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TECHNICAL REPORT

Wind energy generation systems – Part 12-4: Numerical site calibration for power performance testing of wind turbines

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 12-4: Numerical site calibration for power performance testing of wind turbines

FOREWORD

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IEC TR 61400-12-4, which is a Technical Report, has been prepared by IEC technical committee 88: Wind energy generation systems.

The text of this Technical Report is based on the following documents:

Draft TR	Report on voting
88/729/DTR	88/774/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 61400 series, under the general title *Wind energy generation systems*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

IEC 61400-12-1 [1][1] is the International Standard for power performance measurements for electricity producing wind turbines. It specifies that in complex terrain, a site calibration (SC) is required to find the relation in flow characteristics between the measurement location and the test turbine. This approach requires – in addition to the permanent measurement mast that is used to measure the turbine power curve – installing a temporary mast at the location of the turbine being tested, prior to the turbine installation. The IEC 61400-12-1 approach is frequently used in industrial practice; however, it has a number of disadvantages:

- additional cost of the second mast and analysis of the site calibration results,
- additional time required for the site calibration in the range of 3 months,
- a site calibration decision has to be made before installing the wind turbine.

Due to these disadvantages, there is interest in the industry to find alternative methods for site calibration. One alternative is to use numerical simulations to derive flow correction factors (FCFs), i.e., the relation between wind speed at the wind turbine position and wind speed at the reference meteorological mast position.

The IEC TC 88 committee, “Wind energy generation systems,” initiated the work on this document to evaluate the potential application of numerical flow simulations for site calibration, i.e., numerical site calibration (NSC).

With NSC, the flow correction factors are calculated using numerical simulation of the flow. Despite eliminating some of the disadvantages mentioned earlier, NSC brings other challenges:

- dependence on simulation models,
- dependence on the setup of these models,
- dependence on the modeler’s expertise,
- uncertainty quantification of the model performance.

The project team (PT 61400-12-4) has outlined the current state of the art in numerical flow modelling and has summarized existing guidelines and past benchmarking experience of numerical model validation and verification. Based on the work undertaken, the project team identified the important technical aspects for using flow simulations over terrain for wind energy applications as well as the existing open issues including recommendations for further validation through benchmarking tests. The project team concluded that further work is needed before a standard for NSC can be issued.

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[1] Numbers in square brackets refer to the Bibliography.

WIND ENERGY GENERATION SYSTEMS –

Part 12-4: Numerical site calibration for power performance testing of wind turbines

1 Scope

This part of IEC 61400, which is a Technical Report, summarizes the current state of the art in numerical flow modelling, existing guidelines and past benchmarking experience in numerical model validation and verification. Based on the work undertaken, the document identifies the important technical aspects for using flow simulation over terrain for wind application as well as the existing open issues including recommendations for further validation through benchmarking tests.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.2 Abbreviated terms

The following abbreviated terms are used in this document.

AIAA	American Institute of Aeronautics and Astronautics
ABL	atmospheric boundary layer
AEP	annual energy production
AIJ	Architectural Institute of Japan
ALEX17	Alaiz experiment 2017
ASME	American Society of Mechanical Engineers
CEDVAL	Compilation and Experimental Data for Validation of Microscale DispersionModels
CFD	computational fluid dynamics
CHT	computational heat transfer
COST	European Cooperation in Science and Technology
CREYAP	Comparative Resource and Energy Yield Assessment Procedures
DES	detached eddy simulation
DDES	delayed detached eddy simulation
DEWI	Deutsches Windenergie-Institut

DTU	Danish Technical University
EWEA	European Wind Energy Association
EWTL	Environmental Wind Tunnel Laboratory
FCF	flow correction factor
GWh	gigawatt-hour
IEA	International Energy Agency
IEC	International Electrotechnical Commission
LES	large eddy simulation
LIDAR	light detection and ranging
MEASNET	Measuring Network of Wind Energy Institutes
MEP	model evaluation protocol
NEWA	New European Wind Atlas
NSC	numerical site calibration
RANS	Reynolds-averaged Navier-Stokes
RNG	renormalization group
SC	site calibration
SODAR	sound detection and ranging
TC	technical committee
TR	technical report
UQ	uncertainty quantification
URANS	unsteady Reynolds-averaged Navier-Stokes
V&V	verification and validation
VDI	Verein Deutscher Ingenieure
WAsP	Wind Atlas Analysis and Application Program
WFIP	Wind Forecast Improvement Project
WTG	wind turbine generator

3.3 Symbols and units

Table 1 shows the symbols used in the text and equations in this document.

Table 1 – Symbols used in this document

Symbol	Definition	Unit
$\overline{u}_i$	i^{th} component of filtered wind speed	m/s
$\overline{p}$	filtered pressure	Pa
μ	molecular viscosity	Pa s
μ_t	turbulence viscosity	Pa s
C_s	Smagorinsky constant	-
κ	von Karman constant	-
d	distance to the nearest wall	m
Δ	local filter size	m
l	turbulence length scale	m

Symbol	Definition	Unit
l_{RANS}	turbulence length scale obtained from RANS model	m
l_{LES}	turbulence length scale obtained from LES model	m
f_{d}	model constant of DDES model	m
$\overline{U_i}$	average component of velocity in the direction i	m/s
u_i	turbulent component of velocity in the direction i	m/s
x_i	space variable in the direction i	m
$\overline{P}$	average pressure	Pa
ρ	density	kg/m^3
ν	kinematic molecular viscosity	m^2/s
$\overline{F_i}$	body forces in the direction i	kg m / s
$\overline{u_i u_j}$	Reynolds stresses	m^2/s^2
δ_{ij}	Kronecker’s delta	-
ν_T	kinematic turbulence viscosity	m^2/s
k	turbulence kinetic energy	m^2/s^2
L_T	turbulence length scale	m
P_k	production of k	m^2/s^3
ε	dissipation rate of turbulence kinetic energy	m^2/s^3
C_μ	RANS turbulence model constant	-
$C_{1\varepsilon}$	RANS turbulence model constant	-
$C_{2\varepsilon}$	RANS turbulence model constant	-
σ_ε	RANS turbulence model constant	-
E	validation comparison error	
δ_{model}	error due to the modelling assumptions	
δ_{num}	error due to numerical solution of the equations	
δ_{input}	error due to input parameters	
δ_{D}	error in the experimental values	
u_{val}	validation standard uncertainty	
u_{num}	numerical solution uncertainty	
u_{input}	input parameters uncertainty	
u_D	experimental value uncertainty	
r	correlation coefficient	-
γ_d	DDES parameter	-

Symbol	Definition	Unit
A_1	modified DDES constant / stepwise function	-
A_2	DDES constant	-
K_h	effective horizontal kinematic viscosity	m^2/s
K_v	effective vertical kinematic viscosity	m^2/s
$\tilde{u}_i$	velocity perturbation components in the direction i	m/s
$\tilde{p}$	pressure perturbation	Pa
U_j	horizontal velocity components of the unperturbed flow in the direction j	m/s
D	rotor diameter	m

4 Overview of numerical flow simulation approaches

4.1 Linear flow models

Since the late 1980s, when computing resources were limited, linear wind flow models have been the standard for wind resource assessment. These models are based on a linearization of the Navier-Stokes equations, which was originally introduced in reference [2]. They were designed to be used reliably in neutral atmospheric conditions over terrain with sufficiently gentle slopes to ensure fully attached flow conditions.

