A study on the wind energy potential in passages between parallel buildings

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Abstract

Worldwide many research efforts are focusing on solutions for energy-efficient and environmental-friendly buildings. This paper presents a Computational Fluid Dynamics (CFD) study of the wind conditions in passages between parallel buildings with common rectangular floor plans to assess the wind energy potential. The influence of the building geometrical parameters on the wind speed distribution in the middle of the passage is evaluated in order to define the most advantageous configurations in terms of wind speed amplification. An estimate of the wind energy potential is provided for the geometry with the highest amplification factors, using statistical meteorological data of Eindhoven.

1 Introduction

Implementation of a renewable-energy policy has become a priority task among researchers and governors all over the world due to an increase in energy consumption, rise in prices of fossil fuels and electricity and climate change. Regarding ecological value and economical prospects, wind energy generation is considered to be one of the most attractive technologies to moderate the cost of electricity and decrease the reliance on scarce and expensive fossil fuels, due to its inexhaustible resource availability and the potential to reduce CO_2 emissions (IEA Wind, 2011).

Campbell and Stankovic (2001) focused on the development of techniques for integrating wind energy systems into urban areas. Their approach included the balancing of aesthetic, aerodynamic, architectural, environmental and structural concerns. As a result, the authors suggested a method for predicting and assessing energy impacts caused by wind turbine integration, provided a classification of optimal building forms and developed several prototypes for structural systems for supporting turbines. Dutton *et al.* (2005) reviewed different wind energy technologies and introduced their potential of electricity generation as well as disadvantages based on a comprehensive survey. The information about 41 different devices was collected and summarised.

Lu and Ip (2009) and Ayhan *et al.* (2012) investigated the wind conditions between two buildings and wind flow over the building roof in terms of building shape and its geometrical parameters by means of Computational Fluid Dynamics (CFD). The studies revealed the wind speed amplification effect of buildings and possible enhancement of wind power utilisation by a factor up to 8. Abohela *et al.* (2013) used CFD simulation to prove that a vaulted roof has an optimum shape for roof-mounted wind turbines and indicated that a wind turbine should be positioned at a height equal to or more than 1.3 times the height of the building due to high turbulence intensities and low wind speeds above the roof (recirculation region). The authors also advised that the building with a wind-turbine should be higher than surrounding buildings to minimize their influence on the flow. Research in the field of roof-mounted wind turbines with application of CFD was also performed by Balduzzi *et al.* (2012a, 2012b). These studies considered a Darrieus vertical axis wind turbine (VAWT) installed on a building rooftop as one of the most attractive solutions due to its low visual impact, the reduced acoustic emissions and better response to a turbulent and skewed oncoming flow. Results showed a positive influence on the velocity increment for the sloping roof and a higher energy potential for wind turbines due to the skewed flow.

Denoon *et al.* (2008) emphasised in their review paper the significant role of the form of the building in harvesting wind power as well as the importance of a complete assessment of wind flow characteristics at the proposed site. The analysis of wind availability at certain locations and its power utility for electricity production were extensively described in studies of Alnaser *et al.* (2000), that analysed statistical wind data for Bahrain, and Glass *et al.* (2011), that experimentally evaluated the performance of micro wind turbines in urban environment.

The majority of studies regarding wind energy potential in urban environments concluded that wind energy could make a significant contribution to energy requirements for buildings.

However, Carpman (2010) emphasized the occurrence of high turbulence in urban environments due to high dynamic and thermal instabilities, which can generate fatique loadings on wind turbines and cause breakdowns. Similarly, Lubitz (2011) investigated the negative influence of high turbulence levels on performance of small wind turbines in urban areas by measurements and recommended to extensively describe the type of turbine and the turbulence conditions during the testing of the turbines. In common with Lubitz (2011), Blackledge *et al.* (2013) analysed the performance of small wind turbines in turbulent environments and developed mathematical models to predict and assess this influence. Another interesting trend was mentioned by Li *et al.* (2013) in their review regarding zero-energy buildings. The authors pointed out that the fluctuating nature of wind and thus the unstable performance of the wind turbine can be compensated by solar energy produced in hybrid PV-wind power generation systems.

