration in the power system was also a main activity while working for SINTEF Energy Research until 2009. As professor at NTNU his main responsibility has been research and education related to power system stability and control. Recent focus has been on the development and implementation of applications based on Phasor Measurement Units (PMUs) in operation and control. As special advisor at STATNETT, a main goal has been to enable the deployment of R&D results in this area into the control room environment. Kjetil Uhlen has been a member of the IEEE since 1993 and has been co-editor of the *IEEE Transactions on Power Systems*. He was the Norwegian member of CIGRE Study Committee C4, 'System technical performance' (2004–2012), convener of Advisory Group C4.6, 'Power system security assessment' (2004–2010) and CIGRE Working Group WG C4.603, 'Analytical techniques and tools for power balancing assessments' (2009–2015).

Thomas Michael Welte is a Research Scientist in the Power System Asset Management group at SINTEF Energy Research, department of Energy Systems. He holds a Dipl Ing. in Mechanical Engineering from the University of Stuttgart, and a PhD in Safety, Reliability and Maintenance from the Norwegian University of Science and Technology. His research interests include: reliability and lifetime analysis; maintenance planning, modelling and optimization; condition monitoring; degradation modelling and lifetime assessment. He has over ten years of experience in national and international R&D activities related to reliability, operation and maintenance of renewable energy production (wind, hydro) and energy distribution (electricity grid). He has also been involved in international collaborations such as IEA Wind Task 33 on Reliability Data.

Foreword

Wind energy is playing an increasingly vital role in the efforts to decarbonise European and international energy systems. Power grids have seen a strong increase in wind power penetration, enhanced through the development of very large offshore wind farms consisting of hundreds of multi-MW wind turbines. To optimally exploit these very valuable assets, all aspects of the design, operations and maintenance will need to be tightly integrated, and the strategies and algorithms required to achieve optimality will need to be developed.

Since its creation back in 2009, I have followed NOWITECH activities and given advice on its direction through my participation in its Scientific Committee. NOWITECH facilitated an intense cooperation between outstanding researchers (postgraduate students and academics) and strategic industry partners maintaining at all times a strong connectivity with research organisations and programmes in Norway and internationally.

Being an international precompetitive research cooperation with the required depth of experience and breadth of expertise on offshore wind technology, NOWITECH was ideally placed to successfully conduct innovative research on all relevant aspects of offshore wind technology aiming to maximise energy production, minimise downtime, reduce operational and maintenance costs and extend lifetime. This book presents first-class material on some of these aspects.

It gives me great pleasure to write the Foreword for this timely book. I am confident it will be of great value to students, practising engineers and the offshore wind industry as a whole.

Peter Hauge Madsen
Head of Department
DTU Department of Wind Energy
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Preface

The motivation for this book is the rapid growth of offshore wind energy systems and the implications this has on power system operation, control and protection. Developments on wind turbine technology and power electronic converters along with new control approaches have enabled offshore wind energy systems performance to be improved. The authors identified the need for a book that covers up-to-date issues on this dynamic topic. This reference book is based on research material developed by the Norwegian Research Centre for Offshore Wind Technology (NOWITECH)[1] and teaching material developed by the authors over the last 20 years. It is useful to final year undergraduate and postgraduate students, and also practising engineers and scientists in the offshore wind industry. The book addresses offshore wind farm electric design, substructure and foundation design, operation and maintenance modelling, turbine and park control, offshore transmission and power system integration.

The book is organized into eleven chapters. In Chapter 1 the reader is presented with a brief overview on offshore wind developments and further introduced to the topics of the book. Chapter 2 provides a general description on the various topologies of wind turbine generators, main components and capacity sizes. Enhanced power electronic converters for wind turbine generators are also presented. A thorough review of modelling and analysis of drivetrains in offshore wind turbines are presented in Chapter 3 while support structures for offshore wind turbines, that is substructures and foundation, are covered in Chapter 4, which also provides a classification of wind turbine substructure based on water depth covering both bottom-fixed and floating support structures. Chapter 5 addresses the problem of controlling large bottom-fixed offshore wind turbines. In order to make the material broadly accessible, we stick to relatively simple control algorithms and focus on the interplay between the controls and the dynamic response of the wind turbine. Alternative electrical designs of an offshore wind farm are presented in Chapter 6, covering topologies and protection aspects. Chapter 7 provides an overview of, and a brief introduction to, operation and maintenance (O&M) modelling for offshore wind farms, including transportation and logistics for O&M.

1 NOWITECH's objective is international precompetitive (2009–2017) research cooperation on offshore wind technology established as part of the Norwegian Centres for Environment-friendly Energy Research (FME) scheme and cofinanced by the Research Council of Norway, industry and research partners. NOWITECH is hosted by SINTEF Energi AS with SINTEF Ocean, SINTEF Stiftelsen, Norwegian University of Science and Technology (NTNU) and Institute for Energy Technology (IFE) as research partners (www.nowitech.no).

The main focus of the chapter is on strategic O&M modelling. Chapter 8 describes the main objectives of supervisory control, namely: maximize energy production; minimize fluctuating loads; provide ancillary services; handle faults; and global optimization, including enhanced control to reduce O&M costs. The design of enhanced controls to achieve these objectives is explained, including modelling-related issues. The connection to shore is addressed in Chapter 9, which presents the various technologies currently used by industry. The chapter discusses AC transmission, VSC-HVDC and gives an overview of low-frequency AC transmission (LFAC). Chapter 10 discusses aspects of operation and control of power systems with high penetration of wind power and explores the possibilities for offshore wind power plants to provide power system operation support. Chapter 11 presents economics, regulatory and policy issues related to offshore wind power developments.

