Renewable and Sustainable Energy Reviews 89 (2018) 281–291

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A critical review of vertical axis wind turbines for urban applications

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ARTICLE INFO

Keywords:
Wind energy
Vertical axis wind turbine
Blade aerodynamics
Power coefficient
Field performance
Commercial development

ABSTRACT

Wind energy is one of the most promising renewable energy resources for power generation, and rapid growth has been seen in its acceptance since 2000. The most acceptable classification for wind turbines is by its axis of orientation: Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). HAWTs are used in many countries for medium-to-large scale power projects, and most commercial installations around the globe are solely based on these turbines. On the other hand, HAWTs are not recognized as a viable option to harness the energy of the wind in urban areas, where the wind is less intense, much more chaotic and turbulent. VAWTs are suggested as a better choice for cities and isolated semi-urban areas. Several attributes have been suggested for the large-scale deployment of VAWTs, e.g., good performance under the weak and unstable wind, no noise and safety concerns, and aesthetically sound for integration in urban areas. Significant research has been published on wind turbine technology and resources assessment methodologies, and this review paper is a modest attempt to highlight some of the major developments of VAWTs, with a focus on the integration with urban infrastructure. Several recommendations have been drawn based on the state-of-the-art information on the subject for future studies and acceptance of wind turbines in the urban areas. It was concluded that further research is critical in making VAWTs a viable, dependable, and affordable power generation technology for many low and decentralized power applications.

1. Introduction

Global warming, energy scarcity, rapid depletion of fossil fuels and exponential growth in the energy demand in several developing countries has created an excellent opportunity for large-scale acceptance of renewable energy technologies. Wind energy has become one of the fastest emerging renewable energy technologies, with the total capacity by the end of 2016 reaching 487 GW (about 4% of global electricity) [1]. The technology and manufacturing infrastructure of wind turbines have advanced enough for further rapid deployment. As per the 2013 IEA roadmap, about 18% of global electricity needs will be met by wind energy by 2050 [2]. Most of the progress was anticipated on large onshore and offshore projects (MW capacity) far from urban areas, where the wind is most intense, consistent and unperturbed. On the other hand, there is considerable wind in the urban areas with a significant potential for power, viz. road dividers, side of railway tracks, top and around the high-rise buildings. The development of an efficient wind energy system closer to the point of use meets the local power demand, minimizes the use of diesel/gas-based electricity generation, reduces the strain on the existing grid infrastructure, incorporates the sustainability in the cities, supports the local economy, and addresses the environmental concerns [3,4].

The development of an efficient wind turbine (WT) and resource assessment methodology for the urban areas are crucial to increasing the penetration of wind power technology in cities and semi-urban areas [5,6]. Researchers, designers, and project developers have often recommended the installation of small-scale WTs over and around high-rise buildings as a potential power solution for incorporating sustainability, and to support the transition to the future net-zero energy buildings [7–10]. On the other hand, wind patterns in urban environments are much more chaotic and full of turbulence. The traditional methods used for determining wind-energy resource have limitations, especially when applied to more complex urban situations. Site wind resource measurements require time and money that are often not feasible for small-scale power projects. A precise tool for the estimation of wind resources in the built-up areas is one of the fundamental requirements for the expansion of wind energy in urban regions [11,12].

Furthermore, Horizontal Axis Wind Turbine (HAWT) is relatively ineffective in urban situations and face local resistance due to noise, aesthetic, visual and public safety concerns [13]. Alternatively, Vertical Axis Wind Turbine (VAWT) has been predicted as a potential solution for the implementation of WTs in urban and semi-urban areas [14,15].

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https://doi.org/10.1016/j.rser.2018.03.033
Received 29 September 2016; Received in revised form 3 February 2018; Accepted 14 March 2018

Nomenclature

C_P	wind power coefficient/coefficient of performance/power coefficient (it is a ratio of electricity produced by the wind turbine to the total energy available in the wind)
TSR	tip speed ratio (it is the ratio of the peripheral speed of the tip of the blade to the wind speed)
β	overlap ratio (the overlap ratio β of Savonius rotor is expressed as: $\beta = a/2R$, where a is the overlap distance and R is the radius of the blade circle)

Acronyms and abbreviations

AEO	annual energy output
COE	cost of energy
CFD	computational fluid dynamics
CUE	Center for Urban Energy
GHG	greenhouse gas
HAWT	horizontal axis wind turbine
LCOE	levelized cost of electricity
NSERC	Natural Sciences and Engineering Research Council
RPM	rotation per minute
WT	wind turbines
VAWT	vertical axis wind turbine
WWEA	World Wind Energy Association

The VAWTs have a relatively low environmental impact and better adaptable characteristics to the unsteady wind of urban terrains. These turbines can produce electricity from any direction with low cut-in wind speed and are relatively simple in design to integrate with urban buildings and infrastructure.

