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Coupled on-site measurement/CFD based approach for high-resolution wind resource assessment over complex terrains

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ABSTRACT

Wind resource assessment is essential for development of wind energy, particularly in the regions with complex terrains. This study proposes a coupled on-site measurement/CFD (Computational Fluid Dynamics) based approach to reproduce the spatial variability of wind speed for a region with complex terrain conditions. A complete framework is presented for wind resource assessment, which involves on-site measurement, CFD simulations and statistical analysis. Next, a case study on wind resource assessment for an offshore island with complex terrain features where is equipped with anemometers for long-term wind measurement is performed using the developed approach. The microscale effects in the assessment region are justified from CFD simulations with modified RNG k–ε model. A cross-validation of the numerical simulations against wind tunnel experimental results and on-site measurements indicates a good agreement. Consequently, a detailed wind resource map of the offshore island is attained through the wind data from a single measurement site combined with the CFD simulations, which is of great use for future wind farm siting and turbine micro-siting. The coupled on-site measurement/CFD based approach is expected to enable the efficient and reliable wind resource assessment and facilitate the wind energy development in the areas with complex terrain conditions.

1. Introduction

As the remarkable development of technological, institutional and market in the wind power industry during the past decades, the minimally economic viable wind speeds have been lowered, while the profitability of the wind power generations have been increased. By now, the wind energy has well established its role as one of the most important sustainable energy resources. Better wind power estimations of the local wind resource could enhance the operational practices such as integration of larger fractions of wind power into power grids. Recent research works revealed that the reliable and accurate assessment of wind energy potential for previously disregarded complex terrain regions to identify the accessible wind resources can reduce the massive investments in wind prospecting, and hence increase the profitability of wind power investments [49]. Therefore, increasing research efforts have been devoted to perform the wind resource assessment, particularly for the regions under complex terrain conditions [14,33].

Historically, the wind potential for one region was assessed on the basis of the available measurements recorded on the meteorological tower in the area of concern [29]. Since the limited measurements stations could not represent the wind power distribution in the entire area, the wind data at those unequipped locations are sometimes estimated using the geo-statistical techniques (such as distance-weighting interpolation and semi-empirical terrain corrections) with a suitable reference measurement site [25]. This method has been widely used to produce the wind resource maps of the relatively flat regions equipped with well-developed measurement networks. In the past decade, two advanced technologies of LIDAR and SODAR have been strongly promoted by the wind energy community as promising solutions to resolve the spatial variations of wind energy resource [3,10]. However, giant economic and human resources are required to install and maintain the measurement equipment, particularly for the measurement sites in undeveloped or disregarded complex areas. Increase in available computing resources has allowed the high-resolution simulations of atmospheric boundary layer for a detailed understanding of spatial variations of potential wind energy. Ayotte [4] classified the existing numerical methods for wind energy assessment into two main categories: linear wind resource modeling and nonlinear wind resource modeling.

In the linear models, the advection terms in the momentum equations are linearized by assuming that the background flow

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Nomenclature

Symbols

$U(z)$	wind speed at height z (m/s)
U_{ref}	wind speed at reference height z_{ref} (m/s)
z_0	roughness height
$f(U)$	Weibull probability density function
K	Weibull shape parameter
C	Weibull scale parameter (m/s)
$F(U)$	Weibull cumulative density function
U_m	mean wind speed (m/s)
$\Gamma(x)$	Gamma function
P_{op}	operating probability
U_{mp}	most probable wind speed (m/s)
$U_{max.E}$	wind speed carrying maximum energy (m/s)
$E(z)$	fractional error
P/A	wind power density (W/m^2)
ρ	air density (kg/m^3)
k	turbulence kinetic energy
ε	turbulence dissipation rate

Abbreviations

CCH	Cheung Chau weather station

only varies vertically but is horizontally constant. Notable examples based on the linear models include some of the widely used software, such as WAsP [38], MS Micro [53,31] and RAMSIM model [17]. The linear model can greatly reduce the computational cost and provide reasonable predictions in relatively flat terrains with small hills. However, the comprehensive comparisons with experimental observations for complex terrains demonstrate overestimates of the flow accelerations at the top of the hill and underestimates of the lee-side decelerations [5].