The authors would like to thank the following authors for their contributions to this book: Dr Amir Rasekhi Nejad (Chapter 3 in full), Dr Erin E. Bachynski (Chapter 4 in full), Dr David Campos-Gaona (main parts of Chapter 6), Morten D. Pedersen (contribution to Chapter 5) and Dr Thomas Michael Welte, Dr Iver Bakken Sperstad, Dr Elin Espeland Halvorsen-Weare, Dr Øyvind Netland, Dr Lars Magne Nonås and Dr Magnus Stålhane (Chapter 7).

Olimpo Anaya-Lara
John O. Tande
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Karl Merz
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Acronyms

AC	Alternating current
AEP	Annual energy production
AGC	Automatic generation control
AGMA	American Gear Manufacturing Association
ALS	Accidental limit state
BEM	Blade element momentum
BP	Band-pass
BTB	Back-to-back
CAPEX	Capital expenditure
CB	Circuit breaker
CDF	Cumulative distribution function
CFD	Computing fluid dynamics
CM	Condition monitoring
CMS	Condition monitoring system
CSC	Current source converter
CTV	Crew transfer vessel
DC	Direct current
DECC	Department of Energy and Climate Change
DFIG	Doubly-fed induction generator
DMC	Direct matrix converter
DOF	Degree of freedom
DTU	Danish Technical University
ENTSOE	European Network of Transmission System Operators, ENTSO-E
EPSRC	Engineering and Physical Sciences Research Council
FC	Flying capacitor
FC/TCR	Fixed capacitor/thyristor-controlled reactor
FCR	Frequency containment reserves
FCS	Frequency control support
FE	Force element
FEM	Finite element method
FFT	Fast Fourier Transform
FLS	Fatigue limit state
FORM	First-order reliability method
FR	Frequency restoration
FRC	Fully-rated converter

FRR	Frequency restoration reserves
FRT	Fault-ride through
FSIG	Fixed-speed induction generator
FWT	Floating wind turbine
GBS	Gravity-based structure
GDW	Generalized dynamic wake
GRC	Gearbox reliability collaborative
GSC	Generator-side converter
GTO	Gate turn-off thyristor
HPSTC	Highest point of single tooth contact
HTS	High-temperature superconducting
HV	High voltage
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
Hz	Hertz
I	Current
IEC	International Electrotechnical Commission
IGBT	Insulated-gate bipolar transistor
IGCT	Integrated gate-commutated thyristor
iPMSG	Ironless permanent-magnet synchronous generator
L	Level
LCC–HVDC	Line-commutated converter HVDC
LCOE	Levelized cost of energy
LDD	Load duration distribution
LES	Large-eddy simulation
LFAC	Low-frequency alternating current
LPSTC	Lowest point of single tooth contact
LV	Low voltage
MBS	Multibody simulation
MC	Matrix converter
MOSFET	Metal–oxide–semiconductor field-effect transistor
MPPT	Maximum power point tracking
MV	Medium voltage
MW	Megawatt
NOWITECH	Norwegian Research Centre for Offshore Wind Technology
NPC	Neutral-point clamped
NREL	National Renewable Energy Laboratory
NSC	Network-side converter
NTNU	Norges Teknisk-Naturvitenskapelige Universitet
O&M	Operation and maintenance
OPEX	Operational expenditure
ORT	Offshore reference turbine
OWT	Offshore wind turbine
PAC	Power adjusting controller
PCC	Point-of-common coupling
PEX/XLPE	Cross-linked polyethylene insulated cable
PI	Proportional-integral

PLL	Phase-locked loop
PM	Permanent magnets
PMSG	Permanent-magnet synchronous generator
PSG	Passive generator-side
PSS	Power system stabilizer
PWM	Pulse-width modulation
R	Resistance
RFPMSG	Radial-flux permanent magnet generator
RR	Reserve replacement
RSC	Rotor-side converter
SCADA	Supervisory control and data acquisition
SCIG	Squirrel-cage induction generator
SES	Surface effect ship
SF6	Sulfur hexafluoride
SG	Synchronous generator
SLS	Serviceability limit state
STATCOM	Static compensator
SVC	Static var compensator
TE	Transmission error
THD	Total harmonic distortion
TLB	Tension-leg buoy
TLP	Tension-leg platform
TSC	Thyristor-switched capacitor
TSO	Transmission system operator
UCTE	Union for the Coordination of the Transmission of Electricity
ULS	Ultimate limit state
UPS	Uninterruptible power supply
V&V	Verification and validation
VSC	Voltage source converter
VSI	Voltage source inverter
VSR	Voltage source rectifier
WRSG	Wound-rotor synchronous generator
WTG	Wind turbine generator
X	Impedance
XLPE	Cross-linked polyethylene

Symbols (Individual Chapters)

Chapter 2

P_{air}	Power in the airflow
ρ	Air density
A	Swept area of rotor, m^2
v	Upwind free wind speed, m/s
C_p	Power coefficient
$P_{\text{wind turbine}}$	Power transferred to the wind turbine rotor
λ	Tip-speed ratio
ω	Rotational speed of rotor
R	Radius to tip of rotor
V_m	Mean annual site wind speed