In conclusion, it is clear that the built environment offers promising possibilities to generate wind energy, while the main issues are existing buildings which obstruct the incoming wind and cause high turbulence levels.

The research presented in this paper aims to contribute to studies of generating environmentally friendly and cost-effective electricity in the urban environment by using wind turbines in passages between parallel buildings with common rectangular floor plans. The objectives of the current study are: 1) to investigate the influence of geometrical parameters such as building height, length, passage depth and width on the amplification of the mean wind speed in the middle of the passage; 2) to investigate whether a unified parameter can be defined relating building geometry and wind speed amplification in the passage; 3) to assess the wind energy potential in building passages.

2 Building configurations

The aerodynamic study is conducted by means of CFD with 3D steady RANS equations. The proposed set-up represents two simple parallel rectangular building blocks (Fig. 1a). Additionally, the configuration of buildings with rounded edges (radius r = 5 m, Fig. 1b) has been considered in order to investigate the influence of the building shape on wind amplification and turbulent kinetic energy in the passage. The variable parameters are (Fig. 1a): building height H, building length L, passage depth D and passage width w. In order to categorise the building configurations and to arrange the data, the ratio w/S is considered which was proposed by Stathopoulos *et al.* (1992), where S is the building influence factor defined by Wilson (1989) as $S = (B_L B_S^2)^{1/3}$, where B_L is the larger and B_S is the smaller dimension of the windward facade of one of the buildings. All 54 studied configurations are summarised in Table 1. Note that configurations within the range of $0.125 \leq w/S \leq 1.25$ are chosen as they have been determined to be advantageous in terms of wind speed amplification at pedestrian level (Blocken *et al*., 2007a).

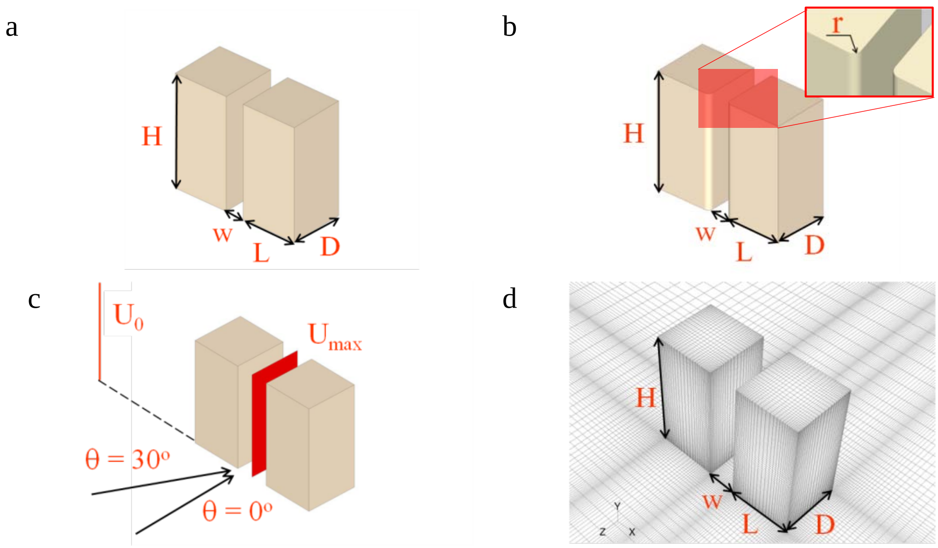

Figure 1: (a) Set-up overview. (b) Configuration with rounded edges (r = 5 m). (c) Indication of considered wind directions and positions where U_{max} and U_0 are obtained. (d)View of the computational model and mesh.

Table 1: Overview of building configurations.

