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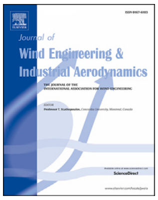

Performance assessment of a special Double Skin Façade system for wind energy harvesting and a case study

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ABSTRACT

The increasing global concern about climate change and energy crisis has necessitated the development of techniques to reach and exploit renewable energy in unexplored regions. As such, decentralized small-scale wind energy harvesting in urban environments has gained momentum in recent years. In this study, a methodology has been developed to assess the performance of a special Double Skin Façade (DSF) system for wind energy generation using CFD simulations and local wind data. As a case study, a story-high corridor-type DSF system equipped with an array of wind turbines was integrated into a high-rise building, and its Annual Energy Production (AEP) within the context of four Australian cities was evaluated. The results showed that the free-stream wind speed can be amplified up to a maximum of 1.8 times inside the corridors of the DSF system. It was concluded that the benefit of the DSF system can be exploited the most in cities with strong bi-directional wind characteristics. Finally, it was shown that wind turbines inside the DSF system can annually generate up to 50% more energy at open terrain and 22%–45% more energy at dense urban and suburban terrains as compared with the same turbines in the free-stream condition.

1. Introduction

Substantial efforts have been made globally to harvest renewable and clean energy in a variety of scales due to obvious advantages of renewable energy generation from the perspective of reduction in carbon emissions and global warming effects. Many governments have set targets for electricity generation from renewable resources. In Australia, renewable energy contributes to approximately 17.3% of total electricity generation in 2016, with 5.3% sourced from wind energy. It is affirmed by the Australian government to generate 33,000 GWh from large-scale and 4000 GWh from small-scale renewable sources by 2020 (Clean Energy Council, 2016). Small-scale Renewable Energy Scheme (SRES) in Australia supports the installation of new small-scale renewable energy generation systems such as micro wind generators, rooftop solar panels and micro-hydro systems (Clean Energy Regulator, 2015).

As a result of increasing interest in distributed micro-grid renewable energy generation in urban environments, wind resource assessment becomes an essential step to identify suitable sites and potential locations for wind energy generation. To increase the accuracy of the wind energy assessment at localized regions in urban environments, great efforts have been made to develop assessment methods that take into account the buildings height, terrain fabric, and mutual effects between buildings. Mertens (2003) proposed a method to consider the development of an Internal Boundary Layer (IBL) from undisturbed upwind rural area to a built environment when evaluating the wind energy on buildings' roof. Heath et al. (2007) considered the urban boundary layer and described a method to calculate the roughness length and displacement height of this profile for an array of cubes as an urban landscape. Walker (2011) presented a review of existing methods for predicting urban wind speed and wind power production and listed the concerns regarding the accuracy of current methods of estimating power output of micro-scale wind turbines in urban environments.

1.1. Aerodynamic devices in urban environment

Since urban environments generally suffer from low wind speed and high turbulence, it is essential to explore the aerodynamic devices available in urban landscape that can enhance the wind flow to a suitable level for energy generation. In general, potential locations for installing wind turbines in and around buildings, particularly high-rise

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List of abbreviations

H	building Height
θ	wind direction
β	building orientation from North direction
f_a	wind speed amplification factor
u_c	average mean wind speed over vertical cross-sectional area at the middle of corridor
u_z	free-stream reference wind speed at the height of 10 m above the ground
u_{opt}	optimum wind speed
u	wind speed
P_w	wind power density
$\overline{P}_w$	average wind power density
$\overline{E}_w$	annual energy production
ρ	density
f	probability of occurrence of a wind condition
f'	probability of occurrence of a wind speed inside corridors
N	number of wind speed observations
k	shape factor of Weibull function
c	scale factor of Weibull function
n	number of wind turbines
t	total number of operating hours of wind turbine
P_c	power curve of wind turbine inside corridor
P_f	power curve of wind turbine at free-stream
z_0	roughness length

buildings, which accommodate aerodynamic devices can be classified into four categories: (a) on roof, (b) between two buildings, (c) inside through-building openings, and (d) integration into building's skin. A wind turbine can also be placed in a suitable position downstream a low-rise building to take advantage of the enhanced flow as a result of wind passing over the building. The enhancement of the wind speed in these locations is affected by a number of factors such as the height of the building, the roof shape and the shadow effect of surrounding buildings. Table 1 lists recent studies that evaluate wind power in potential locations in and around buildings for wind energy harvesting. The table is mainly presented to compare the methods used in different studies and the parameters included or excluded. The reasons of selecting a method or including a parameter are discussed in the following paragraphs.