Chapter 3

A	Weibull shape parameter
B	Weibull scale parameter
C	Bearing basic load rating
D	Fatigue damage
e	Error function
f_{1P}	Tower shadow frequency (external excitation frequency)
f_n	Natural frequency
$F_X(x)$	Cumulative distribution function
$g()$	Failure function
I_{xx}	Mass moment of inertia about xx-axis
I_{yy}	Mass moment of inertia about yy-axis
I_{zz}	Mass moment of inertia about zz-axis
J_r	Rotor inertia (including shaft, hub, blade)
J_g	Generator inertia about the low speed shaft
K_I	Integral gain
K_P	Proportional gain
k_{tr}	Torsional stiffness of main shaft
k_{tg}	Torsional stiffness of generator
k_{teq}	Equivalent torsional stiffness
L	Bearing life

m	SN curve parameter
n	Generator speed over rotor speed (inverse of gearbox ratio)
N_{rotor}	Rotor rotational speed
$n(u)$	Number of stress cycles
N_c	Characteristic value of the number of stress cycles to failure
P	Bearing equivalent radial load
P_f	Probability of failure
$R()$	Resistance function
S	Stress range
$S()$	Load effect or response function
S_F	Safety factor
t	Time
TE	Gear transmission error
T_{Gen}	Generator torque
u	Wind speed
X	Bearing radial load factor
Y	Bearing axial load factor
Z	Number of gear teeth
$\mathbf{F}$	Force matrix
$\mathbf{K}$	Stiffness matrix
$\mathbf{K_b}$	Bearing stiffness matrix
$\mathbf{K_m}$	Gear mesh stiffness matrix
$\mathbf{M}$	Mass/inertia matrix
$\mathbf{X}$	Displacement vector
α	Inverse of gear ratio
β	Reliability index
Δ	Damage limit
ω	Angular velocity
$\Gamma()$	Gamma function
$\Phi()$	Standard Gaussian cumulative distribution function
ϕ	Rotational angle
χ	Model uncertainty

Chapter 4

λ	Length scale factor
A	Added mass
A_{wp}	Waterplane area
B	Linear damping
C	Hydrostatic stiffness
H_s	Significant wave height
I_{55}	Waterplane moment of inertia (in pitch)
K	Mooring system stiffness
M	Dry mass
T_p	Peak period
U_w	Mean wind speed
z_B	Vertical centre of buoyancy
z_G	Vertical centre of gravity

Chapter 5

A Area; Entry in the state matrix; generic parameter
$\mathbf{A}$ State matrix
a Aerodynamic state variable; axial induction factor; transformer step-down ratio; amplitude
$\mathbf{B}$ State space input matrix; transformer matrix
b Generic parameter
$\mathbf{b}$ Row of the $\mathbf{B}$ matrix
C Capacitance
$\mathbf{C}$ Damping matrix; state space matrix
C_P Power coefficient
C_T Thrust coefficient
c Chord length
$\mathbf{c}$ Row of the $\mathbf{C}$ matrix
D Diameter; denominator polynomial
$\mathbf{D}$ Matrix of deformations; state space matrix
d Direct axis
E Energy; expected value operator
$\mathbf{E}$ Matrix of elasticity
$\mathbf{e}$ Environmental inputs
F Force
$\mathbf{F}$ Force vector
f Frequency (Hz); function of…
$\mathbf{f}$ Vector function
$\mathbf{G}$ Gyroscopic matrix
H Transfer function
H_s Significant wave height
I DC current; turbulence intensity
i $\sqrt{-1}$; current
$\mathbf{i}$ Three-phase current
$\mathbf{i}^{\psi}$ d-q current
J Inertia
k Integer index
M Moment
$\mathbf{M}$ Mass matrix
$\mathbf{m}$ Measurement noise; mass matrix
K Gain; generic parameter
$\mathbf{K}$ Stiffness matrix (assembled structure)
$\mathbf{k}$ Stiffness matrix (elemental)
N Numerator polynomial
n Integer index
P Power; rotor rotation frequency; projection
$\mathbf{p}$ Operator inputs
q Quadrature axis
$\mathbf{q}$ Generalized coordinate
R Radius
$\mathbf{R}$ Coordinate vector

r	Radial coordinate
$\mathbf{r}$	Position vector
S	Spectrum
$\mathbf{S}$	Shape function matrix
s	Laplace variable; aux. variable in dynamic inflow
T	Torque
$\mathbf{T}$	Coordinate transform
T_P	Wave period
t	Time; tangential direction (rotorplane)
$\mathbf{u}$	Control vector; state space input vector
V	Velocity, windspeed
V_∞	Remote incoming windspeed
$\mathbf{V}$	Velocity, windspeed vector
v	Voltage; velocity fluctuation; velocity
$\mathbf{v}$	Three-phase voltage; turbulence velocity; velocity
$\mathbf{v}^\psi$	*d*-*q* voltage
w	Structural deflection
$\mathbf{w}$	Structural deflection
X	x-axis
x	x coordinate; state
$\mathbf{x}$	State vector
Y	*y*-axis
y	*y* coordinate; output
$\mathbf{y}$	Output vector
Z	*z*-axis
z	*z* coordinate
α	Angular frequency parameter; angle-of-attack
β	Blade pitch angle; angular frequency parameter
γ	Angular frequency parameter
δ	Shaft tilt angle
ε	Error
ϵ	Strain vector; error vector
ζ	Damping ratio
η	Elastic nodal displacements
θ	Torsional deflection; phase angle
$\mathbf{\Lambda}$	Induction matrix
λ	Tip speed ratio; eigenvalue
$\boldsymbol{\lambda}$	Magnetic flux linkage
ξ	Blade twist angle
$\mathbf{\Pi}$	Participation factor matrix
ρ	Density
$\boldsymbol{\sigma}$	Stress vector
τ	Time constant
$\mathbf{\Phi}$	Mode shape matrix
φ	Cone angle
$\boldsymbol{\varphi}$	Mode shape vector
χ	Yaw angle