L [m]	H [m]	D [m]	w [m]	S [m]	w/S [-]
45	60	30; 45; 60	20; 40; 60	49.53	0.40; 0.81; 1.21
	90	30; 45; 60	20; 40; 60	56.70	0.35; 0.71; 1.06
	120	30; 45; 60	20; 40; 60	62.40	0.32; 0.64; 0.96
70	60	30; 45; 60	20; 40; 60	63.16	0.32; 0.63; 0.95
	90	30; 45; 60	20; 40; 60	76.12	0.26; 0.53; 0.79
	120	30; 45; 60	20; 40; 60	83.78	0.24; 0.48; 0.72

In order to investigate the influence of the approach-flow conditions on the wind speed distribution in the passages, two aerodynamic roughness lengths y_0 are considered in the numerical simulations: y_0 = = 0.03 m and y_0 = 1 m representing grass land and a homogeneous village, respectively (Wieringa, 1992). Two wind directions θ are evaluated in order to observe the dependence of wind speed within a passage on wind direction: parallel to the passage centre line (0°) and 30° (Fig. 1b). This angle span is chosen due to the fact that it provides the most important wind speed amplification and uniform wind distribution in building passages (Stathopoulos *et al.* 1992). An increase in the wind speed through the passage is expected due to the channelling effect and the extent of this enhancement. The so-called wind speed amplification factor K_{max} represents the evaluation parameter in this study. It is defined as $K_{max} = U_{max}/U_0$, where U_{max} is a maximum wind speed at any height within a passage centre plane and U_0 is the reference wind speed at the same height with no buildings present (Fig. 1b).

3 CFD simulations

3.1 Parametric study

3.1.1. Model geometry and grid; boundary conditions

The domain extensions comply with the recommendations stated in Franke *et al.* (2007) and Tominaga *et al.* (2008). The body-fitted grids are generated by a method presented by van Hooff and Blocken

(2010) and based on a grid-sensitivity analysis, yielding grids of up to 2.7 million cells.

The boundary conditions at the inlet are: mean wind speed $U = (u^*/\kappa)\ln((y+y_0)/y_0)$, turbulent kinetic energy $k = (u^*)^2/\sqrt{C_\mu}$, (Richards and Hoxey, 1993) and turbulence dissipation rate $\varepsilon = (u^*)^3/\kappa(y+y_0)$, where u^* is the friction velocity, C_μ is a model constant ($C_\mu = 0.09$), κ is the von Karman constant ($\kappa = 0.42$). The roughness parameters k_S and C_S are determined using the relationship $k_S = 9.793y_0/C_S$, derived by Blocken *et al.* (2007b). The combinations $C_S = 7$, $k_S = 0.042$ and $C_S = 7$, $k_S = 1.4$ are selected for $y_0 = 0.03$ m and $y_0 = 1$ m, respectively. The absence of horizontal inhomogeneity in the vertical profiles of mean wind speed U and the turbulence parameters k and ε is confirmed by performing simulations in an empty domain. The building surfaces are assumed to be smooth ($k_S = 0$ m and $C_S = 0.5$). Zero static pressure is imposed at the outlet of the domain, the top of the domain is modelled as a slip wall (zero normal velocity and zero normal gradients of all variables), symmetry is assigned to lateral boundaries.

3.1.2. Computational settings and parameters

The 3D steady RANS equations are solved in combination with the realizable k-ε turbulence model (Shih *et al.*, 1995) with standard wall functions. Pressure-velocity coupling is solved by the SIMPLE algorithm, pressure interpolation is standard and second-order discretisation schemes are used for both the convection and the viscous terms of the governing equations. Convergence is assumed to be obtained when all the scaled residuals showed no further reduction and reached 10^{-5} for continuity and turbulence dissipation rate, 10^{-7} for velocities and turbulent kinetic energy.

