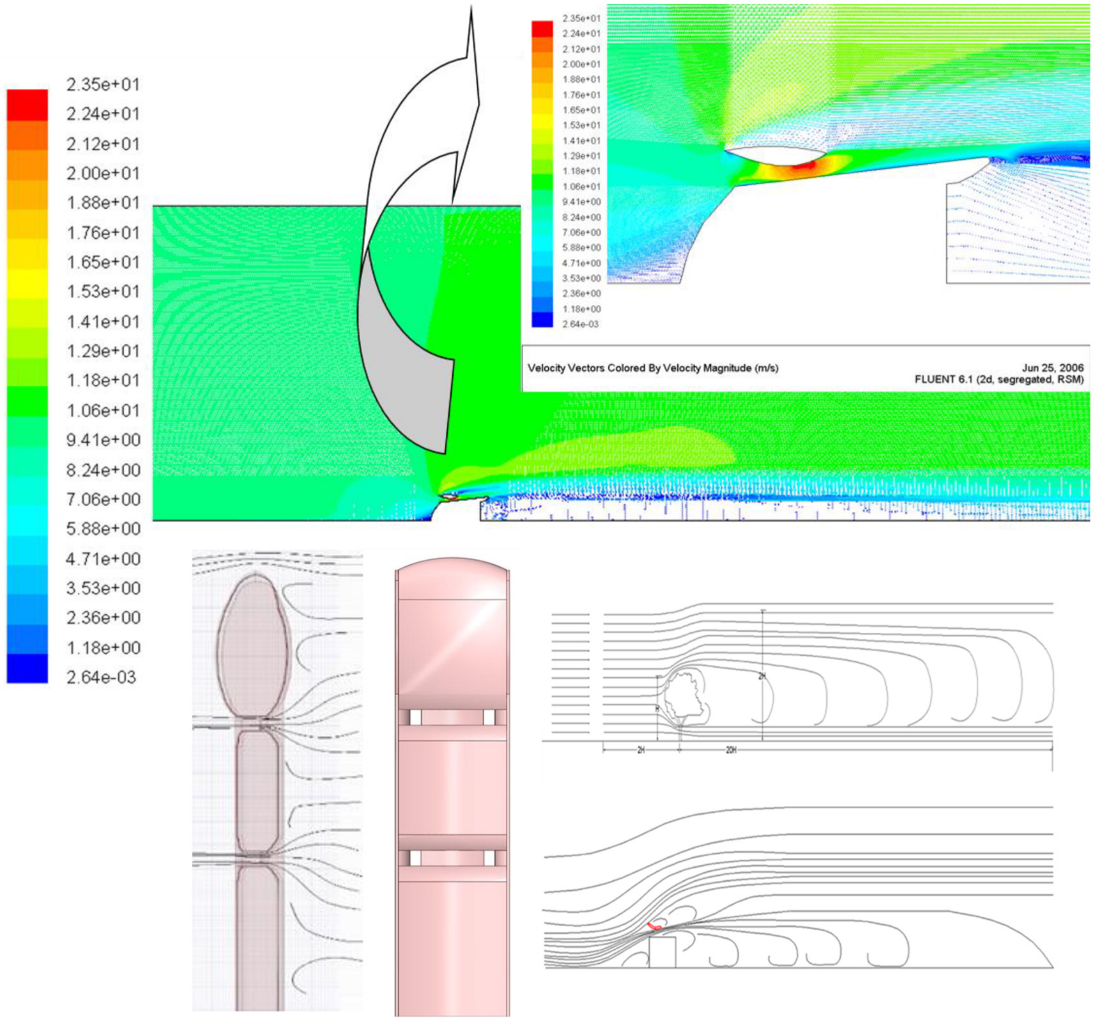
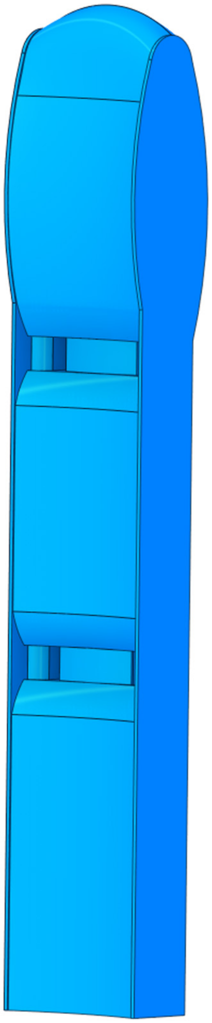
Systematic Architectural Design for Optimal Wind Energy Generation





Abdel Rahman Elbakheit

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Systematic Architectural Design for Optimal Wind Energy Generation

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Systematic Architectural Design for Optimal Wind Energy Generation

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CONTENTS

PREFACE

With a better understanding of building sciences and improved technologies for the utilisation of building physics, architectural form-finding processes became more elaborated with the added consideration for thermal, acoustic, solar, and aerodynamic forms. Majority of these invisible ordering principles have been developed in the last 100 years; however, they have impacted critical decisions about architectural form only in about the last 70 years. The science of architectural acoustics, for example, did not exist until the second half of the twentieth century, and practical auditorium acoustics were not well understood until about 1960s.

The advent and evolution of building sciences and their incorporation into building technologies transformed the means of evaluating architecture. Thus, several qualitative aspects of architectural form were measurable in quantitative terms. Other than all the general means of spatial experience, comfort, music, lighting, colour, and energy requirements could also be measured, totally optimised and reconfigured.

This book concentrates on further elaborations on the influences of wind and architecture on building sciences, architectural form finding and the optimisation of wind energy harvesting using suitable wind turbines. This publication documents case studies on existing buildings' designs incorporating wind energy technology in Chapter 1. Certain processes and key indicators for evaluating and testing any envisioned architectural form have been proposed in this chapter. Moreover, the methods for scanning various wind aerodynamic responses relevant to buildings that could be utilised for wind energy harvesting have been elaborated, along with the various types of wind flows and their characteristics. Further steps for streamlining architectural forms to generate optimal wind flows prior to energy harvesting are discussed in Chapter 2.