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0, \text{ for } i = 1,\ldots,3 \tag{1}$$

$$U_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{\partial}{\partial x_i}\frac{\tilde{p}}{\rho} + K_\mathrm{h}\frac{\partial}{\partial x_j}\left(\frac{\partial \tilde{u}_i}{\partial x_j}\right) + K_\mathrm{v}\frac{\partial^2 \tilde{u}_i}{\partial x_3^2}, \text{ for } i = 1,..,3 \text{ and } j = 1,2 \tag{2}$$

Here, $U_j\,(j=1,2)$ are the horizontal velocity components of the unperturbed flow, $\tilde{u}_i\,(i=1,\ldots,3)$ are the velocity perturbation components, and $\tilde{p}$ is the pressure perturbation. K_h and K_v are the effective kinematic viscosities in the horizontal and vertical directions.

Linear models perform reasonably well where the wind is not significantly affected by steep slopes, flow separation, thermally driven flows, low-level jets, and other dynamic and nonlinear ABL phenomena.

The Wind Atlas Analysis and Application Program (WAsP) [3] has been the most widely used amongst the linear models. WAsP procedures may be considered as a transfer function model linking the wind speeds at the reference with those at the predicted locations. Significant sources of error could be related to the terrain complexity, massive flow separation, wind direction changes, and varying atmospheric conditions. The latter include, among others, channeling effects, blocking effects, and thermally driven flows (e.g., diurnal sea breezes, downslope winds).

Due to their fast and robust performance, linear models are still used in the wind industry.

4.2 Reynolds-averaged Navier-Stokes (RANS) models

Due to the limitation of the linear models, as mentioned in 4.1, computational fluid dynamics (CFD) models became more widely used in the wind industry. CFD application to the atmospheric boundary layer (ABL) has been influenced by both CFD for mechanical engineering and mesoscale meteorological modelling. CFD considers momentum and mass conservation equations with four unknown variables: pressure and three velocity components. Other variables describing the atmospheric state, such as temperature, humidity, and aerosol concentration, are usually not considered.

Typical CFD for atmospheric flow simulation applications follow the single wind direction approach representing a sector from the discretized wind rose. Flow simulations for each sector, considering the effects of orography and roughness, result in speed-up factors.

In the Reynolds-averaged Navier-Stokes (RANS) approach [4], due to the turbulent nature of the flow, the variables are described with statistical functions divided into average and fluctuating (turbulent) components (e.g., $U_i = \overline{U_i} + u_i$ resulting in RANS equations:

$$\frac{\partial(\rho\overline{U_i})}{\partial x_i} = 0 \quad \text{and} \quad U_j\frac{\partial(\rho\overline{U_i})}{\partial x_j} = -\frac{\partial\overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\frac{\partial(\rho\overline{U_i})}{\partial x_j} - \rho\overline{u_i u_j}\right] + \overline{F_i} \quad \text{for } i,j = 1,..,3 \tag{3}$$

In the RANS equations, turbulent correlations $\overline{u_i u_j}$ (also called turbulent fluxes or stresses) have to be parameterized to close the equation system. The Boussinesq hypothesis is used to define the relation between turbulent fluxes and the gradients of mean values by introducing eddy viscosity (first-order closure):

$$-\overline{u_i u_j} = \nu_T\left[\frac{\partial\overline{U_i}}{\partial x_j} + \frac{\partial\overline{U_j}}{\partial x_i}\right] - \frac{2}{3}k\delta_{ij} \quad \text{for } i,j = 1,..,3 \tag{4}$$

Two basic quantities are introduced to describe the turbulence: the kinematic turbulence viscosity ν_T, and the turbulence kinetic energy, k. The kinematic turbulence viscosity depends on the turbulence kinetic energy, k, and the size of the turbulent eddies, L_T, as $\nu_T = k^{1/2}L_T$.

There are different types of closures, e.g., one- and two-equations models. In the one-equation model, the turbulence kinetic energy, k, equation is solved:

$$\overline{U_j}\frac{\partial k}{\partial x_j} = P_k - C_\mu\frac{k^2}{\nu_T} + \frac{\partial}{\partial x_j}\left[\left(\frac{\nu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \quad \text{for } j = 1,..,3 \tag{5}$$

where P_k is the production of k due to mean wind velocity gradients. The turbulence length scale, L_T, is deduced from an analytical model, such as a function of the height above the ground and sometimes the thermal stability [5].

In the two-equation models (k-ε, RNG k-ε, k-ω, ...), the closure is made through two transport equations, one for k and one for the turbulence dissipation, ε:

$$\overline{U_j}\frac{\partial k}{\partial x_j} = P_k - \varepsilon + \frac{\partial}{\partial x_j}\left[\left(\frac{\nu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \quad \text{for } j = 1,..,3 \tag{6}$$

$$\overline{U_j}\frac{\partial \varepsilon}{\partial x_j}=\frac{\varepsilon}{k}\left(C_{1\varepsilon}P_k - C_{2\varepsilon}\varepsilon\right)+\frac{\partial}{\partial x_j}\left[\left(\frac{\nu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] \text{ for } j=1,..,3 \tag{7}$$

The kinematic turbulence viscosity ν_T, is given by the closure equation $\nu_T = C_\mu \frac{k^2}{\varepsilon}$.

Without the steady-state hypothesis used in the RANS model, the equations of motion can be described with unsteady RANS (URANS).

Compared to the linear model, the RANS steady-state model is able to predict flow detachment and reattachments in the separation zone in most cases, but the accuracy of the results in this region is questionable. This limitation is inherent in the statistical nature of the model. The RANS model is mostly applied under the assumption of neutral stratification, which in many cases limits its applicability. There are solutions proposed for coping with the neutral stratification limitation assumption, for example, through modifications of the turbulence closure based on the Monin-Obukhov similarity theory [6] or by solving energy equations and adding a buoyancy term to the RANS equations [7]; however, additional validations are needed.

RANS models require significantly more computational resources than linear models. Presently, they are used for resource assessment and site suitability in complex sites, such as nonflat terrain, abrupt roughness changes, or forested areas.