Ψ Integral of error times gain
$\boldsymbol{\Psi}$ Inverse of mode shape matrix
ψ Rotor azimuth angle
Ω Rotor speed
ω Angular velocity; angular frequency (rad/s)

Chapter 6

I_{pickup} Relay pick-up current
$I_{\max}$ Maximum load current of a feeder
$I_{sc\min}$ Smallest short circuit current at the feeder
r_{cb} Crowbar resistor

Chapter 8

I Equivalent turbulence intensity
U_h Mean hub-height wind speed
σ_u Standard deviation of wind direction turbulence
C_p Power coefficient
V_∞ Average remote wind speed
θ_c Compass direction
P Active power
Q Reactive power
Ω Rotor speed
T Low-speed shaft torque
F_T Rotor thrust

Chapter 9

τ Time constant
V_{dc} DC voltage
M Modulation index
dq dq components
$\Delta V\%$ Voltage drop
A_{core} Core area of a transformer

About the Companion Website

Don't forget to visit the companion website for this book:

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There you will find valuable material designed to enhance your learning, including:

- Definition of the NOWITECH Reference Wind Turbine/Definition of the NOWITECH Reference Wind Farm

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1

Introduction

John O. Tande

CHAPTER MENU

Development of offshore wind energy is a great scientific and engineering challenge. It involves multiple disciplines, thus this textbook aims to contribute by giving concise information on design of offshore wind farms, addressing technology and power system integration. One chapter is devoted to operation and maintenance modelling. Other aspects, such as met-ocean conditions, soil, spatial planning, impact on the environment and so on, are not part of this textbook. This chapter open by describing the historic development of offshore wind energy (Section 1.1) and continues by introducing the topics being addressed in this textbook (Section 1.2). Thereafter, follows a brief section on cost of energy calculations (Section 1.3) before the chapter is concluded with considerations on the future development of offshore wind energy (Section 1.4).

1.1 Development of Offshore Wind Energy

The argument for the development of offshore wind energy is generally for providing clean energy without any emissions of carbon dioxide (CO_2) or other greenhouse gasses and, in this way, battling climate change. Offshore wind development contributes to long-term security of supply as a domestic renewable resource, rather than import or exhausting limited fossil fuel reserves, and can be a means of boosting industry activity with supplies for construction and operation. Many large cities are located close to the sea, hence offshore wind farms can be built in proximity to them. This can be attractive as an alternative to long transmission lines or deploying power plants on land close to large cites with high property values. The wind resource is generally much greater

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offshore than over land, and offshore wind farms can be built with very low negative environmental impact (WWF, 2014).

As can be concluded from the above, there are clearly many good reasons to develop offshore wind energy. But, as for any new source of energy, the market and technology needs to be matured before it can compete without any support. The technology must be proven with a professional supply chain, and developers must be able to carry out offshore wind farm projects with low risk and deliver energy at competitive cost.

The first offshore wind turbine was a 220 kW turbine installed about 250 m from shore at 6 m water depth outside Nogersund in southern Sweden in 1990. The year after, in 1991, the first offshore wind farm was installed. This was Vindeby, comprising eleven 450 kW turbines about 1 km from shore at 2–4 m water depth outside Lolland in Denmark. These early developments may seem small compared to the state of the industry today but were utterly bold and pushed the limits at their time. They demonstrated offshore wind energy to be viable and that challenges related to installation and operation of wind turbines offshore could be overcome. The development of offshore wind energy continued to be slow, however, and it was not before the turn of the century that development started to gain real momentum (Figure 1.1). In this period (2000–2015) the typical size of offshore wind farms increased from tens of MW to hundreds of MW, and wind farms were built further from shore and in deeper waters. By the end of 2015, the accumulated installed offshore wind capacity was 12.1 GW, distributed in 14 countries, with the United Kingdom top of the list with 5.1 GW, followed by Germany (3.3 GW), Denmark (1.3 GW) and China (1.0 GW) (Table 1.1).

Almost all wind capacity built in the period (Table 1.1) was bottom fixed, with the exception of projects in Norway (Hywind, 2.3 MW, 2009), Portugal (WindFloat, 2 MW, 2011) and Japan (Fukushima 2 MW, 2013), which apply floating wind turbines to harness the rich wind resources in deep sea regions. These installations represent a new bold development in offshore wind energy and tens of projects are in preparation to bring the technology forward. For example, in Japan the Fukushima project was expanded, in 2016, with installation of two more floating turbines, rated 5 and 7 MW, and Statoil is continuing development of the Hywind concept, installing six 5-MW units comprising a 30-MW floating wind farm in Scottish water to be completed in 2017 (Figure 1.2).