The ideas presented in this book are a continuation to previous work, aiming to enhance architectural design potential for achieving better prospects of sustainability through the assimilation of wind energy harvesting into architectural form design. In Chapters 4 and 6, the works presented in publications titled, 'Factors enhancing aerofoil wings for wind energy harnessing in buildings'[1] and 'Effect of turbine resistance and positioning on performance of Aerofoil wing building augmented wind energy generation' [2], respectively, are further elaborated. The former study examines how architectural form and aerofoils together can be manipulated to generate continuous wind flows suitable for energy harvesting using wind turbines. Some aerofoil forms are proposed on the basis of their aerodynamic qualities and peculiar attributes capable of assisting wind flow patterns around buildings. The latter study examines different positions of turbines within the same design aspects envisioned in the former study on wind energy harvesting. An independent tool is needed to be employed to 'measure' these attributes of design, which was done in the form of fluid flow computations using computational fluid dynamics (CFD).

Although the content of this study has a well-established scientific basis to it, together with this tool, the design decisions are still on pure architectural forms and their merits of clean energy generation and maximisation. This reflects the capability of a design to transcend the boundaries of science and art in a more unifying and encompassing way. One would recall the following from Richard Buchanan's 'Wicked Problems in Design Thinking', in Margolin and Buchanan, eds., The Idea of Design, 1995:

‘The significance of seeking a scientific basis for design does not lie in the likelihood of reducing design to one or another of the sciences. . . . Rather, it lies in a concern to connect and integrate useful knowledge from the arts and sciences alike’.

In Chapter 5, a thorough review of diffuser augmentation technology for wind turbines amenable to building integration and/or mimicking in architectural forms is undertaken. The key dimensional proportions of a diffuser that critically underlie augmentation level/success and in turn that is suitable for inclusion within an architectural form are highlighted.

In Chapter 7, the overall conclusions and suggestions are elaborated. In case of any feedback, please contact the author at the following email address: abdel.elbakheit@hotmail.com

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The author declares no conflict of interest, financial or otherwise.

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CHAPTER 1

Wind and Architecture

Abstract: In this chapter, the influences of wind on architecture are highlighted. Wind can have both positive and negative effects on architecture. Moreover, architecture can respond in proactive ways to maximise the benefits of wind forces and reduce or eliminate the negative impacts. This chapter sheds further light on notable architectural ideas translated into architectural case studies on harvesting wind energy in the built environment. Moreover, this chapter enables gaining insight into successful practices in architectural design solutions and ways and means to further enhance the performance of the buildings. In addition, the negative impacts of high wind velocities are identified, and possible solutions to mitigate them at their source are presented and discussed. Optimised architectural forms that can completely avoid excessive wind forces and devastating vortex shedding during the design stage are presented.

Keywords: Architectural forms, Aerodynamic architectural optimisation, Architectural form finding, Architectural stability, Vortex shedding, Wind energy, Wind energy harvesting, Wind forces.

1. INTRODUCTION

Mankind encountered wind and its effects from the dawn of existence. The history of using this renewable energy source has been well integrated in human civilisation, being implemented for sailing boats and operating wind mills [1], wind catchers [2], *etc*. However, for buildings in general, architectural form in particular, wind is associated either with structural safety or ventilation of interior spaces. With technology advancement, structural safety and ventilation have developed to be well established aspects of architectural form, although under different specialisations: structural safety under structural engineering [3] and ventilation under mechanical engineering [4]. However, architectural design retained the initiative of combining these two, among others, to produce more environmentally friendly buildings. Thus, the need to adequately benefit from wind arose. In other words, the need to find a way to tame the giant to harvest its energy at the point where it is made. In this regard, some notable conceptual architectural ideas put forth by architect Bill Dunster [5] were ground breaking, wherein he proposed the integration of a flower-shaped structure with at Tall

Abdel Rahman Elbakheit
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building concentracting and accelerating wind flow for energy harvesting.Another wind energy harvesting design was developed by the European funded project of 'WEB – JOR3-CT98-0270' [September 1998–August 2000] [6], which performed a systematic study on the generation of wind flows by design manipulation to enhance wind energy harvesting. This study included the use of two large kidney-shaped towers that channel and accelerate wind flows between them, where large turbines are present. A prototype was erected and tested. Fig. (**1**) shows this prototype, which was designed under the collaborative efforts of Imperial College London, Mecal applied mechanics (*i.e.*, consulting firm), University of Stuttgart, and BDSP partnership Ltd. (*i.e.*, engineering consulting firm). This project highlighted that this architectural design enabled increasing wind energy generation by a factor of at least 25% compared with the annual yield of the same turbines under a standalone scenario.

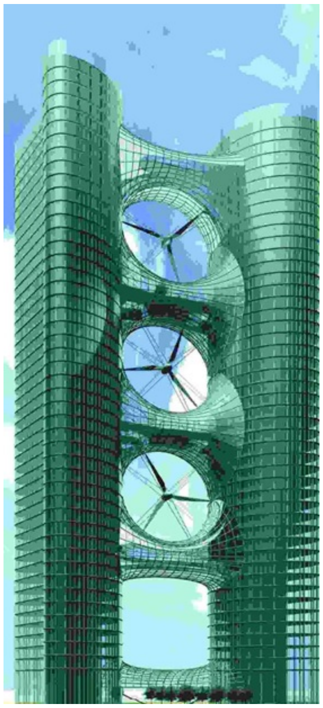

Fig. (1). Conceptual architectural design of kidney-shaped twin towers with three horizontal-axis wind turbines integrated, having diameters of 35 m and generating 250 kW of power [8].

Derek Tayler of Altechnica [7] invented 'the Aeolian roof' that contained a pitched roof with a flat wing at the ridge, which accelerated wind in this area. Wind turbines were then proposed to be used to harvest energy from this accelerated wind.

In 2005, a report was published from the joint venture of the Carbon Trust UK and some consulting and research bodies such as Imperial College London and Altechnica. It detailed the potential of building-integrated wind turbines.

2. EXAMPLES OF FULLY DEVELOPED ARCHITECTURAL DESIGNS FOR WIND ENERGY HARVESTING

Recently, some projects involving architectural forms incorporating wind turbines have been completed around the globe, such as the Bahrain World Trade Center (BWTC) in Manama, Bahrain, Strata SE1 in London, UK, and Pearl River Tower in Guangzhou, China.

