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An empirical–heuristic optimization of the building-roof geometry for urban wind energy exploitation on high-rise buildings

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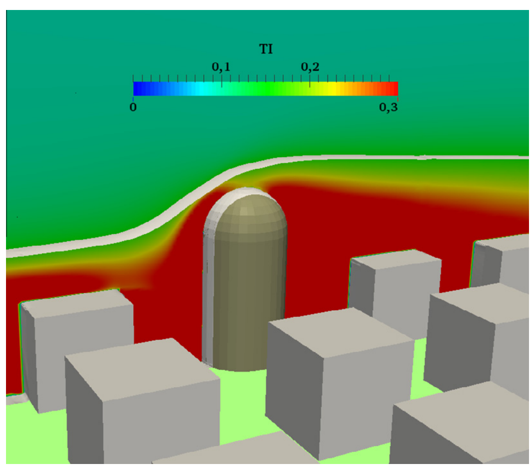
HIGHLIGHTS

- CFD is used to optimize high-rise building-roof for wind energy exploitation.
- Wall-roof transition is investigated.
- A sensitivity analysis of the roof width is carried out.
- The building aspect ratio effect on the wind flow is analyzed.
- The influence of the surrounding buildings is studied for different heights.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban wind energy exploitation is an important topic for smart sustainable cities. The present investigation is a step in this direction, considering the latest advances in building aerodynamics, identifying and analyzing the optimum building-roof shape for the urban wind energy exploitation. This investigation focusses in two aspects: the isolated building shape optimization and the analysis of this building in an urban environment. The optimization includes an analysis of the roof-wall transition geometry by testing different variations of a spherical roof, a roof-width sensitivity analysis of the optimum geometry and an exploration of the building aspect ratio effect on the flow. A comparison of velocity, turbulent kinetic energy and turbulence intensity is carried out. The wind turbine positioning on the roof is analyzed in detail. An exactly spherical roof connected to a cylindrical wall is identified as the most advantageous option. Additionally, the effect of the neighboring buildings is investigated considering different heights for the surroundings. The wind flow on the roof is strongly affected by the presence of surrounding buildings, increasing the turbulence intensity close to the roof surface. Slender shapes are identified as the most interesting building shapes for wind energy exploitation, leading to a higher speed-up and to a lower turbulence intensity.

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1. Introduction

The largest amount of the wind energy power growth comes from flat-terrain installations. However, the urban environment has also great potential for wind power that is yet to be harnessed [1]. The installation of wind turbines on building roofs has as an additional advantage the profitability of the external surfaces (roof) that currently serve only to enclose the building. Another advantage of exploiting wind energy in urban environments is its proximity to the consumption points (distributed electric power generation). Distributed generation offers significant benefits in terms of high energy efficiency, lower emissions of pollutants, reduced energy dependence and stimulation of the economy [2]. The optimization of distributed generation involves voltage profile improvements, reduction of energy losses in power lines and electric devices and the increase of the energy source availability [3]. The reduction of greenhouse gas emissions is another significant advantage [4].

Initiatives such the HORIZON2020 [5] in Future Smart Cities aims to have 20% of electricity produced by renewable sources. This goal underlines the necessity to enhance all the fashions of the wind energy generation. Reducing energy consumption in the building sector, which represents 40% of the European Union energy consumption, is a priority under the "20–20–20" objectives on energy efficiency [6]. The Directive 2010/31/EU [7] sets minimum requirements for the design of new buildings regarding the energy performance before construction starts, looking at the installation of renewable energy supply systems, such as wind energy exploitation devices. New software developments are focussing on the quantification of the urban wind energy resource [8]. The COST Action TU1304 [9] is collecting the existing expertise on building-integrated-wind energy technology with the aim of investigating methods for enabling the concept of smart future cities.

Toja-Silva et al. [10] reviews the opportunities and challenges for urban wind energy exploitation that shows the potential of this environment for wind energy harvesting, while at the same time stressing the importance of a careful analysis of the wind flow around buildings in order to obtain more information about possible positions of wind turbines to take advantage of the accelerating effect of the wind above the building and the most adequate kind of wind turbine. This analysis must include both experimental and numerical investigations [11].