4.3 Large eddy simulation (LES) and hybrid RANS/LES models

The idea of large eddy simulation (LES) [8] is to ignore small-scale turbulences by a low-pass filter and to only solve the turbulence that can be resolved by the grid. The governing equations for incompressible flow (using the Smagorinsky subgrid scale model [8]) can be written as follows:

$$\frac{\partial \rho \bar{u}_i}{\partial x_i}=0 \tag{8}$$

$$\frac{\partial\left(\rho\bar{u}_i\right)}{\partial t}+\frac{\partial\left(\rho\bar{u}_j\bar{u}_i\right)}{\partial x_j}=-\frac{\partial\bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\left(\mu+\mu_t\right)\left(\frac{\partial\bar{u}_i}{\partial x_j}+\frac{\partial\bar{u}_j}{\partial x_i}\right)\right] \tag{9}$$

$$\mu_t=\rho L_\mathrm{s}^2\left|\bar{S}\right| \tag{10}$$

$$L_s=C_s\Delta \tag{11}$$

$$\left|\bar{S}\right|=\sqrt{2\bar{S}_{ij}\bar{S}_{ij}} \tag{12}$$

$$\bar{S}_{ij}=\frac{1}{2}\left(\frac{\partial\bar{u}_i}{\partial x_j}+\frac{\partial\bar{u}_j}{\partial x_i}\right) \tag{13}$$

where $\bar{u}_i$ is the i component of the filtered wind velocity, C_s is the Smagorinsky constant, and Δ is the local filter size, $i,j=1,..,3$. Further information for other subgrid scale models can be found in reference [9].

Unlike RANS, LES does not solve transport equations for subgrid scale parameters, i.e., all eddies that characterize the flow have to be resolved. As a result, LES is highly dependent on grid resolution, and choice of the grid is critical. On the other hand, when the grid is fine enough, LES can resolve the unsteady flow separation that can typically be seen behind a hill or at the edge of a cliff, and a simulated flow field in such a flow separation region is closer to reality than RANS [10].

One major problem of LES, however, is the modelling of surface roughness. For example, for a low-roughness surface, LES requires very fine grids to resolve it, which is too computationally expensive for an engineering application.

Hybrid RANS/LES approaches have been proposed to overcome this problem. Detached eddy simulation (DES) [11] is one such approach. In DES, the transport equation of k and ε is solved, and the length scale, l,can be calculated by using the following equation:

$$l = \min\left(l_{\text{RANS}}, l_{\text{LES}}\right) \tag{14}$$

where

$$l_{\text{RANS}} = \frac{k^{\frac{3}{2}}}{\varepsilon} \tag{15}$$

$$l_{\text{LES}} = C_s \Delta \tag{16}$$

By using this approach, the RANS model is chosen near the boundary and LES is chosen in the region far from the boundary. However, Spalart et al. [12] mentioned that the DES model exhibits an incorrect behavior in the thick boundary layer and proposed a modification called delayed detached eddy simulation (DDES). In DDES, the length scale, l, can be calculated by using the following equation [13][14]:

$$l = l_{\text{RANS}} - f_d \max\left(0, l_{\text{RANS}} - l_{\text{LES}}\right) \tag{17}$$

where

$$f_d = 1 - \tanh\left[\left(A_1 \gamma_d\right)^{A_2}\right] \tag{18}$$

In reference [14], the authors proposed a piecewise function of A_1 instead of a constant to simulate the flow fields in the atmospheric boundary layer.

5 Existing guidelines for numerical flow modelling applications

5.1 General

Scientific communities, certification organizations, and national engineering associations have put together guidelines on verification and validation, quality assurance, and evaluation of numerical flow models. An overview of the most relevant guidelines to NSC is provided here.

5.2 AIAA (1998) *Guide for the Verification and Validation of Computational Fluid Dynamics Simulations*

The American Institute of Aeronautics and Astronautics (AIAA) guide [15] provides guidelines for benchmarking the performance of CFD models. It is a matter of performing as many verification and validation (V&V) tests as possible to gain confidence and credibility on the model results toward the specific intended use of the model. The high complexity of the models makes it very difficult to validate the full range of operating conditions. Hence, the main objective of the validation process is to develop and quantify enough confidence in the numerical models so that they can be used reliably to predict the variables of interest within acceptable limits.

The following elements should be considered for the V&V process:

- general description of the model including its intended uses or applications,
- description of the prognostic equations that the model solves,
- description of the hypotheses and approximations,
- description of the model parameterizations,
- atmospheric scales and spatial/temporal resolutions,
- description of the computational grid,
- boundary and initial conditions,
- input data and sources,
- output data in terms of prognostic and diagnostic (derived from prognostic) variables,
- references to published material addressing model evaluation results from this and other similar models.

5.3 *Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer* – ASME V&V 20-2009

The American Society of Mechanical Engineers (ASME) standard [16] describes the method for V&V in computational fluid dynamics and computational heat transfer (CHT). The idea of this document is that the comparison error, E , between the measured and simulated value can be written by using an error due to the modelling assumptions, δ_{model} , an error due to the numerical solutions, δ_{num} , an error due to simulation input parameters, δ_{input} , and the error in the experimental values, δ_D, as shown in the following equation:

$$E = \delta_{\text{model}} + \delta_{\text{num}} + \delta_{\text{input}} - \delta_D \tag{19}$$

Assuming that δ_{num}, δ_{input} and δ_D are independent, the uncertainty due to these terms (u_{val}) can be written as:

$$u_{\text{val}} = \sqrt{{u_{\text{num}}}^2 + {u_{\text{input}}}^2 + {u_D}^2} \tag{20}$$

where u_{num} is the uncertainty due to numerical solutions (i.e., the standard deviation of δ_{num}), etc.

The purpose of this document is to propose methods to quantify the uncertainty of the modelling assumptions and interpretation of this value. Thus, the content of the document is as follows:

- Uncertainty due to numerical solutions can be quantified by using code verification and solution verification. The code verification can be performed by comparing the numerical solution with analytical solutions. The solution verification can be performed by systematic grid refinement.
- Uncertainty due to simulation input can be estimated by using systematic sensitivity analysis of the input parameters.
- The basic concept to determine the uncertainty in the experimental values.
- The method to quantify uncertainty due to modelling assumptions is described for different cases.
- The interpretation of uncertainty due to modelling assumptions.
- An example of V&V.

5.4 COST Action 732 "Quality Assurance of Microscale Meteorological Models"

European Cooperation in Science and Technology (COST) action 732 "Quality Assurance of Microscale Meteorological Models" [17] has been set up to improve and assure the quality of microscale meteorological models that are applied for predicting wind flow in urban environments. These best practices are based on previous guidelines devoted to steady RANS equations for neutrally stratified flow fields.