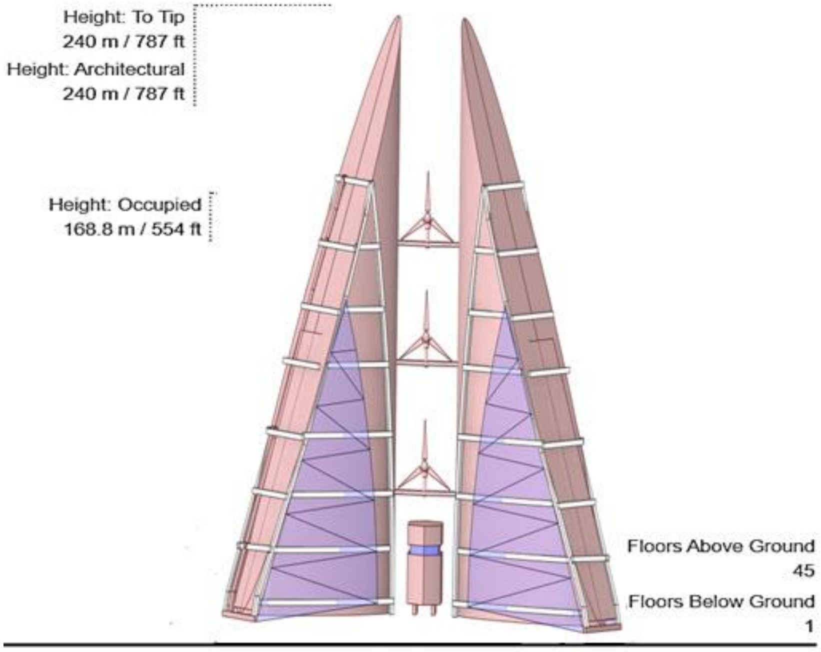

Fig. (2). Schematic of the Bahrain World Trade Center, Gulf view.

2.1. Bahrain World Trade Center

The BWTC is a manifestation of architectural form finding with wind energy integration (Figs. **2** and **3**). The BWTC [9] cleverly integrates the natural wind flow patterns of the wind exchange between the Arabian Gulf and land shore in what is scientifically known as the 'sea–land breeze' phenomenon. The BWTC's

CHAPTER 2

Aerodynamic Architectural Design

Abstract: This chapter attempts to scan various wind aerodynamic responses relevant to buildings that could be utilised for wind energy generation. It highlights some natural ventilation mechanisms and processes that allow continuous air streams amenable to further streamlining for wind energy generation. This study analyses various types of flows and their characteristics. Further streamlining of architectural forms to generate optimal wind flows prior to energy harvesting is discussed.

Keywords: Aerodynamic architectural design, Aerofoils, Aerofoil optimisation, Bernoulli effect, Venturi effect, Wind flow types.

1. INTRODUCTION

Aerodynamic design is a well-established term when it comes to the designs of most transportation means such as cars, trains, ships, and planes. However, apart from planes, only the very high-end products of the other means of transportation are actually designed considering the aerodynamics. This is basically due to the high influence of aerodynamic design on the performance required from racing cars, for instance, wherein air drag and resistance must be exceptionally low, and stability and safety are paramount.

In contrast, for buildings, wind interaction, especially in terms of the design of the building, is normally kept to a minimum either because of the requirement for natural ventilation or because it is stipulated by codes for structural safety and quality of life or comfort. However, for harvesting wind energy as a sustainable energy source at the point where it is made, building design needs to adapt, and therefore, an aerodynamic version of the architectural design must follow suit with high-end transportation means.

The terms aerodynamic architectural design and dynamic design are used in architectural designs to justify ideas that are normally outside the box or more curvilinear and organic in shape. In wind physics, this is not far from the truth;

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however, the air movement mechanisms around buildings are the same regardless of whether the architectural form is curvilinear, organic, or square. However, organic forms may pose less resistance to wind flow.

In nature, wind is produced by various means, such as the Earth's rotation around its axis and temperature differences, which subsequently lead to pressure differences, giving birth to natural convection currents. Air moves from high-pressure to low-pressure regions [1]. These pressure differences are caused by temperature changes in the air due to solar radiation heating of large amounts of land, which, in turn, heats the adjoining air just above the surface. Hot air is less dense and rises, and cooler, denser air descends to take its place. This principle applies to air at all levels in the entire atmosphere, which is hundreds of thousands of kilometres to small rooms, which are several metres in length.

When wind strikes a building's external surfaces, it either separates, accelerates or recirculates, with all three happening simultaneously on the same building, but at different surfaces depending on which surface is facing the wind in which direction. Naturally, only acceleration of wind is favourable for wind energy generation, while recirculation is detrimental. We try to explain some mechanisms that can foster good quality wind for energy generation in the following sections.

2. REASONS FOR AERODYNAMIC ARCHITECTURAL DESIGN

2.1. Ventilation

Ventilation is vital for maintaining freshness, health, and well-being in addition to cooling. Ventilation is needed inside buildings both in summer and winter. In summer, it can further improve passive cooling mechanisms. However, natural ventilation has some limits when it comes to satisfying human comfort to the fullest level. In contrast, unwanted ventilation in winter, where external cold wind infiltrates into the building and is called infiltration, negatively impacts the efficiency of heating systems. A simple solution to this is improving airtightness and seals of windows, fenestrations and other openings. Generally, in buildings, ventilation depends on a number of different factors highlighted in the following sections.

2.1.1. Natural Wind Pressure

Natural wind pressure provides the main general pattern of wind flow at a location. The cityscape generally comes within the natural atmospheric boundary layer, as shown in Fig. (**1**), which contains high wind velocities in the upper levels of the boundary layer and low wind velocities in the lower level, *i.e.* near the ground and around the buildings [2]. However, each building would be more influenced by the structures in its immediate vicinity, such as adjoining buildings and vegetation. Sections 3.4–3.6 highlight simulation studies on the boundary layer around buildings in more detail.

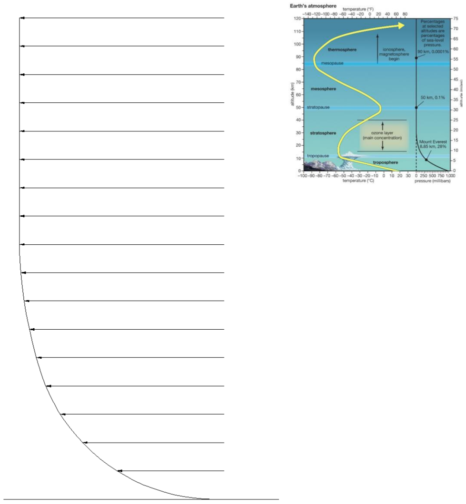

Fig. (1). Natural boundary layer of the atmosphere [3].