The use of chaotic wind flow to generate electricity has been a challenge to the researchers, developer, planner, and considerable work has been done on the subject in the recent decades. The studies were focused on the turbine aerodynamics, blade materials, modelling, simulation, test methods, performance validation, grid integration, and environmental aspects. Several other studies were emphasized on the development of an effective wind resources assessment methodology, equipment, and computational programs. This review paper presents some significant findings on VAWTs from published resources, government reports, non-profit organization publications, and manufacturer's literature. The manuscript has evaluated the information objectively and presents the scope and limitations of VAWTs development. The paper also highlights commercial activities on VAWTs in different parts of the world. It was noted that the opportunities of urban wind turbines are enormous; however, it is evident that further research is critical to improving turbine designs, reducing cost, and making available resource assessment tools for urban conditions.

2. Classification of wind turbines

There are several ways the modern WTs can be classified, such as based on the orientations of the axis of rotation, drag or/and lift forces on the blades, and the power capacity of turbines (Fig. 1). Based on the axis of rotation, there are two main types of WTs: the HAWT and VAWT. In HAWTs, the rotor axis is parallel to the ground and in the direction of the wind. These turbines are usually equipped with self-starter and yaw system to turn the blades towards the wind. The energy outputs of these turbines depend on the site average wind speed and the turbulence in the wind [16]. The ideal aerodynamic efficiency of these turbines is reported in the range of 40–55% under steady wind [17]. HAWTs are widely used in large wind farm applications in remote and offshore locations where the clean and the undisturbed wind are available. In contrast, HAWTs are not considered an effective design for urban environments due to the high value of cut-in wind speed, chaotic nature of the wind and the public perception against these big machines [18]. Instead, VAWTs axis of rotation is perpendicular to the directions of wind and ground. These turbines are relatively simple and do not need any yaw system and a self-starting mechanism (except, Darrieus turbines). VAWTs have low cut-in wind speed and noise level and can be installed in the urban areas that restrict the installation of a tall structure. The low wind energy conversion efficiency is an area of concern of VAWTs [19].

Another classification of wind turbines is based on the aerodynamic forces on the blade surface: drag and lift forces. In drag-based WTs, the aerodynamic force is in the direction of air flow, while, in the lift type machines the force is perpendicular to the flow of the wind. HAWTs and Darrieus turbines (discussed later) are solely lift based machines, while, Savonius turbines (discussed later) and some other new designs of VAWT are based on the drag forces. The drag-based turbines are simple in design but have a rather poor efficiency. On the other hand, the lift-based turbines are complex and extract more energy from the wind per unit swept area [20]. Castelli and Benini [21] presented a comparison of the annual energy output (AEO) of two vertical-axis wind turbines

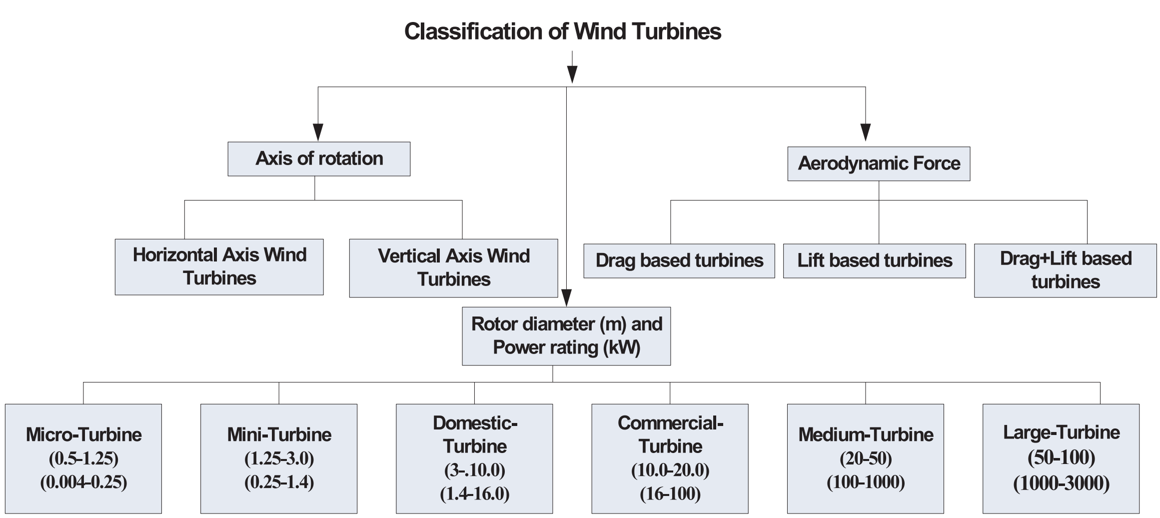

Fig. 1. Classifications of wind turbines.