Investigations on the integration of Vertical Axis Wind Turbines in High-rise Buildings

Omar Osama Helmy

60033

Supervised by:

Dr. Bassam Abu Hijleh

M.Sc. in Environmental Design of Buildings

Institute of the Built Environment

British University in Dubai

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بسم الله الرحمن الرحيم

IN THE NAME OF ALLAH, THE BENEFICENT, THE MERCIFUL

ABSTRACT

The potential of wind energy as a renewable source is widely recognized these days, with wind farms multiplying all around the world. However another application for wind turbine is now gaining interest, the concept of integrating wind power harnessing in the urban environment. The prospective of harnessing energy were it is needed the most and avoiding expensive long distance networks is quiet appealing.

This thesis investigates this potential by studying the suitability of different turbine types for urban integration. From the literature review, it seems that VAWTs though much less common of the two main types, is much more suitable for urban integration.

A mathematical study was then conducted on four different cities with different wind characteristics to estimate the potential power that can be harnessed by each turbine type in each case. Two modern turbine prototypes were then selected from the two main categories and their power curves was applied to the wind data to calculate the potential power output. Last, the enhancement of the wind energy potential for turbines mounted on high-rise buildings was investigated, through calculating the wind speeds at the respective heights.

The second study approach evolved the use of CFD to simulate a number of VAWT integration scenarios in high-rise buildings based on the first part of the research. The wind movement characteristics where observed for the turbine installation location and a calculation was made to estimate the available mass flow rate in each case.

Results show a big potential in the integration of VAWT in buildings and promising power gains from increasing the installation height.

DEDICATION

I dedicate this work to my loving wife
and beautiful daughter…

ACKNOWLEDGMENTS

First of all I must thank Allah the Sustainer and the Gracious for his numerous blessings and bestowments. And pray to him that this work serves the good for this world.

I would like to thank my advisor Prof. Bassam for his continuous guidance, help and support, during this dissertation and throughout the Masters course. His continuous encouragement and enthusiasm in one's work had a positive effect on me to achieve more and work harder…

No thanks are sufficient to the sacrifices that my Mother and Father did for me throughout my life, they are the reason for everything good that I am now, I owe everything to them. Their encouragement was the driver for this challenge…

I would also like to express my everlasting gratitude to my wife who has bared the full burden of my studies throughout the last two years. Without her support and sacrifices I could not have done this…

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NOMENCLATURE

A	Area of air mass
a	Terrain factor at required site
a_{met}	Terrain factor at meteorological station
$BUWT$	Building Augmented Wind Turbine
CFD	Computational Fluid Dynamics
C_p	Coefficient of Power
d	Boundary layer thickness
d_{met}	Boundary layer at meteorological site
h	Height at which the wind speed is required
$HAWT$	Horizontal Axis Wind Turbine
H_{met}	Height of anemometer
m	Mass of air
P_o	Power Extracted by Turbine
P_w	Wind Power
r_m	Maximum radius of rotor
V	Velocity of upwind air
$VAWT$	Vertical Axis Wind Turbine
V_h	Wind speed at required height
V_{met}	Wind speed at meteorological station
V_o	Velocity of downstream wind
w_m	Angular velocity of turbine
x	Direction of air movement
ΔU	Change in Kinetic Energy
Δt	Change in Time
λ	Tip Speed Ratio
U	Kinetic Energy
ρ_o	Standard air density sea level
ρ	Air density

CHAPTER 1 INTRODUCTION

1.1 OVERVIEW

This chapter introduces the problem of Climate Change and the Energy Crisis. Then establishes the use of "Renewable Energy" as a solution for these problems and focuses on wind energy as the topic for this dissertation. Later it highlights the aims, objectives and research questions for this dissertation. Finally it describes the structure of the research.

1.2 OUTLINE

Nearly every single day, in every part of the world we see the effect of wind, blowing leaves, swaying trees or steering waves. However, only recently did we start to scratch the potential of wind energy. And although man has used wind energy for a long time to propel ships across oceans and less often to drive simple machinery and pump water. It seems that the convenience of burning fossil fuels has made us forget this profound bless.