2.1.2. Displacement or Stack Ventilation

Displacement ventilation inside buildings occurs due to temperature difference between the lower and higher levels. Therefore, in tall buildings or atriums the stack effect is much more pronounced compared to that in low-rise or short buildings, wherein air stratification in layers of different temperatures become more pronounced. This is an area where many utilisations of this phenomenon exists. This is valid for chimney stacks, exhaust flues to solar collectors and chimneys. The main concern for this is not to mix stack ventilation with fire exits and routes because this would bring fire and flammable gases into what is presumably designed to be a safe exit from fire.

Similarly, for wind energy generation, a vertical stack has to be devoted to this purpose only, where we can generate appreciable wind velocity from vertical shafts that accelerate wind velocity with virtue of its height, obviously to levels beyond the comfort level of the occupants. The taller the building, the higher the resulting wind velocities will be [4]. Such vertical air movement can be even more enhanced with the introduction of more buoyancy of the air by heating it *via*

CHAPTER 3

Wind as an On-site Energy Source

Abstract: This chapter presents tools and indicators that quantify available wind energy resources on site at global, regional, and territorial levels with passable accuracy. It gives some hints of wind availability locally for areas up to 10 × 10 km^2. Areas with promising energy potential are depicted clearly together with other factors contributing to the further enhancement of wind resources such as height above ground level, terrains, and off-shore areas. Moreover, this chapter sheds some light on the capacity factor and provides the means for its estimation as an indicator for the level of achievable wind energy generation enhancement at a location, rendering the value of the structures erected to harvest wind energy as a step forward towards sustainability.

Keywords: Capacity factor, Global wind atlas, High wind velocities, On-site wind quantification, Wind energy availability, Wind velocities.

1. INTRODUCTION

The quantification of wind energy resource has long been relying on metrological data gathered from stations all over the world, normally from airport weather stations, which are the most reliable sources of data for wind energy generation. These data are not always available at the point of individual sites, where they are most needed. However, wind patterns at individual sites can often be highly uncertain and intermittent. The built-up form of the urban environment is the main determinant of wind flows. Therefore, having an overview of wind profiles and patterns would be the ideal starting point. In this regard, the Global Wind Atlas [1] is highly beneficial.

For harvesting wind energy at individual sites, creating favourable opportunities based on the available conditions along with the right choices and further optimisation of architectural forms are essential. It is vital to yearn for realising continuous laminar flows as divulged in Chapters 2 and 4.

Wind energy [2] is generated using mechanical turbines that drive electric generators to produce electricity. Moreover, wind energy is an inconsistent source of power [3]. Therefore, wind energy needs to be supplemented with other sources

Abdel Rahman Elbakheit
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of power generation, such as batteries, solar energy, hydropower, thermal power or even fossil fuels. Regardless, wind energy is one of the cleanest sources of energy production with little negative impact on the environment.

2. WIND ENERGY AVAILABILITY

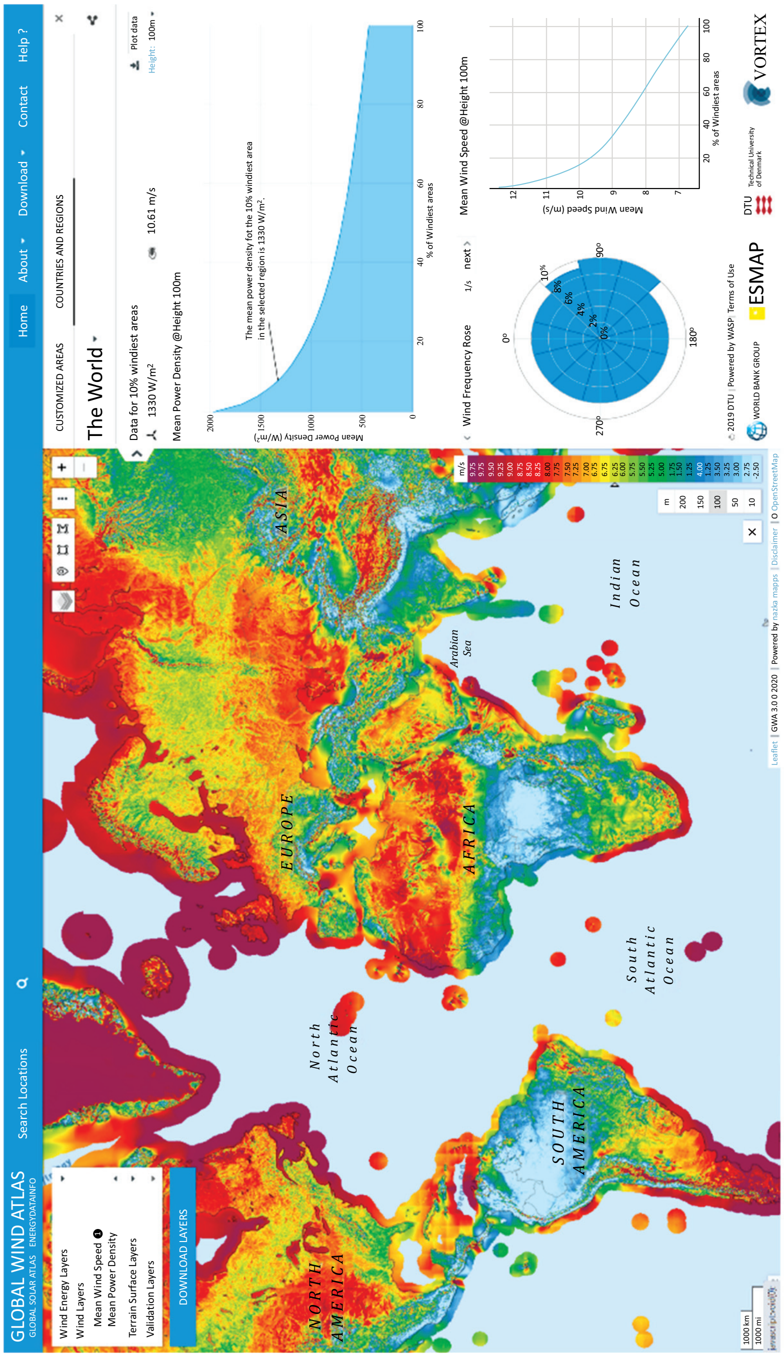
Globally, wind energy has well-established flow patterns [4] considering the geographical locations and timing of the year. Although this (*i.e.*, flow pattern) would be a major stimulant for any particular location, any site can be considered unique in terms of its potential to harvest wind energy [5]. This is particularly evident in urban terrains compared to rural areas because the presence of building clusters, tall or short, trees and other obstructions are detrimental for wind directions, flows and velocities. However, unlike solar energy, wind energy can be available all times of the day, if the relevant measures are taken to reduce the effect of obstructions and to carefully design the required architectural forms.