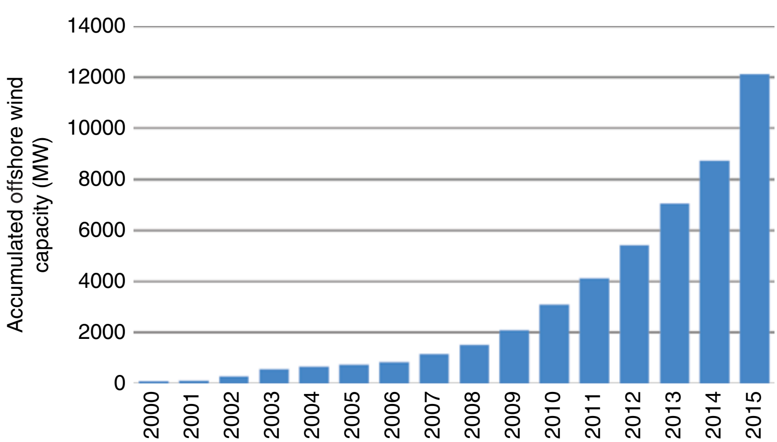

Figure 1.1 Global accumulated offshore wind capacity since 2000. *Source:* Data from Nikolaos 2004, McCarthy 2013 and GWEC 2016.

Table 1.1 Installed offshore wind capacity by the end of 2015. Data from GWEC (2016).

Country	Capacity (MW)
UK	5067
Germany	3295
Denmark	1271
PR China	1015
Belgium	712
The Netherlands	427
Sweden	202
Japan	53
Finland	26
Ireland	25
South Korea	5
Spain	5
Norway	2
Portugal	2

The largest offshore wind farm built up to 2015 was the London Array that was completed in 2013. It has an installed capacity of 630 MW, consisting of 175 turbines each rated 3.6 MW. The wind farm is located about 20 km offshore with an area of about 100 km^2 at water depths up to 25 m in the outer Thames estuary, UK. In 2015 the wind farm produced about 2.5 TWh (London Array, 2016), that is corresponding to a capacity factor[1] of 45% or almost 4000 full load hours.[2] In comparison, wind farms on land are generally exposed to less favourable wind resources and, therefore, achieve lower generation. For example, the International Renewable Energy Agency (IRENA, 2016) reports that the global average capacity factor for onshore wind was 27 % in 2015, that is corresponding to 2365 full load hours.

The energy from offshore wind farms can replace generation based on fossil fuel, hence reduce emissions of CO_2 by some 300–700 g CO_2 per kWh wind generation, that is about 300 g/kWh for replacing natural gas and about 700 g/kWh for replacing coal fired power plants. Indeed, the actual savings will depend on how the power system is operated together with the wind farm. For the London Array (Figure 1.3), on average, yearly savings are assumed to be 925 000 tonnes of CO_2 based on 420 g/kWh and a wind farm capacity factor of 39%, or, to put this in perspective, savings equal to the emissions of 289 000 passenger cars (London Array Limited, 2016).

1 The capacity factor is a normalized measure of the generation defined as the ratio between the annual average generation and the installed capacity: $C_F = 100\frac{E}{8760 \cdot P_r}$
Here, C_F is the capacity factor (%), E is the annual generation and P_r is the installed capacity.

2 Full load hours (FLH) is another normalized measure of the generation. It is defined as the ratio between the annual generation and the installed capacity: $FLH = \frac{E}{P_r}$
Here, FLH is the full load hours (h), E is the annual generation and P_r is the installed capacity.

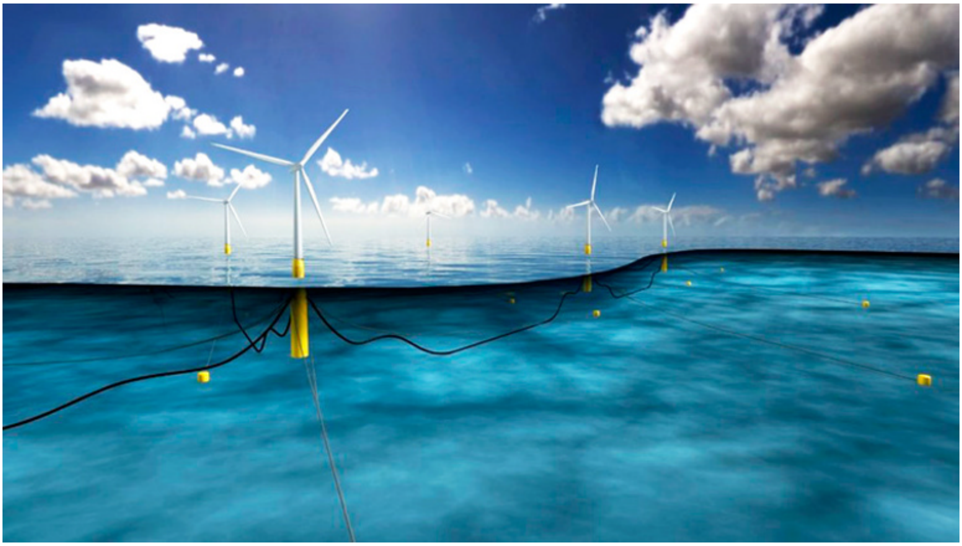

Figure 1.2 Illustration of the Hywind Scotland 30-MW floating wind farm scheduled to be in operation by late 2017 about 25 km offshore from Peterhead. The turbines are each rated 6 MW and the water depth is 95–120 m (Statoil, 2015). *Source:* Reproduced with permission of Statoil.

Figure 1.3 The London Array 630-MW offshore wind farm in operation in the outer Thames estuary. The wind farm spans about 100 km^2 and includes 175 turbines each rated 3.6 MW installed in waters up to 25 m deep (London Array Limited, 2016). *Source:* London Array Limited.

1.2 Offshore Wind Technology

The significant elements of an offshore wind farm are (i) the wind turbines themselves, (ii) their substructure and foundation, (iii) the internal collection grid, (iv) the substation and (v) the transmission to shore (Figure 1.4).