General guidelines are developed to reduce errors and uncertainties in modelling the physics and in numerical approaches. Uncertainties in modelling can be related to:

- target variables,
- approximate equations describing the physics of the flow, such as the turbulence models,
- the geometrical representation of the obstacles,
- the definition of the computational domain including the boundary and initial conditions.

Uncertainties in the numerical approach can be related to:

- computational grid,
- time step size,
- numerical approximations (discretization schemes),
- iterative convergence criteria.

The COST action 732 guideline remains general for most of the criteria and encourages engineers to use best practices to reduce errors. Most parameters depend, to a large extent, on the details of the application problem and cannot always be precise in the general guidelines. For instance, no best practice for the choice of the turbulence models is given. Nevertheless, for some parameters, such as the choice of the computational domain, the guideline gives precise recommendations: domain size should be defined as a function of the urban size model, especially the height of the urban canopy. The guideline also gives clear advice on spatial and time discretization, as well as convergence criteria, to reduce numerical errors.

The guideline encourages the application of numerical sensitivity tests and validation of the model performance on test cases available in the literature.

5.5 Architectural Institute of Japan guidelines

5.5.1 General

Two guidelines for CFD applications were proposed by the Architectural Institute of Japan (AIJ). One is *The guidebook for practical applications of CFD to pedestrian wind environment around buildings* [18] and the other is the *Guidebook of recommendations for loads on buildings 2* [19]. Both guidelines contain the best practice for setting the computational conditions and benchmark procedure. The computational conditions are as follows:

- computational domain extension,
- grid generation and resolution,
- boundary conditions,
- numerical scheme,
- turbulence model,
- convergence of solution.

5.5.2 *The guidebook for practical applications of CFD to pedestrian wind environment around buildings* [18]

This guideline summarizes important points for using the CFD technique for appropriate prediction of the pedestrian wind environment. The variables of interest are mean wind speed ratio and turbulence kinetic energy. The guideline is based on the results of benchmark tests, such as flow around a single building and blocks of buildings, and buildings in an actual urban area and tree canopy. The validation database is available on the AIJ web site [21].

5.5.3 *Guidebook of recommendations for loads on buildings 2* [19]

This document provides a practical guide for predicting the design wind loads on a building, including the effect of terrain using CFD based on reference [20]. According to this guideline, CFD can be used as an alternative to a wind tunnel test. The variables of interest are peak pressure coefficient as well as mean wind speed and turbulence kinetic energy. In this guideline, LES is a recommended technique to predict peak wind loads during strong wind events due to the reproducibility of the turbulent boundary layer and separation flow around the buildings requirement. This guide shows requirements for model setup, accuracy verification and validation, and wind loads design.

5.6 VDI 3783 Part 9 *Environmental meteorology – prognostic microscale wind field mode- evaluation of flow around buildings and obstacles*

Verein Deutscher Ingenieure (VDI, German Engineers Association) guidelines describe the state of the art in science and technology in the Federal Republic of Germany and serve as a decision-making aid in the preparatory stages of legislation and application of legal regulations and ordinances.

The purpose of guideline VDI 3783 Part 9 [22] is to evaluate microscale CFD wind field models over terrain that explicitly resolve the flow field around obstacles in the near-ground ABL. The purpose of the evaluation procedure given in this VDI guideline is to ensure a high-level quality of the models. The guideline contains recommendations on convergence criteria and grid resolution independence. It also provides test cases (including analytic and experimental reference data) to validate model consistency. The experimental reference data originate from the CEDVAL database by the Environmental Wind Tunnel Laboratory (EWTL), Meteorological Institute of University of Hamburg [23]. These data were designed and are suitable for the evaluation of RANS models. Due to the lack of detailed inflow conditions, they are not applicable for LES model validation. Validation metrics and passing criteria are provided in the VDI guideline.

5.7 International Energy Agency Task 31 Wakebench – *Model Evaluation Protocol for Wind Farm Flow Models*

A model evaluation protocol (MEP) for wind farm flow models has been developed in the frame of the International Energy Agency (IEA) Wind Task 31 “Wakebench” [24]. The protocol addresses a V&V framework for wind farm flow models at the microscale level, typically used in wind resource/site assessment and wind farm design applications.

The MEP is developed as a basis for a framework for activities related to V&V of wind flow models. The MEP consists of:

- model qualification by scientific review,
- code and solution verification,
- validation, which includes:
  - a building-block validation approach,
  - validation data requirements and sources,
  - variables of interest,
  - setting up and running a model,
  - metrics,
  - quality acceptance criteria,
- model calibration.

5.8 MEASNET – *Evaluation of site-specific wind conditions*

Measuring Network of Wind Energy Institutes (MEASNET) is a co-operation of companies that are engaged in the field of wind energy and want to ensure high-quality measurements, uniform interpretation of standards and recommendations, and interchangeability of results. The MEASNET document *Evaluation of site specific wind conditions* [25] outlines the procedure for site assessment agreed upon between the MEASNET members. The document describes topics from required input data to results reporting. The most relevant part for NSC is the spatial extrapolation guidance that requires numerical modelling of the wind field. MEASNET provides general recommendations on model verification, model assumptions, model validation, and sensitivity analysis. MEASNET also recognizes that the uncertainties of flow modelling will both depend on the topography and site meteorological complexity (vertical and horizontal distance between the measured and extrapolated position, terrain roughness, stability conditions, and the used model approximations).

6 Summary of benchmarking validation tests

6.1 General

Clause 6 provides a summary of comparison tests from wind flow modelling validation campaigns. Some of the projects have been completed and some are ongoing at the time of writing.

6.2 DEWI *Round Robin on Numerical Flow Simulation in Wind Energy*

This blind test was commenced in 2004 and finished in 2008 [26]. Numerical models at that time were already widely used in wind energy analysis to extrapolate the wind conditions from a point where wind conditions are measured to other points of a wind farm where wind conditions are unknown. The aim of the round robin test was to systematically evaluate the capabilities of the considered models of extrapolating wind measurements horizontally and vertically. Therefore, the participants were given topographical data and requested to perform a simulation that takes as input wind measurements at one reference point in order to calculate wind conditions for two other target points for which wind measurements were available but unknown to the participants.

There were eight participants using various numerical models (e.g., mesoscale simulations, RANS, and LES), with no participants using the same model. The predicted results were compared to the measured data at these two locations. Input height was 43 m and outputs were requested at up to 80 m.

The average of sector-wise absolute values of mean wind speed error was between 5 % and 18 %. However, the individual sector deviations were larger than this. The absolute mean energy yield error was between 1 % and 36 %.