The World Bank has funded an international database for wind energy potential for every region on Earth called the Global Wind Atlas (Fig. **1**). This database is an online platform available to the general public to download the prevailing statistical data on the wind velocities, wind direction, energy density, mean power density and capacity factor at a range of heights from the ground. The data are quite accurate obtained using a simulation software that has been verified and tested. However, it is not suitable for accurate simulations in areas less than 10 × 10 km^2 plots, where on-site measurements are preferable.

Fig. (**2**) represents the mean power density per square metre globally at a height of 100 m above ground level, where 10% of the windiest areas have a potential of wind energy generation of about 1330 W/m^2 (Fig. **2**). Mean wind velocities within these areas are 10.61 m/s (Fig. **3**). The direction and frequency of wind occurrence throughout the year are presented in Fig. (**4**) *via* a wind rose diagram.

The prevailing wind patterns at a particular site can be obtained in the form of wind rose diagram, as shown in Fig. (**4**), which is obtained from relevant metrological registration offices, showing information about the distribution of wind velocities as well as the frequency of varying wind directions. For instance, Fig. (**4**) reveals that the east and east–south directions are the directions of prevailing wind patterns for the site in question.

It is worth mentioning that when designing buildings incorporating both solar and wind harvesting technologies, there could be some conflict between the need for south-facing orientation with east or west patterns of wind in the same site, in terms of the orientation of the buildings and opening locations.



The mean power density fot the 10% windiest area in the selected region is 1330 W/m².

Fig. (1). Global Wind Atlas showing the calculated wind distribution and the likely frequency with micro level details up to 10 × 10 km^2 at 100 m above ground level [1].

CHAPTER 4

Architectural Aerofoil Form Optimisation for Wind Energy Generation

Abstract: This chapter presents a process enabling architectural design to achieve better prospects of integration of wind energy technologies to achieve sustainability. The process aims to utilise architectural forms, masses and profiles to streamline wind flows around buildings for harvesting wind energy using suitable conversion technology (*i.e.* wind turbines). It extends architectural design palette of form-finding rationale in terms of functionality and economic viability forward to achieve sustainability. Computational fluid dynamics (CFD) provided a springboard for navigating, evaluating and optimising design proposals. CFD capability of projecting air movements around buildings considering the magnitude, direction and pressure impact on the building surfaces is of paramount utility. In this chapter, ways and means to utilise wind separation around buildings are examined, together with aerofoil profiles capable of providing conducive conditions for wind flows to be harvested by turbines. Some parameters of these aerofoils are investigated, and guidelines for their optimum performance are defined, namely, aerofoil proximity to the building surface and the angle of attack of the aerofoil. This process would multiply incident wind velocities by up to 30% during periods of low wind velocities (*i.e.* lower than 5 m/s) and up to 150% during periods of high wind velocities (*i.e.* greater than 5 m/s).

Keywords: Aerofoils, Augmented wind energy system, BAWES, CFD, Ducted wind turbine, Fluent, Wind energy optimisation, Wind energy integration in buildings.

1. INTRODUCTION

Wind energy integration into buildings has been gaining growing interest and implementation from both the building industry and the wind energy industry, such as the work of Grant A. and Kelly N. [1], wherein they introduced a prototype of ducted wind turbine at the parapet of a tall building.

The study in this chapter started in 2003 as a part of the author's PhD research that was completed in 2007 [2], was developed further for publication in 2014 [3] and has been updated for this book. Concurrently, since 2007 numerous researchers have worked on small-scale building containing mounted turbines

Abdel Rahman Elbakheit
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within a shrouded or ducted system. Sharpe T. and Proven G [4]. integrated wind turbines in a concept called Crossflex building. Buildings integrated with vertical-axis wind turbines were worked on by Müller G. *et al* [5]. Suitability and estimation of wind energy generation in urban settings was investigated by Walker S [6]. Buildings integrated with ducted wind turbine prototypes were tested and modelled by Andrew G. *et al* [7]. Site conditions for roof mounted turbines were examined by Ledo L. *et al* [8]. The Makoto Iida proposal of the vernacular design for wind turbines was studied by Chuichi A. and Seiichi A [9].

An innovative design for a ducted wind turbine claiming an extraction power of 80% higher than that of a standalone turbine, nevertheless without building integration, was introduced by Ssu-Yuan H. and Jung-Ho C [10].

A theoretical model and simulation comparison of a ducted wind turbine mounted on a building was introduced by Watson *et al* [11]. The building's influence on wind separation and acceleration and turbine resistance to flow patterns in the duct were discussed by them. They concluded that the inlet of the duct should be optimised in order to improve the swallowing of air into the duct. This is investigated in more detail in sections 6, 7 and 7.1.

Further on the issue of building-integrated wind turbines, this study adopts an approach that focuses on specific scenarios of architectural forms, masses, and components, with favourable conditions suitable for an extra boost to wind energy generation, besides being readily available for replication or reproduction in one way or other. In an attempt to improve the reliability and continuity of wind energy generation, wind separation and its due acceleration is the cornerstone of this investigation. Thus, it is vital to understand how to utilise wind separation in an effective manner.

2. ANALYSIS OF WIND TURBINE INTEGRATION INTO BUILDING DESIGN

2.1. Assumptions

A house with a generic design (Fig. **1**) is prepared to optimise wind energy generation through the integration of wind turbines. Several houses are linked together to form a cluster, which will endorse the assumption of using asymmetry condition for any section across the cluster in CFD simulations.