However now with the increasing awareness of the problems our world is facing, people are looking back to natural sources of energy as an alternative to fossil fuels and polluting energy sources. Wind energy is a major source of sustainable energy that is relatively pollution free, abundant nearly everywhere and tap-able on site. Scientists estimate that 72TW of wind energy can be commercially viable from the wind on Earth. *(Wikipedia Online Encyclopedia, 2009. Wind Power)*

With the exponential increase in the world's population and move towards urbanization, cities are growing bigger and bigger. This made the concept of integrating wind energy (or any other renewable energy source) within the urban environment that more attractive. Being able to tap energy right where it is needed makes sense. However, as will be explained in detail, this requires advanced technological measures to make this concept viable. Mounting a wind turbine in an urban environment is a totally different exercise from wind farm implementations.

Another phenomena that is now widely apparent in our urban environment, is vertical development. With the ever increasing price of land near city centers, tall-buildings, towers or skyscrapers are becoming a sign of rapidly growing cities. Looking at a city like Dubai or Shanghai, one realizes that towering buildings that were considered feats of isolated ambition are now the paradigm's norm.

These tall buildings though are usually considered a strain on the environment. Are now being looked at for their potential in harnessing local forms of renewable energy. Towering above the urban fabric, they have the advantage in the exposure to higher velocity, less turbulent wind at height. This potential if realized could offer great advantages.

This research investigates the potential of integration wind energy harnessing turbines in the urban environment with the emphasis on tall buildings.

1.3 BACKGROUND

1.3.1 CLIMATE CHANGE / GLOBAL WARMING

The Earth's Climate is apparently in a state of continuous change. This has happened naturally throughout the life of the planet for several reasons, including major volcanic eruptions, changes in the Earth's orbit, Sun surface activity and meteor collisions. These changes have been proved and documented by scientists. The number of Ice ages that the planet has seen is a proof for this change. *(United Nations Environment Programme, 2002)*

However, recent findings have proved that although man's existence on Earth has been found to be as old as hundreds of thousands of years, the last 100 have been the most severe. With the industrial revolution and the beginning of the industrial age, man's foot print on earth has multiplied significantly. The amount of CO_2 and other forms polluting gases that have been emitted from burning fossil fuels, together with the huge deforestation that has taken place. Both contributed to severely affect the climate on Earth. These gases prevent heat absorbed by the earth from re-radiating back to space, just like glass panels do in greenhouses.

These facts though have been doubtful for years, have now been proven several times, in many ways including CO_2 levels in ice core samples from the South Pole. This has also happened in the past for several natural reasons as explained before. Also the relation between CO2 levels and the world surface temperatures have been proven from past records.

“According to NOAA and NASA data, the Earth's average surface temperature has increased by about 1.2 to 1.4ºF in the last 100 years. The eight warmest years on record (since 1850) have all occurred since 1998, with the warmest year being 2005. Most of the warming in recent decades is very likely the result of human activities.” *(Adam, D., 2008)*

At the start of the Industrial revolution in the mid 18th century, there were 280 parts per million (ppm) of CO2 in the atmosphere. Today the overall amount of GHGs has topped 390 ppm CO2e (parts per million of carbon dioxide equivalent – all GHGs expressed as a common metric in relation to their warming potential) and the figure is rising by 1.5–2 ppm annually. Reputable scientists believe the Earth’s average temperature should not rise by more than 2°C over pre-industrial levels. *(US Environmental Protection Agency, 2009)*

The effects of climate change are profound and widely reaching. These effects include the rising of sea levels due to the melting of the ice shelves, altering of precipitation patterns, which means flooding in parts of the world and droughts in others. Also it has been predicted that climate change can cause the increase in the frequency of extreme weather.

The predictions made on the long term effects of climate change include: Vast areas of land will be submerged by the rising sea levels, loss of fertile land

and inhabited areas. This will definitely lead to migration of millions of inhabitants to parts less affected, which will further strain the resources. *(Bates, B.C., et al., 2008)*

1.3.2 ENERGY CRISIS

From the early days of mankind, human beings have realized that our planet is abundant with different forms of energy that can be tapped and made use of to facilitate his everyday life. The first forms of energy used by man were the forces of nature like the force of flowing water and blowing wind. However for the most part of the human existence, man has mainly relied on his own strength or that of cattle to drive his machinery. *(Worldwide Energy Shortages, 2008)*

This all gradually changed in the late 1700s when the scale of human manufacturing grew beyond the capabilities of man or animal power. At the same time several inventions were realized that made use of other forms of energy. Mainly the use of fossil fuels started taking center stage. Beginning with the use of steam engines powered by coal, to the internal combustion engine and gas turbines. Man found an easy and relatively abundant form of energy that can be tapped and used efficiently.

