Renewable Energy 89 (2016) 598–605

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A new methodology for urban wind resource assessment

Teresa Simões, Ana Estanqueiro*

Laboratório Nacional de Energia e Geologia – LNEG, Estrada do Paço do Lumiar, 1649-038 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form
10 August 2015
Accepted 6 December 2015
Available online 24 December 2015

Keywords:
Urban wind
Resource assessment
Micro-generation
CFD

ABSTRACT

In the latest years the wind energy sector experienced an exponential growth all over the world. What started as a deployment of onshore projects, soon moved to offshore and, more recently to the urban environment within the context of smart cities and renewable micro-generation. However, urban wind projects using micro turbines do not have enough profit margins to enable the setup of comprehensive and expensive measurement campaigns, a standard procedure for the deployment of large wind parks. To respond to the wind assessment needs of the future smart cities a new and simple methodology for urban wind resource assessment was developed. This methodology is based on the construction of a surface involving a built area in order to estimate the wind potential by treating it as very complex orography. This is a straightforward methodology that allows estimating the sustainable urban wind potential, being suitable to map the urban wind resource in large areas. The methodology was applied to a case study and the results enabled the wind potential assessment of a large urban area being consistent with experimental data obtained in the case study area, with maximum deviations of the order of 10% (mean wind speed) and 20% (power density).

1. Introduction

Urban wind energy has a large potential to be explored in the context of smart cities, whether through the installation of small wind turbines in the domestic sector (building rooftops and surrounding areas), or integrated in the building envelope providing that they are designed with wind energy exploitation in mind [1]. The wind potential in urban areas is difficult to characterize due to the high impact of obstacles and structures on the atmospheric flow. Buildings often cause flow separation, wind speed reduction and high turbulence on the top and around buildings. Also, in economic terms, the high costs of wind measurements campaigns are an important barrier to the development of this sub-sector of wind energy. Other data sources may be used for the characterization of the wind flow in urban environment, such as databases and national and regional wind potential atlas. These solutions are usually based on the application of data from mesoscale models (MM5[1] – Fifth Generation Mesoscale Model, WRF – Weather Research and Forecasting) to standard microscale models (e.g. WASP - Wind Atlas Analysis and Application Program [2]) that despite their validity, are not adapted to these environments. In both methods, the wind potential is often overestimated [3].

The use of CFD (*computational fluid dynamic*) models to characterize the wind behavior around buildings is nowadays state of the art. Nevertheless, the application of these models is highly time consuming, in particular when one needs to model large areas to adequately assess the impact of structures on the wind flow. The complexity of the domain's geometry requires the use of powerful computers in order to obtain reliable results, and reinforces the non-suitability of most CFD programs to the study of large areas. In this context, a methodology was developed to characterize the urban wind potential, based on the construction of a surface involving the buildings' area, so that it can be treated as a very complex orography. This methodology considers the application of CFD models to small areas of a certain urban region, enabling the establishment of correction factors to the overall spatial distribution of the wind flow. In recent years the CFD sector has developed several commercial products, with some of them especially oriented to urban wind applications. In this particular case, the WindSim model [4] (referred subsequently as CFD-Complex) is used to model the surface of the buildings and the surrounding terrain (urban digital terrain model: U-DTM) and the Meteodyn model [5] (referred subsequently as CFD-Urban) is used to model

Abbreviations: MM5, Fifth Generation Mesoscale Model; WRF, Weather Research and Forecasting; CFD, Computational Fluid Dynamics; U-DTM, Urban Digital Terrain Model; PD, Power Density.

* Corresponding author.
E-mail addresses: teresa.simoes@ineti.pt (T. Simões), ana.estanqueiro@ineti.pt (A. Estanqueiro).

http://dx.doi.org/10.1016/j.renene.2015.12.008

the natural geometry of the buildings in a small area. In both cases, the wind data from the Wind Potential Atlas for Mainland Portugal [6] are used. The results obtained by each model are compared and discussed in this paper.

2. The wind in urban environment

The urban wind resource has been object of several studies. Although there are few references to urban wind energy planning in a smart city context, there are a few R&D projects dedicated to the study of the wind behavior around and above small groups of buildings aiming at the installation of small scale energy systems, e.g. Ref. [7].

One of the most important barriers for the study of the wind in urban environments is the lack of adequate wind data measurements and CFD models are frequently used to fill this gap. Ultrasound and conventional anemometry is sometimes used to assess the wind in urban areas, mainly in the scope of R&D projects [8]. LiDAR (Light Detection And Ranging) measurement systems [9] and statistical methods such as the Weibull distribution based on large wind databases have also been used by the scientific community for this purpose, although the scale of application is, in most cases, of the order of few tens of meters [10]. The physical representation of the urban fabric is of outmost importance, independently of the methodology applied for the wind measurement and its energy resource assessment. . Most of the areas considered in these studies are in the order of tens of meters with maximum dimensions of approximately 2000 m. Although the methodologies developed are suitable to neighborhood and street scales, they often do not apply to city scale or larger areas [11]. The NUDAPT database project - National Urban Database with Access Portal Tool, is an exception. It contains 2D and 3D information on a set of American cities and allows the user to download and use it in research projects. The use of GIS – Geographic Information Systems – is also frequent to model the urban fabric in larger areas, especially when these areas are located in complex terrains [12].