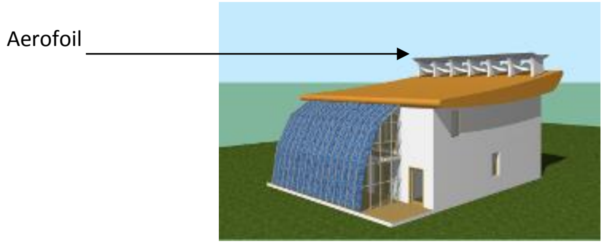

Fig. (1). Typical wind turbine integrated in a prototype house. Aerofoil profile on the high end of the roof.

2.2. Wind Turbine Integration

As mentioned in Chapters 1 and 6, higher heights from the ground level in the built environment would be more suited for integrating wind turbines due to the mainstream flow that is more continuous with less turbulence and interruptions. Therefore, the wind turbines were integrated on top of the roof. The roof is a single-pitch roof sloped to the side facing the wind from the lower edge of the roof. The building façade from windward side shaped like a curved curtain wall starting from the ground and ending at the eave of the roof from its lower edge (Fig. **1**). The curtain-wall façade incorporates photovoltaic panels. However, more importantly, it reduces resistance to wind flow to the top of building where the turbines are placed. An aerofoil is incorporated at the top of the roof with turbines integrated in the space between it and the roof of the house. Vertical-axis wind turbines are fixed with their axes aligned horizontally, as shown in Figs. (**1** and **2**). This allows shorter distances between the aerofoil and the roof to be examined as well as the many benefits of vertical-axis wind turbines, such as quietness, low speed operation and less vibration.

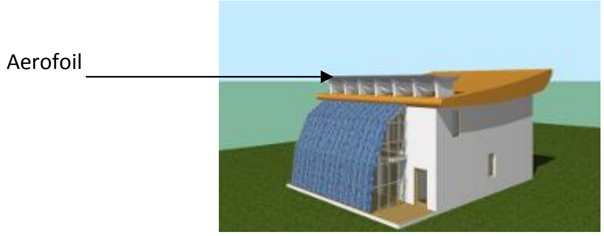

Fig. (2). Typical wind turbine integrated in a prototype house. Aerofoil profile on the low end of the roof.

CHAPTER 5

Building-Integrated Wind Turbines

Abstract: Building-integrated wind turbines have special qualities that distinguish them from the entire wind turbines industry, which include the need to be much quieter, while maximising energy generation considering the limited swept area of the turbines. This has inspired a great deal of innovations that need to be investigated and revisited for further improvements across architecturally optimised buildings incorporating wind energy generation or building-integrated wind turbines. The aim is to draw some lessons or perhaps to mimic their principles within suitable architectural forms. One of the lessons learnt from a diffuser design that can be translated into building design to augment wind turbines is the area ratio, *i.e.* ratio of outlet to inlet areas, and length–diameter ratio, *i.e.* ratio of length to diameter. The larger these ratios, the larger the expected power output of the augmented wind turbines will be.

Keywords: Building-integrated wind turbines, Diffusers, Duct augmented wind turbines, Silent wind turbines, Vibration control.

1. INTRODUCTION

There is a specific chapter in this book only on building-integrated wind turbines because majority of the enhancements in architectural designs to meet elevated extents of wind energy generation could be made at the level of individual small wind turbines. As such, they can operate as stand-alone machines or integrated into buildings at some point. Although these individual turbines may be very well engineered to solve several specific issues, it would be sometimes too late for them to be integrated in buildings in the first place, or if they do, they would likely lose out on maximising the potential of the available wind resources for harvesting it, unless the individual turbines are considered as a part of the architectural design from the onset.

These stand-alone turbines or ‘building-integrated wind turbines’ can be very innovative in solving issues such as noise and vibrations and can maximise the wind velocity to a great extent. Some of these features are discussed in the following sections:

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2. NOISE REDUCTION OR PREVENTION

'Swift wind turbines' are good examples of addressing the problem of noise in wind turbines. These turbines were originally designed and engineered by the Scottish company, renewable Devices, a resemblance of which is shown in Fig. (**1**). The original 'Swift wind turbine' had five blades made of carbon fibres with an overall diameter of 2.1 m and a distinctive circular outer rim and two positioning blades. This turbine can produce 1.5 kW of electricity from 14 m/s of wind velocity. They work on the principle that the sound generated by the evenly spaced blade tips actually comes from the blade's tips having the maximum rotating speed on the turbine, disturbing the wind molecules at equal intervals (*i.e.* the spacing between the blades). This is how sound waves are generally created in nature [1]. By providing an extra outer rim connecting the tips of the blades, they eliminate the interval gabs that create the rhythmic excitation of the wind molecules. Therefore, reducing or eliminating the noise created by the tips of the blades, which is typically the loudest noise generated by such small-scale turbines. Other inner parts of the blade can also create this noise, but they rotate at a lower velocity and therefore create lesser noise.

Fig. (1). Swift wind turbine with rim around tip of blade. Courtesy of the Scottish company, Renewable Devices.

This noise generated by wind turbines is classified as airborne noise, where the sound is generated and propagated through air. The most efficient way of blocking it, is by total isolation of the air around the source of the noise from the air where occupants reside. Architecturally, this means providing an air-tight building envelope that separate and isolate these two areas of noise generation and noise reception. However, outside the building, the noise would still be present. Therefore, only activities that are not affected by noise could be undertaken outside the buildings.

3. WIND-INDUCED VIBRATIONS IN WIND TURBINES

Wind-induced vibrations in wind turbines can be expressed in two forms:

First, vibrations induced by the mechanical energy resulting from the rotation of the turbines. These vibrations reduce the mechanical energy conversion into electricity and may influence potential faults. Second, vibration induced by the aerodynamic excitation of the structures supporting the turbines. These vibrations result from the uniformity of the support sections and affect the stability of turbines and structures alike.

Moreover, reducing these vibrations can considerably diminish if not eliminate damage to critical parts of wind turbines such as supporting posts, drivetrain, blades and gear [2], if simulated beforehand using computational fluid dynamics, CFD for instance. While vibrations are mostly caused due to aerodynamic behaviour, different parts of the turbines react to the vibrations differently. In addition, different components have different types of vibrations. For example, low-frequency vibrations in the range 0–200Hz are common in the tower post or the main structure, while high-frequency vibrations in the range 3–20 kHz are common in the gear and drivetrain. We can identify the causes of vibrations in different parts according to the steps followed in a previous study [2]:

Tower Post: It is the supporting structure that is usually towering high to support and enable turbines to harvest energy from high-velocity winds. This post may be subjected to vortex shedding that causes vibrations and oscillations due to the uniformity of its cross section. It worth mentioning that tall buildings can function as supports to wind turbines, thereby eliminating the need for separate supports for the turbines.