3.2 Validation study

Validation of the computational model is performed based on wind tunnel data from related studies of Stathopoulos and Storms (1986) and Beranek and Van Koten (1982). Reported data provide values of the wind amplification factor around the buildings at pedestrian level (z = 2 m). In this case the amplification factor is defined as the ratio of wind speed measured at a certain point around the buildings at pedestrian level height to the reference wind speed at the same height measured in the absence of the buildings (U/U_0).

Boundary conditions for the validation studies are taken equal to the reported ones and computational settings are the same as described in section 3.1.2. Validation study (1), using the experimental data by Stathopoulos and Storms (1986), provided deviations lower than 10% between values obtained by CFD simulation and wind tunnel data. Study (2), using the experiments by Beranek and Van Koten (1982), showed a fair to good agreement between the experimental and numerical results, especially in the target area within the passage. The deviations between the results for study (1) can be explained by the physical modelling error in CFD, discretisation errors, and the complexity of the experiments in the wind tunnel, for example, absence of roughness elements on the turntable over which the internal boundary layer develops. The validation studies in general show a fair to good agreement, and provided confidence in the use of the computational settings in the remainder of this study.

4 Results of parametric study

4.1 Amplification factors

Figure 2a illustrates the values of K_{max} for the two aerodynamic roughness lengths y_0 of the terrain as a function of w/S for different building geometries. The values of K_{max} range within 1.12 – 1.30 for $y_0 = 0.03$ m and 1.05 – 1.13 for $y_0 = 1$ m. The values of K_{max} reach their maximum around w/S = 0.32 and w/S = 0.64 for $y_0 = 0.03$ m and $y_0 = 1$ m, respectively. In addition, Figure 2a demonstrates a significant difference up to 20% between the values of K_{max} calculated for different aerodynamic roughness lengths.

The wind speed distribution within a passage for one additional wind direction angle $\theta = 30^o$ is studied for 18 configurations. The calculated values of K_{max} for $\theta = 30^o$, summarised in Figure 2b, are in the range of 0.98 – 1.02 meaning a small effect on the flow amplification. Comparing the amplification factors defined for parallel and angular wind directions, it can be concluded that amplification factors are generally lower in the second case (Fig. 2b).

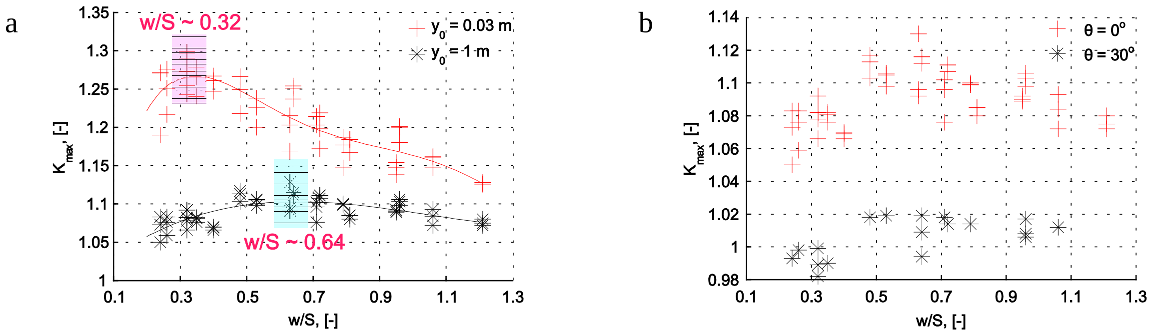

Figure 2: Overview of calculated amplification factors K_{max}: a) for different aerodynamic roughness lengths ($\theta = 0^o$); b) for different wind directions ($y_0 = 1$ m)

4.2 *Wind energy calculation*

The electrical power-producing potential of the wind energy concerns (Manwell *et al*., 2009):

- meteorological potential (available wind resource based on statistical wind distribution data);
- building site potential (based on meteorological potential and related to building design);
- technical potential (based on building site potential and related to applied wind turbines).