Along with the advances in numerical modeling and increasing computing power, more complex and computationally demanding non-linear modeling, Computational Fluid Dynamics (CFD), has made itself inroads into the fields of wind modeling and prediction, turbine micro-siting and blade optimization etc. The applications of advanced numerical modeling approaches in wind energy have improved the levels of efficiency of wind power generation not possible before [36]. The non-linear models solve the Navier–Stokes (N–S) equations numerically, which have the advantages of simulating more complex and complete physics schemes compared with the linear models. Therefore, the non-linear models are mathematically more accurate and feasible for wind modeling and predications under complex terrain conditions. Several studies compared the numerical results between various linear and non-linear models [39,7], which showed that the non-linear models can better simulate the wind flows over complex terrains with steep slopes and large altitude differences. The most common non-linear model is RANS (Reynolds Averaged Navier–Stokes Equations) model, which is able to accurately simulate the mean wind flow fields over real complex terrains [16]. Recently, the even more computationally demanding Large-eddy simulation (LES) approach has been adopted to simulate the wind flow over complex terrain, which offered the time-dependent flow features [47]. But, its applications are limited by huge computational demands and long simulation time.

To include the mesoscale effects for site-specific microscale simulations, the mesoscale models for atmospheric simulations have been coupled with high-resolution CFD. The Karlsruhe Atmospheric Mesoscale Model (KAMM) was combined with WAsP to produce the wind maps of Ireland [22], Egypt [37] and some other European nations [23]. Similarly, WAsP was later combined with other mesoscale models such as TAPM model [18] and WRF (Weather Research Forecasting) model [9]. Nevertheless, the accuracy of coupled mesoscale and microscale models might be compromised due to the systematic errors accumulated from the coarse-scale mesoscale models.

This first objective of this study is to present a coupled approach that combines wind data measured at a single measurement site with CFD simulations to reproduce the spatial variability of wind speed. This approach just requires the wind data measured at a single measurement site, which significantly reduce the investments to develop a costly measurement network. In addition, the real meteorological features of on-site measurements enable the considerations of mesoscale effects without the use of mesoscale models, and hence avoid the propagated systematic errors. Furthermore, CFD simulations allow the use of non-linear models to predict the microscale effects with high-resolution grid and adequate accuracy. The second objective is to propose a complete framework that integrates the wind measurements, microscale simulations and statistical analysis for wind resource assessment. To the best knowledge of the authors, such a framework has rarely been in detail described in the accessible documents. The third objective is to apply the proposed approach and developed framework of wind resource assessment to a case study with complex terrain conditions.

Section 2 of this paper introduces the coupled approach and the complete framework. The CFD methodology adopted in this study is briefly presented in Section 3. Section 3.4 summarizes the on-site wind speed measurement, wind tunnel experiment and numerical setup of the case study with complex terrain features. Section 4 presents the results of wind resource assessment and detailed discussion. Section 5 summarizes the conclusions of this study.

2. Methodology

2.1. Coupled field measurement/CFD based approach

The wind resource assessment requires considering both mesoscale and microscale effects, which involves combing the meteorological data with site-specific features. Since the wind data obtained from surface wind stations may be influenced by local complex terrains and obstacles, the direct usage of the meteorological data would introduce significant errors in surface wind speeds on the order of 40% [42]. Therefore, the measured wind data at surface wind stations should be transformed to a generalized wind climate (GWC) (formally called "wind atlas") or potential wind speed [50] by subtracting the site-specific effects. The GWC denotes wind conditions that would ideally exist at a reference height z_r above a standard terrain of roughness height z_{0r} that is flat, homogeneous and obstacle-free (i.e. z_r = 10 m and z_{0r} = 0.03 m are adopted in this study). There exist several methods of transforming the measured wind data to GWC, such as ESDU (Engineering Science Data Unit) method [19,20], WMO method [50] and the scheme proposed by Masters et al. [34]. Due to the aforementioned methods limited to the flat terrain conditions, He et al. [27] proposed a data-driven scheme applicable to rugged terrains. In this study, this data-driven scheme is first adopted to calculate the GWC. And then, the site-specific effects are modeled by using microscale CFD simulations.