Turbine Blade: Turbine blades with different pitch angles can produce vibrations in the turbine, accompanying gear and supporting structure, or in any of these components alone. Different pitch angles would also cause an unsteady angular rotational speed.

CHAPTER 6

Effect of Turbine Resistance and Positioning on the Performance of Aerofoil Building-Augmented Wind Energy Generation

Abstract: In this chapter, more insight into the benefits of aerofoils and their integration into architectural forms to further enhance wind energy generation is investigated. More light is shed on wind flows around and under the aerofoil, when introducing turbines as resistance to flow under aerofoils. Turbine resistance is introduced using porous jump in CFD ANSYS FLUENT. The estimated energy generation is calculated based on the resulting wind velocities, pressure drop and area per square metre. In general, resistance from turbines lowered the resulting wind velocities; however, this reduction was the lowest for the optimised case (Chapter 4). The resulting wind velocity was 13.2 m/s for optimised case and 10.85 m/s for the unoptimised case. In addition, the optimised case exhibited a greater pressure drop across the turbine than that of the unoptimised case, thus producing 1.6–1.9 times more energy than that of the unoptimised case. For the same cases, an increase in energy production of up to 3.38 times is obtained by appropriately placing the turbine (*i.e.* 2 m from the tip of the aerofoil on the windward side) [1].

Keywords: Aerofoils, Architectural forms, BAWES, Building-augmented wind energy systems, Building-integrated wind turbines, CFD, Duct-augmented wind turbines, Wind energy optimisation.

1. INTRODUCTION

Renewable energy technologies are increasingly developing to become the next primary sources of energy worldwide [2]. This is especially evident with the promise it holds for solving some of the most pressing problems facing the globe (IPCC 2014 annual report [2]), such as increased CO_2 emissions, increased energy demands and continuous population growth. Renewable energy sources such as wind, solar, geothermal and tidal energies can significantly contribute to this.

Owning to the high energy demand from the built environment, which amounts to higher than 60% of the global energy demand, great efforts are in dire need to provide reliable sustainable options to satisfy such a large share of energy

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demand. Moreover, the high potential of wind energy generation complements the requirements of the built environment in terms of versatile perspectives, such as availability, accessibility, reliability and return on investments. This appears to be a very plausible option to purse. In this regard, small-scale wind turbines provide a very promising option for the built environments. However, several obstacles must be combated, such as very low wind velocities to be harvested and the variability of wind patterns or turbulence. Few remedies to these problems already exist, which are architectural forms, aerofoils and shrouds [3].

The choice of architectural forms, building massing, solids and voids in buildings' forms have great influence on wind patterns at a certain location. Aerofoils and shrouds are fixed shapes designed to channel wind around buildings and reduce turbulence, while accelerating wind flow [4]. Turbines are normally fixed in between aerofoils and buildings. Aerofoils provide further enhancement to the environment around buildings by reducing noise levels from turbines, protecting the buildings in the event of blade detachment and enhancing the appearance of buildings. Further investigation into the wind velocity augmentation by means of aerofoils is undertaken in this chapter. Following on the discussion in Chapter 4 and using the same building design of a detached house described in that chapter, this investigation was conducted.

2. EFFECT OF TURBINE RESISTANCE ON RESULTING VELOCITIES AND FLOW PATTERNS

To examine turbine resistance to the flow under an aerofoil, a turbine is simulated as a pressure drop surface by means of a porous jump boundary condition in ANSYS FLUENT. Initially the turbine is positioned at the shortest distance between the aerofoil and roof at 3.39 m to the right of the aerofoil.

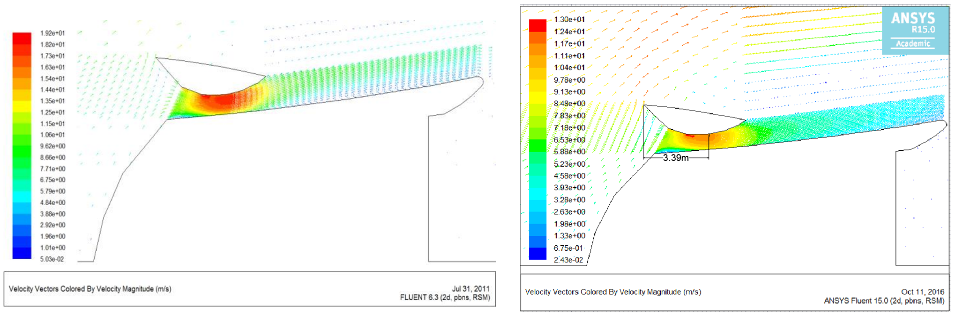
'Turbine resistance' or 'blockage effect' are two terms denoting the same effect, which is how a turbine is obstructing wind flow. This obstruction applies more for drag type turbines than for lift type turbines.

This parameter is calculated as $\frac{A^T}{A^T - A^F}$,where A^T is the space below the aerofoil and A^F is the turbine swept area.

Two main scenarios are followed. The first is the optimised case with the aerofoil placed 85 cm from the roof surface with an angle of attack of 50°. The second is the base case of investigation, wherein the aerofoil is placed 220 cm from the roof surface with an angle of attack of 20°. The study compared these cases with and without turbine resistance effect. As a result, two categories of results were obtained:

2.1. Effect of Turbine Resistance on Wind Flow Patterns

We know that the shape of the aerofoil is the main determinant of the flow around it, specifically the angle of attack and the aerofoil's distance from the roof [3]. In Figs. (**1** and **2**), the flow patterns around the aerofoil are compared for two scenarios. The optimised case is shown in Fig. (**1**), and the unoptimised in Fig. (**2**). Furthermore, for each case, an additional case with turbine resistance is incorporated with the ensuing wind pattern revealed.



1(a) 1(b)

Fig. (1). Optimised aerofoil **(a)** with no turbine resistance and **(b)** with turbine resistance: 90% blockage effect.