For the reasons discussed in the previous paragraphs, Computational Fluid Dynamics (CFD) analysis of the wind flow around buildings is of great interest from the point of view of the wind energy exploitation and in several different engineering applications [12–14]. Since we are dealing with full-scale buildings the computational cost of LES is too expensive nowadays [15,16], and there is a necessity of using a well-parameterised RANS turbulence modelling to effectively deal with a full-scale case. The choice of the turbulence model is a compromise between the accuracy and the computational cost. Toja-Silva et al. [17] have extensively analyzed 2-equation RANS turbulence models using the free open source CFD software package OpenFOAM [18], focussing on the urban wind energy application for the benchmark case A of the Architectural Institute of Japan [19]. The new modification of the Durbin [20] k–ε turbulence model presented in [17] is used to perform the CFD simulations in the present investigation.

In urban areas, local increases of wind velocity and turbulence intensity take place due to the presence of buildings. These two aspects require special attention [21–24]. Some authors as Ledo et al. [22] and Lu and Ip [23] studied the influence of sharp building-roof shapes on both the wind velocity and turbulence intensity from results obtained using CFD simulations. Four common types of building roofs were studied in these investigations: flat, shed, pitched and pyramidal. Abohela [25,26] extended these investigations to both vaulted and spherical roofs, and demonstrated their clear advantage for wind energy exploitation. Toja-Silva et al. [27] present a detailed study, including a roof-edge analysis, that identifies the basic geometrical issues involved in the maximization of the speed-up and the minimization of the turbulence intensity on high-rise building roofs. The necessity of considering curved shapes is demonstrated in [27]. Additionally, the building aspect ratio has an influence on the performance of the application. The buildings aspect ratio is studied in the literature specially for pollutant dispersion [28] and thermal performance [29,30] purposes.

There are some illustrative estimations of the wind resource (wind energy maps) in real cities such Barcelona [31]. These maps can bring an estimation of the resource, but it does not bring feasible wind resource data for a specific building roof region. Therefore, an additional analysis of the target building must be carried out considering the surroundings. Some authors have analyzed a target building considering the surrounding for natural ventilation problems. These studies included specific surrounding buildings for a particular case [12,32] and a generic pattern of surrounding buildings [33], as in the present case.

The present investigation is a step beyond the latest advances in building aerodynamics, identifying and analyzing the optimum building-roof shape for urban wind energy exploitation. In what follows, Section 2 explains and justifies why the optimization must be empirical–heuristic, the computational modelling of the flow is commented in Section 3, the roof-wall coupling analysis (including solution verification) is presented in Section 4, the sensitivity analysis of the roof width in Section 5, the analysis of the influence of the building aspect ratio in Section 6, the effects of the surrounding buildings on the wind flow on the target building roof are investigated in Section 7 and engineering applications derived from the research results are shown in Section 8. Finally, the conclusions are commented in Section 9.

2. Why "empirical–heuristic"?

The title of the article is "An empirical–heuristic optimization of the building-roof geometry for urban wind energy exploitation on high-rise buildings". The question here is: why the optimization must be empirical–heuristic?

Optimal design methods involving the solution of an adjoint system of equations (adjoint method) are often used in Computational Fluid Dynamics (CFD), particularly for aeronautical applications [34]. The most common use of the adjoint method is shape optimization problems related to the design of airfoils, wings, compressor–turbine blades, etc. The objective of the application of such method is lift maximization, drag minimization and control of flow separation [35].

In the present study, the objectives of the optimization are speed-up maximization and the turbulence intensity minimization. Both objectives are not related to the building surface but to the surrounding fluid. This is one of the reasons why the adjoint method is not used here. Additionally, there are many subjective restrictions to the optimum building shape (aesthetics, feasibility, habitability, etc.). Therefore, neither the adjoint method nor other deterministic mathematical optimization method known today [36] can be used to fulfill the objectives of this study. The optimization must be empirical–heuristic, i.e. carrying out numerical experiments using accurately validated CFD tools.

3. Governing equations, turbulence modelling and computational settings

We use the steady-state Reynolds Averaged Navier–Stokes (RANS) equations [37] implemented in the OpenFOAM [18] solver.