2.1. Models for the urban wind resource assessment

Models based on the potential flow theory are widely used for the development of wind parks but they do not usually have the capacity to model the wind flow in urban areas (e.g. WASP). As an alternative, CFD numerical models have been widely used in recent years. These models have high computational requirements when compared to standard models, but technology advances in the latest years made their use in simulation possible in nearly standard computers especially when applied to small areas. The application of CFD models for wind resource assessment is performed by solving the RANS equations – Reynolds Averaged Navier-Stokes – with turbulence closure [13,14], where the turbulence models most commonly used are k–ε and k–ω. CFD models with mesoscale outputs as boundary and initial conditions, or with time varying boundary conditions, have been applied by some authors [15,16]. Their use is justified by the fact that the sole use of mesoscale models for this purpose will overestimate the wind energy obtained at the city scale.

Although CFD models are state of the art in urban wind modeling, its application presents some disadvantages: they are highly computation time-consuming; the construction of the domain geometry is difficult and complex; and convergence problems often occur introducing errors in the results. These disadvantages are important in the choice of the methodology to follow when characterizing the wind resource, especially in extensive areas. Nevertheless, in this work a CFD model for urban environments (CFD-Urban) was used in small areas, with the main purpose of "calibrating" results with simple standard models for a large city area. The models here used solve the RANS equations for an uncompressible flow (Eqs (1) and (2)) and the k–ε turbulence model (Eqs. (3) and (4)) [17,18].

$$-\frac{\partial(\rho u_j u_i)}{\partial x_j} - \frac{\partial \overline{p}}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \rho\overline{u_i' u_j'}\right] + \overline{f}_i = 0\,; \tag{1}$$

$$-\frac{\partial \rho \overline{u_i}}{\partial x_i} = 0 \tag{2}$$

where the term $\rho\overline{u_i' u_j'}$ represents the Reynolds tension tensor, that corresponds to the additional transference of momentum due to the turbulence fluctuations [19,20].

$$\frac{\partial}{\partial x_i}(U_i k) = \frac{\partial}{\partial x_i}\left(\frac{\nu_T}{\sigma_k}\frac{\partial k}{\partial x_i}\right) + P_K - \varepsilon \tag{3}$$

$$\frac{\partial}{\partial x_i}(U_i \varepsilon) = \frac{\partial}{\partial x_i}\left(\frac{\nu_T}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_K - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{4}$$

where C_μ, σ_k, σ_ε, $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are known constants, P_K is the turbulent kinetic energy production given by Eq. (5), and ν_T is the kinematic viscosity.

The CFD-Complex model solves the RANS equations using the finite element method, along with initial conditions, referred to as the solution's first estimates. This model may use two types of solver – namely *Segregated* and *Coupled*. The Coupled solver (Migal) [21] refers to the coupling technique '*speed – pressure*' and to a linear solver that simultaneously updates the speed and pressure fileds across the domain. The linear solver performs only the first part of the speed-pressure iteration and is followed by, Phoenics [22] model that completes the non-linear part of the iteration. The CFD-Complex process involves the execution of several modules which includes models that are executed sequentially in order to obtain the results [18].

The CFD-Urban model also solves the RANS equations and uses the finite volume method and a turbulence closure. The boundary conditions and the domain are generated automatically and the wind profiles are obtained according to a theoretical reference wind. The turbulent kinetic energy is constant and it is evaluated according to the input roughness data from the simulation domain [13]. Both models use wind frequency distributions (Weibull distributions and wind rose) as input data.

3. Methodology for the wind resource assessment in urban environments

The methodology presented in this paper is based on the generation of a digital terrain model which includes the terrain and the existing buildings as a whole, thus representing an *urban digital terrain model*: U-DTM. The urban DTM can be treated as a very complex terrain and be used as input for a standard wind resource assessment model (e.g. Wasp, WindSim). This methodology strongly reduces the computational costs associated with standard CFD models to simulate groups of buildings; it simplifies the geometry of the urban mesh and permits to extend the area of simulation to a city scale.

The U-DTM is then inserted into the CFD-Complex and, by using synthetic wind data series obtained by mesoscale modeling, which enables the urban wind potential to be estimated in the absence of experimental wind data. Since the U-DTM will, in some regions, smooth the city geometry, and since wind data from numerical mesoscale modeling usually overestimate the wind potential in