Offshore wind turbines are typically quite similar to land-based turbines but with greater rating and adapted to the marine environment. The largest turbines (2016) are 8 MW with 180 m rotor diameter (Campbell, 2016). Chapter 2 gives more details on turbine technology with emphasis on the electrical design, while Chapter 3 addresses the mechanical drivetrain.

In shallow water (up to 40–60 m), monopiles or other bottom-fixed structures are commonly used, whereas in deeper water floating support structures are generally thought to be a better option. Chapter 4 gives more details on support structures, both bottom-fixed and floating.

Modern wind turbines include advanced control systems that provides for autonomous and safe operation generally aiming to maximize the energy output at all times, though respecting constraints that may be set by the wind farm Supervisory Control and Data Acquisition (SCADA) system. Turbine control systems are elaborated in Chapter 5, while wind farm control is described in Chapter 8.

The internal grid, substation and transmission to shore can have alternative configurations depending on the size of the wind farm and distance to shore. The internal grid is commonly operated with alternating current (AC) at about 33 kV, though 66 kV solutions are emerging for connecting larger turbines. The design should be carefully assessed, including application of broadband models of the electrical system to accurately calculate switching transients and high frequency resonance phenomena (Gustavsen *et. al.*, 2011). Alternative internal grid design with direct current (DC)

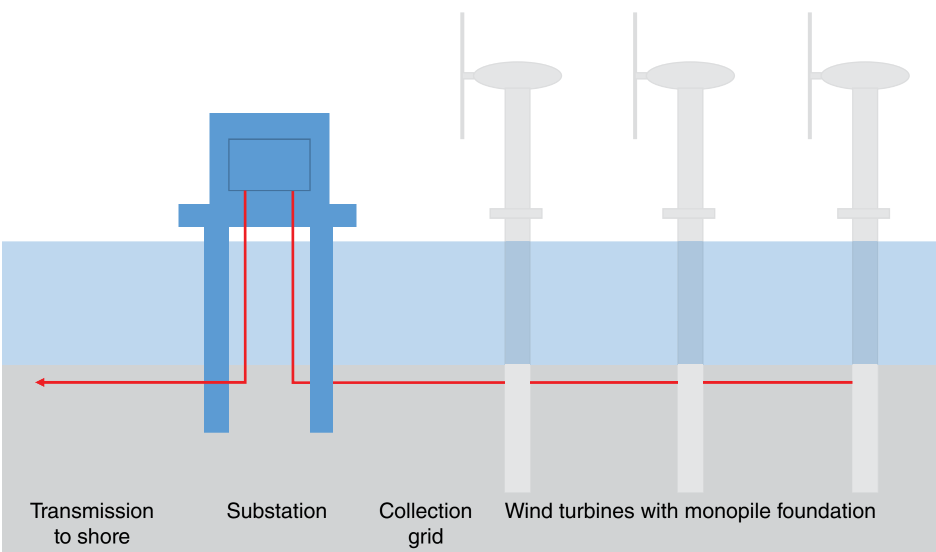

Figure 1.4 The main elements of an offshore wind farm. (Not to scale, for illustration only.) The turbines are normally installed 5–10 rotor diameters apart. Graphic by Tande, SINTEF.

collection systems have been proposed, though so far such systems have not been implemented in any commercial offshore wind farm (Chapter 6). The internal grid is coupled to one or more offshore substations that are connected to the transmission network. The substation normally includes a transformer that brings the voltage up to transmission level, for example 150 kV. If the distance to shore is short and the wind farm has limited capacity, transmission by high voltage alternating current (HVAC) is the normal option. Often it is suggested that if the wind farm is more than 100 km from shore and rated above 200 MW, high voltage direct current (HVDC) may be the preferred option. This requires, however, application of a HVDC converter station offshore and on land. These represent quite significant investments, thus industry has recently shown interest in also applying HVAC for longer distances and higher capacities. Studies conducted as part of NOWITECH give evidence that losses in HVAC may be reduced by operating the HVAC cable at a variable voltage below rated, thus stretching the limits in terms of distance and capacity of HVAC transmission (Gustavsen and Mo, 2016). Chapter 9 gives more detail on alternative transmission technologies and substation configuration.

Operation and maintenance (O&M) of wind farms are significantly more challenging offshore than onshore. Getting service personnel on-board offshore wind turbines is not trivial, and the same goes for equipment and spare parts. While various options can be applied to secure efficient O&M, it is not straightforward to select the best one. Chapter 7 elaborates on this, presenting an O&M simulation model and a model for O&M vessel fleet optimization.

Chapters 10 and 11 consider how offshore wind farms interact with the power system. Chapter 10 starts with an introduction to power system operation and control, and the connection requirements for generators in an interconnected power grid. Thereafter, the possibilities for offshore wind power plants to provide power system operation support are elaborated. Chapter 11 discusses the economics of offshore wind power in view of the relevant electricity markets and regulatory and policy issues related to incentive schemes for offshore wind development.

1.3 Levelized Cost of Energy

Offshore wind farms need to be designed to be safe, reliable, comply with grid and environmental requirements and give high energy output. An optimized design can be said to achieve this at minimum cost per kWh produced over the lifetime of the wind farm. It is, therefore, useful for anyone engaged in design of offshore wind farms to understand the basic concept for calculating cost of energy. As an example, say that it is found that by expanding the space between the turbines in an offshore wind farm some additional energy output can be gained. But this also means additional cost to pay for longer cables between the turbines. So, is it a good idea or not? This can be answered in economic terms by comparing the cost of energy for both cases.