The evaluation of the potential of wind energy is assessed for the building geometry with dimensions L x H x D = 45 x 120 x 60 m^3, for which the highest amplification factors (up to 1.3) can be obtained. These virtual buildings are placed in Eindhoven, The Netherlands and are oriented in the prevailing south-west wind direction of 225° (Fig. 3a). The passage width varies between w = 20, 40, 60 m and three types of horizontal axis wind turbines (HAWT) are applied (Table 2, Fig. 3b).

Table 2: Overview of applied wind turbines (HAWT).

Passage width [m]	Turbine	Rotor diameter [m]	Rated power [kW]/ Wind speed [m/s]	Manufacturer website
20	WES18	18	80 / 13	www.windenergysolutions.nl
40	E33	33.4	330 / 12	www.enercon.de
60	E53	52.9	800 / 13	www.enercon.de

The technical specifications of the turbines and the meteorological data covering a period of 30 years (1971-2000) provided by Dutch Meteorological Institute are taken into account (Fig. 3a). The data of the wind speed distribution is fitted by Weibull distribution functions for different wind directions. Given the assumption that the buildings are oriented to the prevailing wind direction and HAWTs are fixed in one orientation, the wind distribution defined by the angle span of 170° – 280° is taken into account (Fig. 3a).

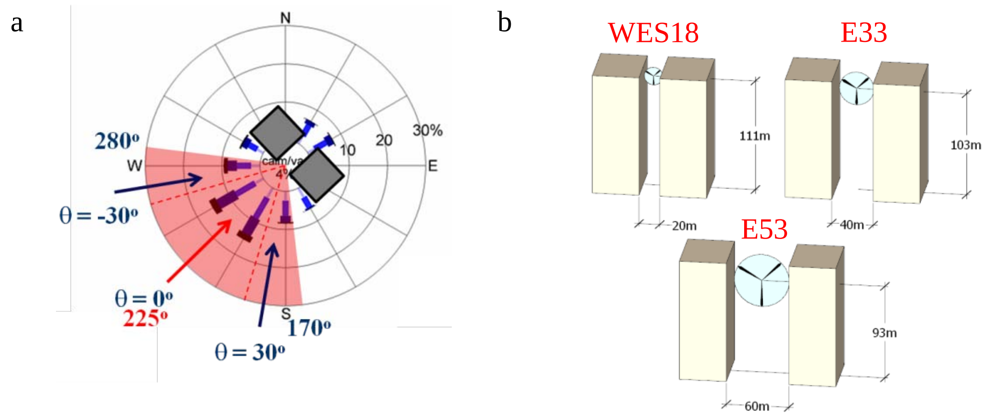

Figure 3: (a) Orientation of buildings in prevailing wind direction based on annual wind rose (top view); (b) Positioning of wind turbines depending on passage width

Within the framework of the current project the aerodynamic roughness length for the building site is assumed to be equal to y_0 = 0.03 m. Weibull probability density functions (Fig. 4, indicating angle span of 200° – 250°) are modified by the conversion factor $\gamma = (U_{ref}/U)(U_{turb}/U_{ref})$, representing the influence of buildings on wind amplification, where U_{ref} – reference wind speed at the height of 60 m at building site, U – wind speed at meteorological site at the height of 10 m, U_{turb} – wind speed at position of the prospective wind turbine.

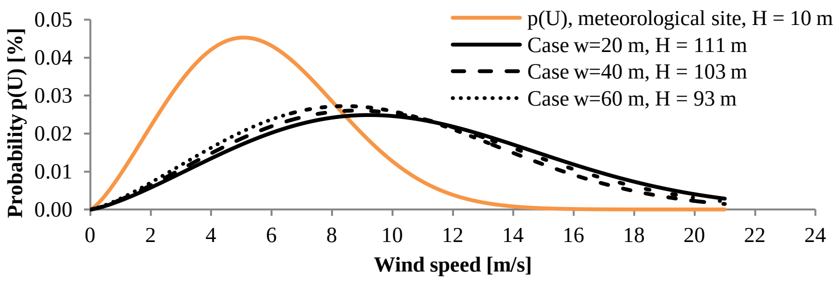

Figure 4: Modified wind PDFs for passage widths of 20m (γ = 1.82); 40 m (γ = 1.74); 60 m (γ = 1.66)