6.3 Bolund experiment

The Bolund Hill blind test was organized by the Danish Technical University (DTU) in 2009 and focused on flow modelling [27], [28]. A small island (12 m high, 130 m long, and 75 m wide) near Roskilde, Denmark, had an extensive wind measurement campaign at 2 m, 5 m, and 9 m above ground level. Participants were provided with all input data required for a flow simulation of the site and had to provide results at specific points reflecting the measurement points. It should be noted that the steepness of the hill and the abrupt roughness change in that experiment violated the linear model assumptions.

Four wind directions were defined and 57 models ranging from numerical to physical were used, including LES models, RANS models, and linear models, in addition to wind tunnel and water channel experiments. All participants were obliged to return their results at 600 positions.

In this particular test, the RANS methods with two-equation turbulence closures gave the most consistent results. The best-performing model showed mean errors for all cases of 10,2 % (test case 1 to 4: 9,6 %, 10,6 %, 13,8 %, and 7,0 %, respectively) on speed-up factor. For the wind direction with the most moderate slope (test case 4), the smallest error occurred. The importance of having experienced modellers using well-founded numerical approaches was underlined in the project’s final report.

6.4 European Wind Energy Association *Comparative Resource and Energy Yield Assessment Procedures* I and II (2011, 2013)

The Comparative Resource and Energy Yield Assessment Procedures (CREYAP) Part I [29] test was conducted by DTU and results were presented at the European Wind Energy Association (EWEA) Wind Resource Assessment Technology Workshop 2011, with 37 sets of results submitted by 36 organizations from 16 countries. The test was carried out on a 28MW wind farm (14 wind turbine generators) with 1 meteorological (met) mast. It included a wind farm case study comprising:

- wind farm and turbine data,
- wind climatological inputs,
- topographical inputs.

A comparison of model results was done on:

- long-term corrected wind speeds at 50 m and 60 m,
- vertical extrapolation (wind shear),
- cross energy yield,
- potential energy yield,
- net energy yield P50 and P90.

The reported wind shear results were in the range of 0,015 to 0,237 (standard deviation 0,037 – variation coefficient 22 %) and the gross energy yield of the wind farm was in the range of 113 GWh to 127 GWh (standard deviation 3,5 GWh – variation coefficient 3 5 %) amongst the 37 sets.

The CREYAP Part II [30] test was conducted by DTU and results were presented in 2013 at the EWEA workshop. There were 60 teams from 17 countries including consulting firms, wind park developers, and academia. The test was carried out on a 28,6 MW wind farm (22 wind turbine generators) with 7 met masts.

The round robin test highlighted the spread of the numerical results during the prediction process of annual energy production. Comparisons were made at each step of the annual energy production estimation process including:

- long-term correction,
- vertical extrapolation (wind shear),
- flow and wake models,
- technical loss estimates,
- uncertainty quantifications.

The reported wind shear results were in the range of 0,105 to 0,179 (standard deviation 0,013 – variation coefficient 10 %) and the gross energy yield of the wind farm was in the range of 79,3 GWh to 106 GWh (standard deviation 5,7 GWh – variation coefficient 5,8 %) amongst the 60 sets.

6.5 IEA Task 31 Wakebench experiments

Wakebench [31] test cases are selected based on similarity theory for the ABL and wind turbine wake flows, wind tunnel and field research experiments, and operational measurement campaigns from the wind industry. The cases include canonical benchmarks (e.g., the infinite wind farm), both on land and offshore (e.g., Alaiz, Lillgrund), flat to very complex terrain (e.g., Sexbierum, San Gregorio), and neutral to stratified ABL (e.g., Askervein, Leipzig). Results can be found online in reference [31].

6.6 New European Wind Atlas experiments [32]

6.6.1 Perdigão (double ridge)

One of the New European Wind Atlas (NEWA) experiments is taking place in Portugal near Perdigão around two steep, parallel ridges. The experiment started in the fall of 2016 and the main campaign began in the spring of 2017. More than 50 met masts with heights ranging from 10 m to 100 m and 19 scanning light detection and ranging (LIDAR) instruments were used to measure the flow in this area. A variety of instruments including sonic anemometers, Doppler LIDARs, a profiling humidity LIDAR, a radar Doppler profiler, radiosondes, pressure sensors, and tethered balloons were used.

6.6.2 Alaiz (complex terrain with a strong mesoscale component)

An open-access experiment, ALEX17, was planned to commence in July 2018. This experiment consists of five long-range wind scanners, six 80 m met masts, one LIDAR, one sound detection and ranging (SODAR) device, and ten meteorological stations in Navarra, Spain. The objective is to characterize the flow in the valley stretching around 6 km between the Alaiz mountain range and an upstream ridge, which influences the wind conditions at the test site and operational wind farms downstream.

6.6.3 Østerild (flow over heterogeneous roughness)

This experiment studies how varying surface roughness (alternating fields and forests) affects the wind resources at hub height over an otherwise almost completely flat terrain. Two mast-mounted horizontally scanning Doppler LIDARs with a range of 5 km are currently measuring at the experiment site in Østerild, Denmark.

6.6.4 Kassel (flow over forested hill)

Twelve long-range scanning Doppler LIDARs measured winds over a forested hill near Kassel, Germany, starting in August 2016. In conjunction with a 200 m and 140 m met mast, they mapped the flow in a terrain type where underestimation of wind resources is not uncommon.

References to preliminary results from all NEWA experiments can be found on the project website [33].

6.7 Wind Forecast Improvement Project 2 [34]

The Wind Forecast Improvement Project 2 (WFIP2) has as primary goal to improve model forecasts of wind speeds in complex terrain. In support of WFIP2's goals, participants have conducted a field campaign in the eastern Washington and Oregon Columbia Basin to assess how physical *processes* over a broad range of spatial scales alter wind speeds across the rotor diameter. The overall design for WFIP2 focuses on a set of weather phenomena that poses particular challenges for wind and wind power forecasting in the complex terrain of the Columbia Gorge. A large, diverse suite of meteorological observing instrumentation has been deployed for WFIP2, including wind profiling radars, SODARs, profiling and scanning LIDARs, microwave radiometers, microbarographs, sonic anemometers, and surface energy balance systems. WFIP2 represents a partnership of industry, academia, and federal laboratories.

6.8 Wind tunnel test validation data

6.8.1 Compilation of Experimental Data for Validation of Microscale Dispersion Models [23]

Compilation of Experimental Data for Validation of Microscale Dispersion Models (CEDVAL) includes wind tunnel data sets that can be used for validation of numerical flow models. All data sets within CEDVAL follow a high-quality standard in terms of complete documentation of boundary conditions and quality assurance during measurements. These data are used for V&V procedures in the guideline described in 5.6.