The levelized cost of energy (LCOE) is the most commonly used metric to describe the cost of electric energy from power plants. It gives the average cost of production of one unit (kWh) levelized over the lifetime of the power plant. The total energy output and the total costs over the lifetime of the plant are both discounted to the start of operation by means of the chosen discount rate, and the LCOE is derived as the ratio of the discounted total cost and energy output. For offshore wind energy, the LCOE can be calculated according to Equation 1.1, based on (IRENA, 2016):

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{1.1}$$

Here, LCOE is the average lifetime levelized cost of electricity generation, I_t is the investment expenditures in the year t, M_t is the operations and maintenance expenditures in the year t, E_t is the electricity generation in the year t, r is the discount rate and n is the lifetime of the offshore wind farm.

By definition, if the LCOE of a project is equal to the average lifetime selling price of electricity from the project, the investment gives a return equal to the discount rate. A higher electricity price means higher profit, whereas an electricity price lower than the LCOE would mean less return on the investment or possibly a loss.

The level of detail for describing the expenditures, I_t and M_t, and the electricity generation, E_t, depends on the scope of the analysis. The elements shown in Figure 1.5 are included in the LCOE calculation (IRENA, 2016). The lifetime n of an offshore wind farm is typically assumed being 25 years, although, for financial decisions, often a shorter time is required for return on investment. The discount rate, r, should generally reflect the cost of capital and vary from market to market and over time, also depending on the perceived risk of the project. Typically, discount rates are assumed in the range of 5–10% in LCOE studies.

The LCOE of offshore wind farms put in operation in the period 2010–2015 are shown in Figure 1.6. It can be seen that there is a significant spread in cost between the projects, which is typical for market and technologies in their infancy. Projections for future cost indicate significant potential for cost reduction and that, by sometime after 2025, the LCOE of offshore wind energy can be brought down to grid parity. In 2016, three offshore wind projects awarded through auctions got much attention because of their low kWh selling price. These are marked with the star symbol in Figure 1.6. The

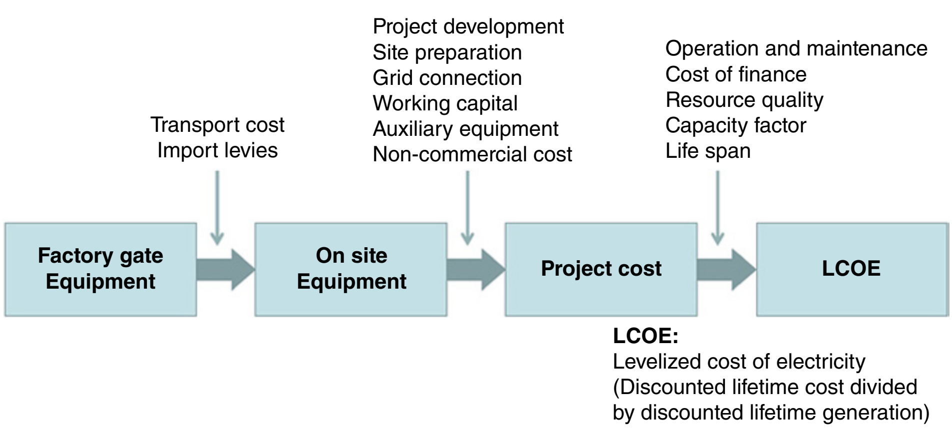

Figure 1.5 Metrics in calculation of LCOE. *Source:* IRENA (2016).

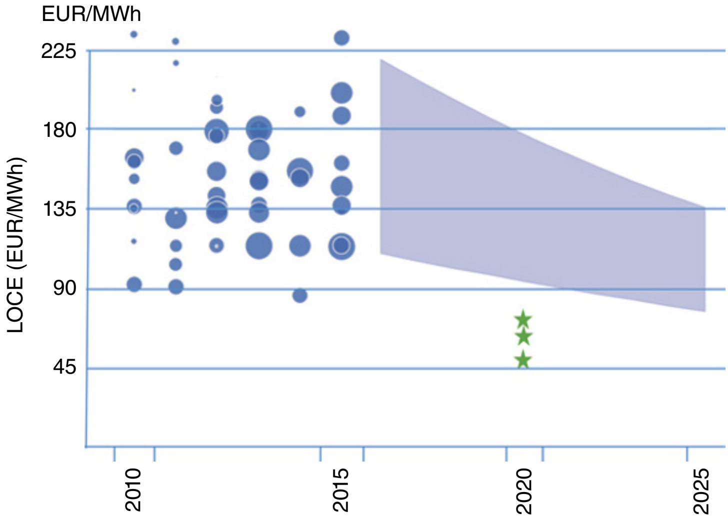

Figure 1.6 Historical LCOE of offshore wind farms and projection as reported by IRENA (2016) compared with reported auction prices for three new offshore wind farms to be in operation by 2020 (star symbols). Costs for these three wind farms are, from the top, 72.7 EUR/MWh for Borssele (NL) 700 MW (Dong, 2016), 63.8 EUR/MWh for Vesterhav (DK) 350 MW (Vattenfall, 2016a) and 49.9 EUR/MWh for Kriegers Flak (DK) 600 MW (Vattenfall, 2016b). The graph is prepared converting data from IRENA (2016) to EUR/MWh assuming an exchange rate of 9 EUR = 10 USD for 2015.

three projects are all at very favourable locations with no or negligible cost for grid connection to shore, excellent access to site and other conditions that can explain the low price, and are not 'typical' for future offshore wind farms. Still, they give a clear signal that possibly, the cost of offshore wind energy can be brought down more quickly than earlier anticipated.