Considering the annual electricity power produced by the largest wind turbine E53 within a wind span of θ = ±30° and neglecting the other wind directions due to the wind-blocking effect caused by presence of the buildings, an amount of 1913.5 MWh can be produced. It can supply up to 8% of the annual energy demand calculated according to U.S. Department of Energy (2012) for the two office buildings with a total office space area of 110,000 m^2. Note that the annual energy potential of a free-standing wind turbine E53 with active yawing system under the same meteorological conditions with all the wind directions considered constitutes 1970.7 MWh at the hub height of 93 m. An overview of the produced wind power for all three wind turbines is presented in Figure 5.

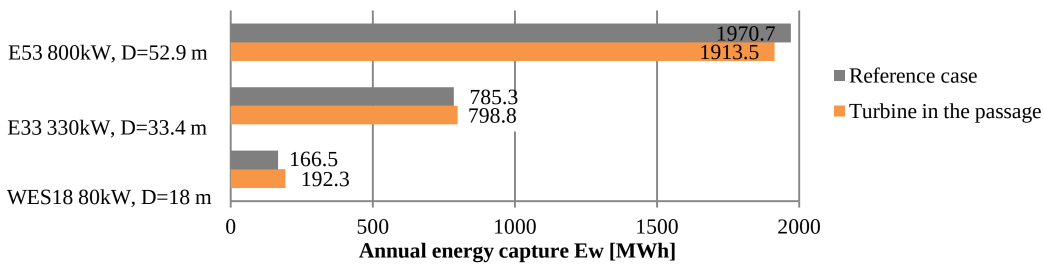

Figure 5: Annual energy produced by free-standing wind turbines and turbines in passages

4.3 Influence of building corners

According to the observed results, by rounding the edges, amplification of a wind speed is reduced by 2.3% but the production of undesirable turbulent kinetic energy within passage centre at wind turbine height is reduced by 25% comparing to the sharp-edged buildings. Therefore, by applying minor architectural changes to the buildings the performance of certain wind turbines can be improved.

5 Discussion

The results presented in this paper are a first step to study the wind energy potential in passages between buildings with rectangular ground plan. Future research will comprise:

- Analysis of aerodynamically enhanced building shapes, which are advantageous for wind amplification.
- Evaluation of the influence of the wind direction on the power output of wind turbines within building passages.
- Assessment of the impact of turbulence intensities within the building passage on wind turbine performance.
- Investigation of the influence of terrain roughness on wind distribution within building passages.
- Assessment of the performance of vertical axis wind turbines within building passages.
- Analysis of pedestrian wind comfort around the buildings.

6 Conclusions

The following conclusions can be made based on this study:

- Although the distribution of the wind amplification factors can hardly be described as a function of w/S, the building configurations which are the most advantageous in terms of wind speed amplification can be defined by the ratio w/S = 0.32 for y_0 = 0.03 m and w/S = 0.64 for y_0 = 1 m.
- Significant influence of the aerodynamic roughness length and wind direction on the wind speed distribution within passages is revealed.
- The power output is highly dependent on building geometry and on the type of wind turbine, which should be carefully determined depending on the geometrical and structural parameters of the buildings, taking into account the level of noise and vibration during operation as well as the effect on site aesthetics and human perception.

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In this paper, therefore, to examine the wind conditions in passages between the impact of the arrangement of high-rise buildings parallel buildings for assessing wind energy potential on the wind energy potential is investigated. The [3]. Chaudhry et al. studied the influence of building findings of the study support the design of high-rise morphology, including triangular, square and circular buildings with respect to integrated wind energy cross-sections, on the efficiency of building- harvesting especially. In addition, the studied results integrated wind turbines (BIWT) [4]. Balduzzi et a