In these figures, the following have been noted:

First, less pronounced separation and therefore lower resistance to flow was observed in the optimised case compared to those in the unoptimised case.

Second, better acceleration is noted in the optimised case than that in the unoptimised case, despite the fact that both have improvement in wind velocity or acceleration as Tables **1** and **2** reveal.

Table 1. Effect of turbine resistance below the aerofoil (turbine simulated with porous jump).

Case	Mean Velocity. m/s	Max. Velocity m/s	Pressure Coefficient Cp
Optimised	10.44	13.2	−82.03
Unoptimised	9.90	10.85	−40.41

CHAPTER 7

Conclusion

When considering the architectural design process in general and system-based architectural design in particular, the architectural form-finding process can be further elaborated by taking wind energy generation potential on board. However, as usual, every building design has it peculiar set of requirements from the client's brief, code requirements, context site stipulations, just to name a few, which also must be accounted for. Therefore, each building design is unique and tailor-made. Aerodynamic architectural design follows suit in this regard. However, there are principles of air movements that should be considered as opportunities to arrive at good working solutions. In this sense, aerodynamic form may resemble the acoustical form in the careful planning, arrangements need to be in place, and then, testing/simulation and optimisation are done until a final resolution is obtained. Thus, the architectural design palette of form finding could be further enhanced with aerodynamic optimisations to achieve sustainability. Whereas the acoustical form represents favourable sound performance and interior views of auditoriums, aerodynamic form represents the visual image of the project, in addition to invisible, but quantifiable, valuable renewable energy. Thus, the entire architectural form of the project has to mix the architectural expressions with wind aerodynamics. Another benefit of aerodynamically optimised architectural forms is that it takes full control of the building's structural stability and eliminates vortex shedding through the choice of unsymmetrical, carefully sculpted forms. Not optimising architectural aerodynamic forms may render buildings susceptible to huge costs of employing structural damping measures and solutions. Tall buildings benefit from the high wind energy potential compared to low-rise buildings owing to their height and the unobstructed air flow of the upper atmospheric layers. Architectural form for wind energy generation capabilities can be optimised, gauged and compared based on 'capacity factor' determination, which provides an indication of how the design improves wind energy generation potential in a particular site, thereby gauging its level of sustainability.

This book proposes a number of aerodynamically stable forms of tall buildings along with measures for combating vortex shedding, of which, rotational forms are generally considered one of the safest forms that exhibit high stability in wind tunnel tests and CFD smulations. Moreover, architectural design may utilise natural wind movements as an impetus for both natural ventilation and wind energy generation.

Low-rise buildings lead to more of wind separation occurring at the corners of the built environment since they evoke wind acceleration amenable for harvesting using the right technology.

A simultaneous product of wind separation is a varied distribution of pressures, which leads to suctions, turbulences and uplifting. These may be resolved by the right forms of profiles of aerofoils as well as by the right choice of materials that may limit if not eliminate the unwanted effects of wind separation.

Otherwise, resolution to some special structural design has to be made. Structures have always been the backbones of architecture. Their role may extend to supporting some architectural designs integrated with wind energy generation equipment for stability. In addition, the Bernoulli effect, Venturi effect and stack effect are techniques to generate continuous fairly speedy streams of air that could be employed for building-integrated wind energy systems.

Aerofoils are an invaluable asset in streamlining wind separation around buildings, and the therefore assist wind turbines in receiving the laminar flow needed for successful operation. The acceleration between aerofoils and buildings occurs because for an incompressible fluid flow, the product of the flow velocity and cross-sectional area at any point along the flow within a restriction is constant. This can be expressed as follows:

$$V1\ A1 = V2\ A2 = VnAn, \qquad \textbf{(3) (Chapter 2)}$$

where V is the flow velocity at a point and A is cross-sectional area at the same point.

Hence, the velocity V2 can be increased to the desired value by reducing the area A2 accordingly.

When considering quantifying the wind resources at a given site, wind energy availability can be obtained from accurately simulated data in addition to the metrological data. However, the former is not always readily accessible, while the latter is normally confined to macro levels. Nevertheless, each site has its own architectural form that entirely dictates the type of wind regime.

CFD assists in examining flow conditions around buildings and guide processes of optimising wind flows for optimum performance of wind energy generation technologies.

The study has confirmed the usefulness of aerofoils in augmenting wind flows that could be harvested using turbine's efficiencies exceeding the Betz limit compared to those of standalone turbines.

The investigated aerofoil profile could accelerate wind velocities by factors varying from 0.53 to 3.5 times compared to those under the Betz limit, *i.e.* from below the limit to over 6 times over the limit, depending on present wind flows.

Aerofoil profiles to boost wind energy generation can be incorporated into buildings during the design stage or after construction. Small- to medium-sized vertical-axis Savonious wind turbines are recommended for use with aerofoils.

The main factors influencing wind acceleration into turbines using aerofoils are the proximity of the aerofoil to the building surfaces and the angle of attack.

This investigation revealed that an angle of attack of 50° would assist aerofoils under consideration achieve the highest possible wind acceleration.

The proximity of aerofoil to the roof of the building that delivered the highest possible wind acceleration is 85 cm.

This investigation has shown that aerofoil position has a great influence on the ensuing wind acceleration. Aerofoil positioning together with careful planning for wind separations secures successful performance.

This process can be applied to any given building design situation to guarantee optimum performance.

Aerofoil parameter optimisation can enhance control over wind separation and can eventually lead to both lower resistances to flow and better energy harvesting.

Wind flow patterns under the aerofoil can vary from localised jets under the aerofoil to the entire area under the aerofoil flowing as a high-velocity jet of air. Optimisation generally leads to the entire area being under the influence of the highest wind velocity. However, localised jets may be much suited to Savonius wind turbines.

The incorporation of wind turbines under the aerofoil eliminated flow separation on the leeward side.

Wind acceleration under the aerofoil would be higher when no turbines are integrated. However, optimising aerofoil parameters ensures the highest possible wind acceleration under the aerofoil even after turbine integration.

Turbine resistance to flow lowers the pressure drop.

SUBJECT INDEX

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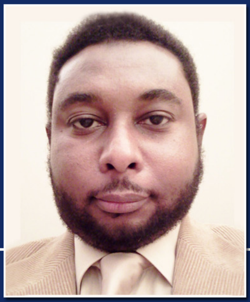

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