6.8.2 AIJ wind tunnel

Cross comparisons of wind tunnel experiments, field measurements, and CFD results of flow around a single high-rise building placed within the surface boundary layer, flow within a building complex in an actual urban area, and flow around a tree, are obtained from various k-ε models and LES [35]. These data are used for the guidelines in 5.5.

6.8.3 Wind tunnel test for flow over hill

Wind flow over a simple two-dimensional ridge and three-dimensional hill was assessed in a boundary layer wind tunnel with the scale of 1/1 000. Two different surface roughness values were tested: a coarse roughness with z_0 = 0,3 mm and a smooth one with z_0 = 0,01 mm. The mean and fluctuating components of inflow at the points over the terrain were recorded [36]. Validation of RANS, URANS, LES, DES and modified DDES models was performed by using this wind tunnel test data [14]. For the rough surface case, it was shown that on the lee side of the hill, all the models exhibited good agreement with the measurements. For the smooth surface case, RANS and URANS overestimated the speed-up factors; among LES, DES and modified DDES, the latter shows the best performance at the lee side.

7 Important technical aspects for performing flow simulations over terrain for wind energy applications

7.1 General

Clause 7 describes the important technical aspects for setting up, running, and extracting data from flow simulations over terrain. In the context of NSC, it is important to set the measurement mast position according to IEC 61400-12-1 [1] recommendations.

7.2 Quality of topographical input data

Using high-quality topographical (orography and roughness) data to set up a numerical model is a key element in allowing the model to calculate the most accurate wind conditions and gaining high model performance. Using orography data with a horizontal resolution of 10 m or finer around the points of interest is strongly recommended. At longer distances, coarser resolution of elevation information will be sufficient (but no more than a 30 m horizontal resolution).

Moreover, a detailed roughness map should be created and validated, particularly in the sensitive areas with high roughness surface values (e.g., forested areas).

7.3 Computational domain

Extensions of the domain in the horizontal and vertical direction should ensure that the flow field in the area of interest is not affected. Therefore, it is recommended to perform a sensitivity study for domain extension size for each particular site. Using a smooth buffer zone at the terrain perimeter is a recommended best practice to improve simulation convergence.

7.4 Boundary conditions for computational domain

Surface boundary conditions should be checked to correctly represent the roughness of the terrain. This check can take place by site images or visiting the site. All other boundary conditions should be prescribed so that the flow field in the area of interest is not significantly affected.

7.5 Mesh parameters

A sensitivity study on horizontal and vertical mesh resolution, first cell size, and vertical expansion ratio should be performed to make sure that the flow field in the area of interest is not significantly affected by changing the mesh.

7.6 Convergence criteria

Convergence criteria should ensure that the flow field in the area of interest is not affected.

7.7 Atmospheric stability

Atmospheric stability is often ignored because of the assumption of neutral conditions during strong wind events, but for NSC lower wind speed conditions are important hence stability should be considered. Proper modelling of stability of the ABL is still under development in the research community and several approaches exist. One approach is through modification of the RANS turbulence closure to account for changes in turbulence fluxes in different stability conditions [6]. Another known approach is through adding a buoyancy term to the Navier-Stokes equations and solving an energy equation (Boussinesq approximation) [37].

7.8 Coriolis effects

With modern turbines reaching hub heights well above 100 m, Coriolis force effects can be observed to cause wind direction changes (Ekman spiral) over the rotor height, especially during stable atmospheric conditions. It is recommended that Coriolis force effects be included in the model.

7.9 Obstacles effects

In this document, obstacles are considered obstructions that block the wind and create distortion of the flow. Flow around obstacles can be resolved through meshing and imposing proper boundary conditions to the obstacle surface. Another way of modelling the flow around obstacles is through parametrization of obstacle effects. In the latter approach, canopy models are widely used for representing the effect of obstacles on the flow. With sufficient validation, canopy models can be used to model forest effects [7], [38], [39], and [40].

7.10 Suggestion on model range applicability for NSC

By nature, linear models have more limitations than nonlinear models when terrain slopes above 10 % are present. The use of linear models in such conditions may introduce additional uncertainty in the NSC results [41].

RANS models have higher potential than linear models for predicting speed-up factors on terrain slopes higher than 10 %. However, wind tunnel validations show that RANS models could also miscalculate wind flow downstream of hills and obstacles. The use of RANS models in such conditions may introduce additional uncertainty in the NSC results [42].

LES and hybrid RANS/LES models have the highest potential in terms of resolving the flow field over complex terrain. Compared to RANS, these models exhibit significantly higher sensitivity to input parameters (e.g., grid resolution, as pointed out by a benchmarking test [43]).

Higher model fidelity requires higher expertise and higher computational power.

NSC on sites with predominantly stable conditions would require the flow model to consider the stratification of the ABL [37].

8 Open issues

8.1 General

The site calibration, as described by IEC 61400-12-1, suggests the use of two instrumented met masts: the permanent met mast and the temporary met mast at the turbine position. Upon completion of the site calibration, the wind speed transfer function and the associated uncertainty is specified, the temporary met mast is removed, and the turbine is installed to commence the power performance validation measurements.

During performance validation in complex terrain, the NSC is envisaged to avoid using a temporary met mast to produce the wind speed transfer function. The combination of the permanent met mast with the numerical simulation results will produce the wind speed at the turbine location. In Clause 8, the potential drawbacks of using the existing methodologies for numerical flow modelling and their application for NSC are presented. A benchmarking validation campaign is suggested to support breaching the existing gaps prior to future applications.

8.2 Determination of flow correction factors from numerical simulation results for power curve testing

8.2.1 General

The site calibration (SC) procedure is a normative part of IEC 61400-12-1. This document describes how to calculate the SC results and also when the results are considered as valid for power performance testing purposes. It is suggested that NSC considers the data quality checks specified in IEC 61400-12-1.

A key result of an SC test is a table of flow correction factors (FCFs) for all wind directions in the measurement sector. For each 10° wind direction bin, an ordinary least squares linear regression will be made with the turbine location wind speed as the dependent variable and the reference wind speed as the independent variable. If wind shear has a significant influence, the method of bins of wind direction and wind shear will be applied. The test may provide information that justifies a change to the allowable measurement sector. IEC 61400-12-1:2017, Annex C, introduces quality check procedures that can trigger exclusion of wind sectors, measurement data, or an increase of uncertainty. The main quality checks are described below.

8.2.2 Correlation check for linear regression

For each wind direction bin, the level of correlation should be assessed based on the correlation coefficient of the regression, commonly known as the r value. Through the K-fold analysis, IEC 61400-12-1, the uncertainty values are adapted according to the quality check results.

8.2.3 Change in correction between adjacent wind direction bins

It is recommended to eliminate wind direction bins from the measurement sectors when flow corrections change by more than 2 % between neighboring bins.