To better understand the LCOE numbers in Figure 1.6 or others, it is useful to do some simplified calculations. Lumping all investment expenditures to $t = 1$, assuming the annual energy output to be the same for all years $t = 1$ to n and assuming the annual operations and maintenance expenditures to be the same for all years $t = 1$ to n, Equation 1.1 can be rewritten as:

$$\mathrm{LCOE} \cong \frac{I}{E \cdot a} + \frac{M}{E} = \frac{i}{FLH \cdot a} + \frac{m}{FLH} \tag{1.2}$$

Here, i is the lump sum investment expenditures I expressed per installed kW, m is the assumed annual average operations and maintenance expenditures M expressed per kW, FLH is the assumed annual average electricity generation E divided by the rated capacity of the wind farm, and a is the annuity factor:

$$a = \frac{1}{\sum_{t=1}^{n} (1+r)^t} = \frac{1-(1+r)^{-n}}{r} \tag{1.3}$$

where a is the annuity factor, r is the discount rate and n is the lifetime of the offshore wind farm.

Table 1.2 Example calculation of LCOE for three characteristic cases.

Case	A	B	C
FLH (h)	3767	3942	4200
Capacity factor (%)	43	45	48
Investment (EUR/kW)	4185	3555	1800
Discount rate (%)	10.0	8.0	8.0
Lifetime (yr)	25	25	25
Annuity factor	9.1	10.7	10.7
Investment (EURc/kWh)	12	8	4
Annual O&M (EUR/kW)	127	71	42
O&M (EURc/kWh)	3	2	1
LCOE (EURc/kWh)	**15**	**10**	**5**

Applying these formulas (Equations 1.2 and 1.3), Table 1.2 sums up assumed input parameters and resulting LCOE for three characteristic cases. Cases A and B are applying input data as given by IRENA (2016), converting from USD to EUR assuming 9 EUR = 10 USD. The two cases mimic the central LCOE estimates for offshore wind in 2015 and 2025 (IRENA, 2016), stating that cost could be reduced from USD 0.17/kWh in 2015 to USD 0.11/kWh in 2025.

Case C illustrates a possible combination of parameters to give a LCOE of EUR 0.05/kWh, taking information from Vattenfall (2016) as the starting point. The full load hours and the capacity factors are for sites with good wind resources, although there will be offshore wind projects with both higher and lower production. The investment expenditure for cases A and B include significant costs for transmission to shore, whereas for case C no such transmission costs are assumed.

Distribution of investment expenditures for a 'representative' offshore wind farm is shown in Figure 1.7. It should be noted to this that with the given USD 4650/kW, the wind turbines only (44 %) would cost EUR 1841/kW, that is about two times the cost of land-based wind turbines, and seems a bit on the high side. Certainly, the investment expenditure for case C can only be achieved with turbine cost being close to that of land-based wind turbines. The O&M cost of case C is approaching that of land-based windfarms, and would be truly astonishing to achieve.

1.4 Future Offshore Wind Development

The offshore wind potential is tremendous. Assuming resources within 50 nautical miles of shore with a maximum water depth of 200 m, and omitting areas with low wind resources, the global offshore potential is estimated to 192 800 TWh (Arent *et al.*, 2012), that is eight times global electricity generation in 2014, which was 23 816 TWh (IEA, 2016a). Exactly how much of the potential will be realized is hard to say, but to reach climate targets renewable energy will play a central role. In the 450 Scenario by the International Energy Agency (IEA), the global operating wind capacity is expected to be 2312 GW in 2040, delivering 6127 TWh annually (IEA, 2016b). Exactly how much of this will

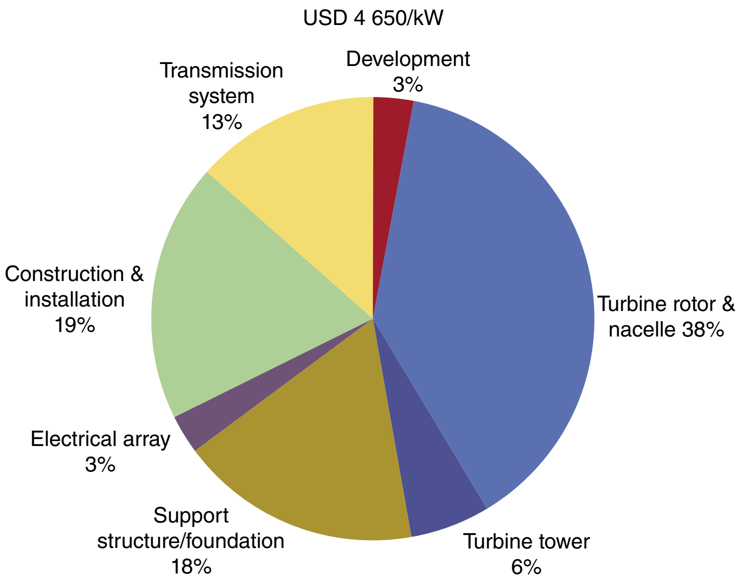

Figure 1.7 Distribution of investment expenditures for a 'representative' offshore wind farm. *Source:* IRENA (2016).

be offshore is not depicted but about 10% is indicated for a number of regions/countries. With the current trend providing continued reduced cost of energy from new offshore wind projects, this seems realistic. It requires though sustained strong efforts in developing market and technology.

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