From there, societies grew in leaps and bounds and growth occurred on unprecedented rates. The GDP of countries doubled in no time and with better working conditions and health services the population of the world grew rapidly. This lead to a world highly dependent on fossil fuels and with fading interest on natural occurring energy. In 2004 the Global energy consumption was about 15TW, with renewable energy accounting for less than 1% of that (0.13TW). *(Wikipedia Online Encyclopedia, 2009. World Energy Resources and Consumption)*

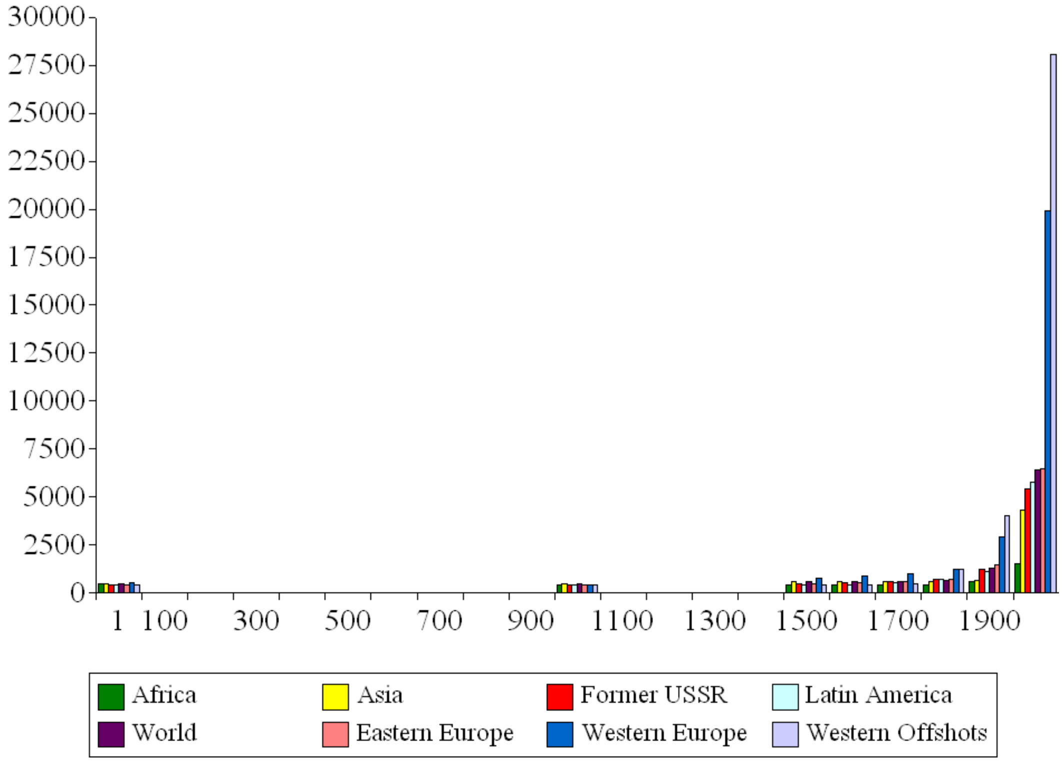

Figure 1 - World GDP Capita 1-2003 A.D

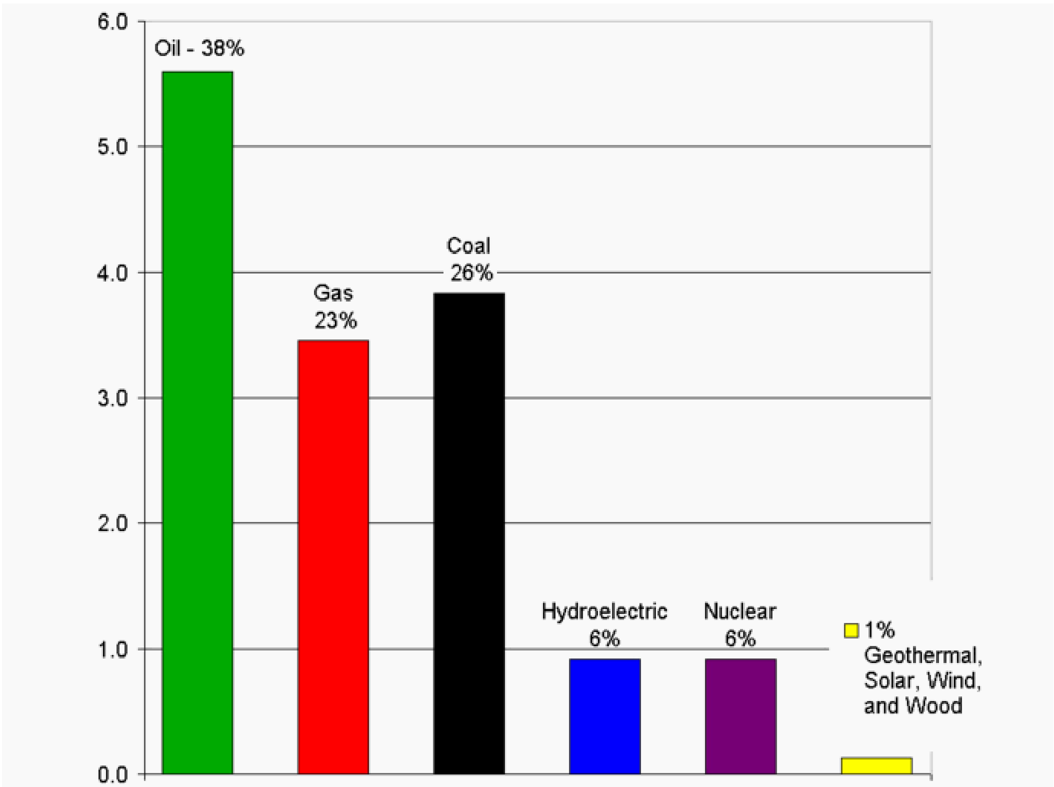

Figure 2 - 2004 Worldwide Energy Sources

This not only meant that the world resources of fossil fuels are over-consumed, but more importantly that the major sources of energy are running out. Many of the oil fields currently tapped are expected to be depleted within the next 80 years. *(AME Info, 2005)*

Moreover, the price of fossil fuels rose continuously over the past 40 years, reaching a level where it had an immense impact on the economies of developed and undeveloped countries alike. For example the average price of a barrel of crude oil from the 1980s till 2003 was usually under 25$. However since 2003 a steady increase in the price, peaked out on July 2008 at around 147$ per barrel. *(TFC Commodity Charts, 2009)*