8.2.4 Site calibration and power performance measurements in different seasons

Seasonal changes in wind conditions and changes in surface roughness due to vegetation, precipitation (snow and ice), and freezing of bodies of water may cause a seasonal dependency on the site calibration flow corrections. Therefore, it is recommended to conduct the site calibration and power performance measurements during the same season of the year (e.g., both occurring in summer).

Similar procedures for defining the valid sectors to be used for NSC (for the purpose of power curve validation) will be investigated further. Based on the results of the NSC benchmarking validation case proposed in 8.4, detailed procedures for NSC could be established. Procedures related to uncertainty quantification are discussed in 8.3.

8.3 Uncertainty quantification

Uncertainty quantification for site calibration is defined in IEC 61400-12-1:2017, Clause C.6. For calculating uncertainty quantification for NSC, another approach should be developed to determine an uncertainty number associated with the flow correction factor for each valid sector. This new approach should consider the uncertainties due to measurements along with the following other sources of uncertainties:

- parameters associated with initial and boundary conditions, environmental conditions, forcing functions, and constitutive equations of the numerical model used,
- lack of linear or nonlinear equation solver convergence and the lack of grid convergence.

The methodology to estimate model uncertainty due to parameter and grid convergence uncertainty is provided in references [15], [44], and [45].

8.4 Proposal for validation campaign for nsc procedures

8.4.1 General

The intention of 8.4 is to address missing measurement campaigns related to NSC procedure validation. The use of the NSC as a replacement of measurements has not been validated and verified against measurements. Therefore, a validation test is suggested, wherein the NSC results are compared against the results of a site calibration using two met masts as defined in IEC 61400-12-1.

The proposed site and experimental layout for such a test is described below.

8.4.2 Assessment of terrain at the test site

IEC 61400-12-1:2017, Table B.1, describes the criteria (in terms of terrain slope and maximum terrain variation from the plane as a function of the distance between the turbine and the wind measurement equipment), when a site calibration shall be performed. Sites with different degrees of complexity exceeding the criteria in IEC 61400-12-1:2017, Table B.1, should be investigated.

8.4.3 Experimental layout

Existing experimental site calibration data could be used to validate the NSC procedures but a more detailed experimental setup is recommended to validate all numerical model aspects and should include the following:

- Two met masts in complex terrain should be at a distance that corresponds to 2,5D of a modern turbine (e.g., if D = rotor diameter, assumed 130 m then 2,5D = 325 m).
- The height of the top anemometer should be equal to the expected hub height of the turbines (e.g., 100 m hub height).
- The installation of the measurement equipment should fulfill the criteria of the IEC 61400-12-1 recommendations.
- The met masts alignment should be in the prevailing wind direction.
- All measurements should be taken in the same time period.
- Instrumentation for each met mast should include at least the following:
  - The top and reference anemometers should be the same make and type installed according to IEC 61400-12-1.
  - Wind vanes should be installed according to IEC 61400-12-1.
  - Anemometers at two additional locations (same make and type) – lower tip height and the middle between lower tip and hub height – should be installed to estimate wind shear.
  - Sonic anemometers should be mounted between 5 m and 10 m from the hub height and at a lower tip height to evaluate the three-dimensional flow effects and atmospheric stability.
  - Another three-dimensional sonic anemometer should be placed 3 m above the ground, to obtain heat fluxes with a rate of at least 10 Hz.
  - Differential temperature sensors should be placed at reference anemometer height and lower tip height to be able to verify atmospheric stability.
  - A humidity sensor should be placed 3 m above the ground.
  - The test duration of the measurement should be aligned with the time required by IEC 61400-12-1 to collect a minimum amount of data; however, it is suggested that the test duration allows the collection of significantly higher data amounts to allow for more detailed evaluations (e.g., day-night, seasonal variations, stability variations), which is twice the time requirements in the IEC 61400-12-1.
  - Data filtering should be applied using the same conditions as IEC 61400-12-1 performance measurements.

- A minimum continuous 60° measurement sector is recommended.
- A precipitation sensor is recommended to be able to filter out and separately analyze data in precipitation periods.
- Time series data with a minimum frequency as recommended in IEC 61400-12-1 should be collected and stored in the original sampling frequency.

Bibliography

[1] IEC 61400-12-1:2017 *Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines*

[2] JACKSON, P. S. and HUNT, J. C. R., Turbulent Wind Flow over a Low Hill, *Quart. J. R. Met. Soc.*, 101, 929-955, 1975

[3] TROEN, I., A High Resolution Spectral Model for Flow in Complex Terrain, *Proc. 9th Symposium on Turbulence and Diffusion*, Roskilde, Denmark, 1990

[4] WILCOX, D. C., Turbulence modelling for CFD, DCW Industries Inc., 1993

[5] HURLEY, S. P. J., An evaluation of several turbulence schemes for the prediction of mean and turbulent fields in complex terrain, *Boundary Layer Meteorology*, 83(1) 43-73, 1997

[6] LI, R. and DELAUNAY, D., A new Turbulence Model for the Stable Boundary Layer with application to CFD in Wind Resource Assessment, *Proc. EWEA 2015*, 2015

[7] SOGACHEV, A., KELLY, M. and LECLERC, M. Y., Consistent Two-Equation Closure Modelling for Atmospheric Research: Buoyancy and Vegetation Implementations, *Boundary-Layer Meteorology*. 145(2) 307-327, 2012

[8] SMAGORINSKY, J., General Circulation Experiments with the Primitive Equations, *Monthly Weather Review*, 91 (3), 99–164, 1963

[9] SAGAUT, P., Large Eddy Simulation for Incompressible Flows, ISBN 978-3-540-26403-3, Springer, 2006

[10] BECHMANN, A., SØRENSEN, N. N. and Johansen, J., Atmospheric flow over terrain using hybrid RANS/LES., *Proc. EWEA2007*, Milan, 2007

[11] SPALART, P. R., Comments on the feasibility of LES for wing and on a hybrid RANS/LES approach. *1st ASOSR CONFERENCE on DNS/LES*. Arlington, 1997

[12] SPALART, P. R., DECK, S. and SHUR, M. L., SQUIRES, K. D., STRELETS, M. Kh. and TRAVIN, A., A new version of detached-eddy simulation, resistant to ambiguous grid densities, *Theoretical and computational fluid dynamics* 20(3) 181-195, 2006

[13] GRITSKEVICH, M. S., GARBARUK, A. V., SCHÜTZE, J. and MENTER, F. R., Development of DDES and IDDES formulations for the k-ω shear stress transport model, *Flow, Turbulence and Combustion* 88(3), 431–449, 2012