Regarding the method, conventional techniques for wind resource assessment involve installing anemometers and on-site measurements (Heath et al., 2007). However, these measurement campaigns are usually lengthy and not economically feasible for small-scale projects (Heo et al., 2016; Yang et al., 2016). Moreover, due to the geometrical complexity of urban environments, wind flow can change substantially over a relatively small distances and thus, the traditional techniques are not capable of mapping the wind flow in an area with a high-resolution (Tabrizi et al., 2014). Computational Fluid Dynamics (CFD) has been proven to be an affordable, effective and more robust alternative for investigating flow characteristics in built environments (Chaudhry et al., 2015; Yang et al., 2016). The growing applications of CFD as a result of growing computational power-to-cost ratio can be recognized in Table 1.

The accuracy of the wind flow simulation and the power of the computing resources are the main factors to be considered when choosing an appropriate CFD method (Ledo et al., 2011; Tabrizi et al., 2014). Hence, there is always a compromise between accuracy and computational cost (Toja-Silva et al., 2015a). Although Large Eddy Simulations (LES) provide more accurate results and better agreement with experimental data, its computational cost is still high, because it needs very high-resolution computational grids. The Reynolds-Averaged Navier Stokes (RANS) equations coupled with a range of suitable turbulent models are commonly used due to their efficiency (Toja-Silva et al., 2015b). Regarding the most accurate RANS turbulence model for simulating the flow in urban environment, mixed conclusions are found (Larin et al., 2016). Nevertheless, the standard and realizable $k-\varepsilon$ models are widely used for modelling atmospheric boundary layer and flow around buildings (Dannecker and Grant, 2002). The Shear Stress Transport (*SST*) $k-\omega$ model has been shown to be able to predict flow separation under adverse pressure gradient more accurate than $k-\varepsilon$ models, and it is more reliable in the case of bounded flow and ducted flow (Ledo et al., 2011; Tabrizi et al., 2014; Watson et al., 2007).

In general, the potential of high-rise buildings for wind energy generation is great because of the high wind velocity around high-rise buildings that have little shadowing effect from the low to mid-rise neighboring buildings (Li et al., 2016a; Park et al., 2016; Toja-Silva et al., 2015a). Low-rise buildings are the main interest in rural areas (White and Wakes, 2014) or in areas with a great number of low to mid-rise buildings (Heath et al., 2007).

'Specific' in Table 1 refers to the target building models that are replicated from real buildings in specific locations. 'Generic' refers to the generic forms of a building which are not necessarily representative of a real building. It is very often the case that surrounding buildings are included in CFD simulations or wind tunnel tests when investigating the flow in or around specific buildings (Balduzzi et al., 2012; Ledo et al., 2011). However, surrounding buildings are often not modelled when the primary focus of a study is the identification of potential locations of installing a wind turbine or the effect of building geometrical characteristics such as roof shape on wind energy harvesting (Balduzzi et al., 2012; Ledo et al., 2011; Yang et al., 2016). Moreover, surrounding low-rise buildings are usually not considered when the target location is a rooftop of a high-rise building (Abohela et al., 2013).

To enhance wind power generation, a wind turbine is often enclosed in a specially designed shroud, known as Diffusor Augmented Wind Turbines (DAWTs). In some especial cases, DAWTs utilize ducted flow and pressure difference in building openings for wind power generation (Hassanli et al., 2018; Toja-Silva et al., 2015a; Watson et al., 2007). The simplification of not modelling the wind turbine is frequently made especially in the case of examining wind energy available on rooftop of buildings and investigating the effect of roof shapes or complex terrain (White and Wakes, 2014).

As indicated in Table 1, when dealing with a generic form of a building, Atmospheric Boundary Layer (ABL) velocity profiles were preferred as the inlet boundary condition for CFD simulation. On the other hand, to model a specific building, Integral Boundary Layer (IBL) profiles that consider a displacement height corresponding to the mean height of surrounding buildings were often used (Heath et al., 2007; Balduzzi et al., 2012).

Apart from having higher velocities, another advantage of rooftop installation is that wind turbines do not occupy the useful space of occupants and can be retrofitted into existing buildings (Chong et al., 2016; Grant et al., 2008). However, turbines should be installed above a minimum height because the separation of flow from building edges generates strong turbulence close to the roofs. Raising turbines to the level where the effect of wind turbulence is weak requires a strong foundation, especially in the case of high-rise buildings, which sometimes is not viable (Kono et al., 2016). Furthermore, there is no control over the directionality of wind, which can also be negatively influenced by the edges of buildings and create large regions of high turbulence and low velocities (Toja-Silva et al., 2013).