[14] ISHIHARA, T. and QI, Y. H., Numerical study of turbulent flow fields over steep terrains by using a modified delayed detached eddy simulations, *Boundary-Layer Meteorology* pp.1-24, https://doi.org/10.1007/s10546-018-0389-8, 2018

[15] AIAA Guide for the Verification and Validation of Computational Fluid Dynamics Simulations. American Institute of Aeronautics and Astronautics, AIAA-G-077-1998, 1998

[16] ASME V&V 20-2009 Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer, The American Society of Mechanical Engineers, 2009

[17] FRANKE, J., HELLSTEN, A., SCHLÜNZEN, H. and CARISSIMO, B. ed., Best practice guideline for the CFD simulation of flows in the urban environment – Quality Assurance of Microscale Meteorological Models, COST Action 732, 2007

[18] The guidebook for practical applications of CFD to pedestrian wind environment around buildings (in Japanese), ISBN 978-4818926653, Architectural Institute of Japan, 2007

[19] Guidebook of recommendations for loads on buildings 2 – Wind-induced response and load estimation/Practical guide of CFD for wind resistant design (in Japanese), ISBN978-4818906389, Architectural Institute of Japan, 2017

[20] AIJ recommendations for loads on buildings (in Japanese), ISBN978-4-8189-0626-6, 2015

[21] AIJ Benchmarks for Validation of CFD Simulations Applied to Pedestrian Wind Environment around Buildings, http://www.aij.or.jp/eng/publish/index_ddonly.htm, Accessed on 13 September 2018

[22] VDI 3783 Blatt 9:2017-05, Environmental meteorology – Prognostic microscale wind field models – Evaluation for flow around buildings and obstacles, Verein Deutscher Ingenieure, 2017

[23] Data sets, CEDVAL at Hamburg University, http://mi-pub.cen.uni-hamburg.de/index.php?id=432, Accessed 13 September 2018

[24] JAVIER, S. R. and MORIARTY, P. ed., WAKEBENCH Model Evaluation Protocol for Wind Farm Flow Models, First Edition, IEA-Wind Task 31, 2015

[25] Evaluation of site-specific wind conditions version 2, *MEASNET*, 2016

[26] DURANTE, F., RIEDEL, V., BUNSE, U., BUSCHE, P., MELLINGHOFF, H., MONNICH, K. and SCHORER, T. ed., Round Robin Numerical Flow Simulation in Wind Energy, Final Report, DEWI GmbH-Deutsches Windenrgie-institut, 2008

[27] BERG, J., COURTNEY, M. S., JØRGENSEN, H. E., MANN, J. and SØRENSEN, N. N., The Bolund Experiment: Overview and Background, Risø-R-1658(EN), 2009

[28] BECHMANN, A., SØRENSEN, N. N., BERG, J., MANN, J. and RÉTHORÉ, P. E., The Bolund Experiment, Part II: Blind Comparison of Microscale Flow Models, *Boundary-Layer Meteorol.*,141, 245–271, 2011

[29] MORTENSEN, N. G. and JØRGENSEN, H. E., Comparison of Resource and Energy Yield Assessment Procedures, *EWEA Wind Resource Assessment Technology Workshop*, 2011

[30] MORTENSEN, N. G. and JØRGENSEN, H. E., Comparative Resource and Energy Yield Assessment Procedures (CREYAP) Pt. II, *EWEA Technology Workshop: Resource Assessment*, Dublin, 2013

[31] IEA-Wind Task 31 WAKEBENCH, http://windbench.net/wakebench, Accessed on 13 September 2018

[32] MANN, J., ANGELOU, N., ARNQVIST, J., CALLIES, D., CANTERO, E., CHÁVEZ ARROYO, R., COURTNEY, M., CUXART, J., DELLWIK, E., GOTTSCHALL, J., IVANELL, S., KÜHN, P., LEA, G., MATOS, J. C., VEIGA RODRIGUES, C., PALMA, J. M. L. M., PAUSCHER, L., PEÑA, A., SANZ RODRIGO, J., SÖDERBERG, S., VASILJEVIC, N., Complex terrain experiments in the New European Wind Atlas. *Phil. Trans. R. Soc. A*, 20160101, doi: 10.1098/rsta.2016.0101, 2017

[33] New European Wind Atlas, http://www.neweuropeanwindatlas.eu/, Accessed on 13 September 2018

[34] WFIP2 Wind Forecast Improvement Project 2, Atmosphere to Electrons, US Department of Energy, https://a2e.energy.gov/projects/wfip2, Accessed on 13 September 2018

[35] Architectural Institute of Japan, Guidebook for Practical Applications of CFD to Pedestrian Wind Environment around Buildings, http://www.aij.or.jp/jpn/publish/cfdguide/index_e.htm, Accessed on 13 September 2018

[36] ISHIHARA, T., FUJINO, Y. and HIBI, K., A wind tunnel study of separated flow over a two-dimensional ridge and a circular hill, Journal of Wind Engineering, 89: 573-576, 2001

[37] ALINOT, C. and MASSON, C., Aerodynamic simulations of wind turbines operating in atmospheric boundary layer with various thermal stratifications, *ASME Wind Energy Symposium*, Reno, U.S.A., 2002

[38] QI, Y. H. and ISHIHARA, T., Numerical study of turbulent flow fields around of a row of trees and an isolated building by using modified k-ε model and LES model, *J. of Wind Engineering and Industrial Aerodynamics*, 177:293-305, 2018

[39] SOGACHEV, A. and PANFEROV, O., Modification of two-equation models to account for plant drag, *Boundary-Layer Meteorology*, 121, 229–266, 2006

[40] CHÁVEZ ARROYO, R., SANZ RODRIGO, J. and GANKARSKI, P., Modelling of atmospheric boundary-layer flow in complex terrain with different forest parametrizations, *Journal of Physics: Conference Series* 524, 2014

[41] YAMAGUCHI, A., ISHIHARA, T. and FUZINO, Y., Applicability of linear and nonlinear wind prediction models to wind flow in complex terrain, *Proc. World Wind Energy Conference and Exhibition*, Berlin, Germany, 2002

[42] BECHMANN, A., SØRENSEN, N. and JOHANSEN, J., Atmospheric Flow over Terrain using Hybrid RANS/LES, *Proc. European Wind Energy Conference and Exhibition*, 2007

[43] HEFNY, M. M. and OOKA, R., Influence of cell geometry and mesh resolution on large eddy simulation predictions of flow around a single building, *Building Simulation*,1(3), 251–260, 2008

[44] OBERKAMPF, W. L. and ROY, C. J., Verification and Validation in Scientific Computing, *Cambridge University Press*, 2010

[45] ROACHE, P. J., Fundamentals of Verification and Validation, *Hermosa Publishers*, 2010

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