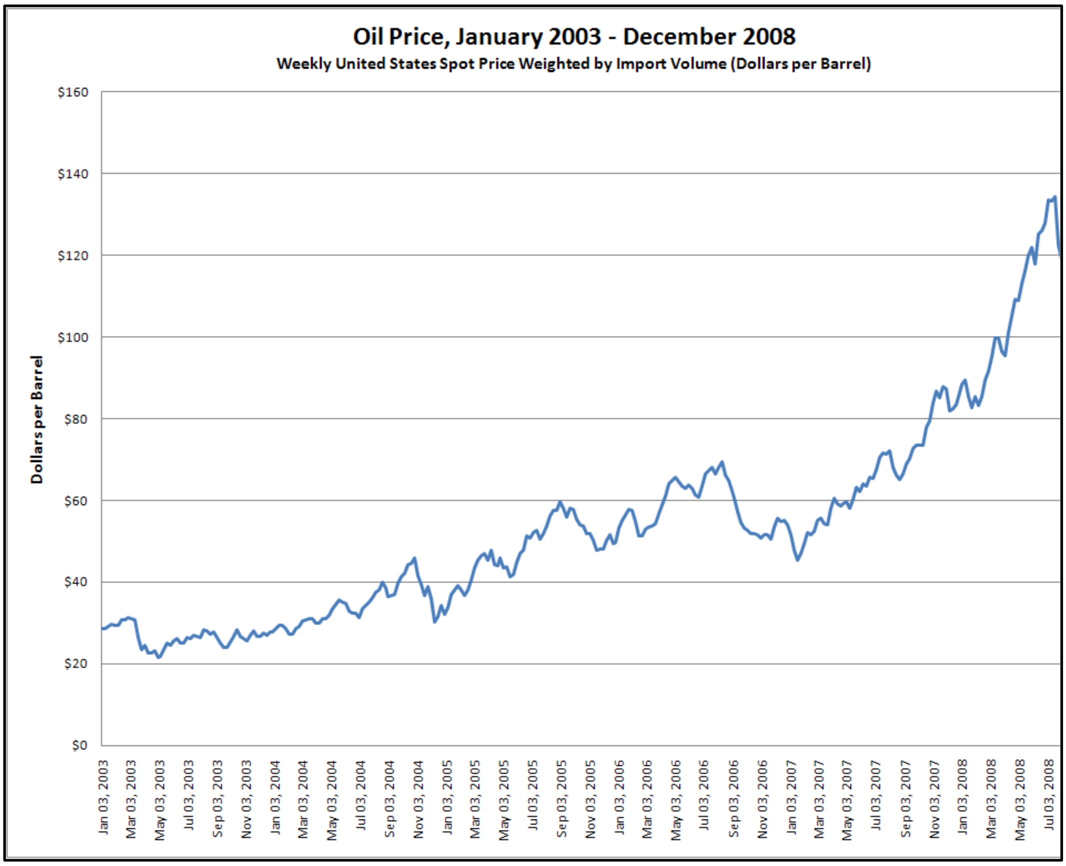

Figure 3 - weekly United States spot price of crude oil

1.3.3 SOLUTIONS

As the dangers of Global Warming and the Energy Crisis has been highlighted, it's very essential that measures should be taken to help solve and mitigate those problems. Three main approaches have been highlighted:

1. Increasing the efficiency of current power plants and propulsion engines to use less fuel and to burn it more cleanly.

2. Reduce the dependence on fossil fuel usage by introducing renewable energy sources that have a very low or no negative impact on the environment.

3. Energy conservation methods to reduce the quantity of energy requirements especially in the built environment.

1.3.4 RENEWABLE ENERGY

DEFINITIONS AND TYPES

Renewable energy sources are generally understood as those sources of energy that are generated from natural resources like the power of sun, wind, tides and biomass. These resources are relatively abundant and widely available on earth and can be distinguished from un-renewable sources of energy in being continuously replenished naturally. *(Clean Energy Ideas, 2008)*

"Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time". Renewable energy resources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action. *(Texas Renewable Energy Industries Association, 2008)*

A number of energy sources are currently known to man, with different approaches to harness these sources. During the 20th century, especially the first half (till the 70s) low prices of fossil fuels have discouraged extensive work on harnessing renewable energy, and renewable energy remained relatively expensive except in isolated areas outside the reach of power networks. However due to the two previously mentioned reasons (Spiraling fossil fuel prices and international awareness of the global warming phenomena) Interest in Renewable Energy resources have gained momentum. And currently every nation and community is looking locally for the available natural energy sources and researching the possibility of harnessing these resources.

Below is a summary of the more established forms of renewable energy currently explored. *(Beckert, E. & Jakle, A., 2008)*

SOLAR ENERGY

From the early days, human beings have realized the potential in the sun's light and warmth. Civilizations have tended to settle where enough sun light is available. However we had to wait till the 20th century to realize the full potential of the sun's energy and its importance to life on earth. Literally most forms of energy on earth are derived from solar energy.

The Earth receives every hour more energy through solar radiation than is used by the whole world in full year. This radiation ranges from visible light spectrum to the invisible ultra violet and infrared rays as well as x-rays and gamma rays. About 30% of this radiation is reflected by the Earth's Troposphere, while the rest is absorbed. Just harnessing a small fraction of this energy could supply the whole

Figure 4 - Solar Panel Array

earth with it’s energy needs. *(Patel, M. R., 1999)*

For the most part of our history we have been trying to harness this energy, simply by exposing ourselves to sun rays for warmth and letting in the sun light. However as technology advanced, two main methods of harnessing solar energy have been realized:

PHOTOVOLTAICS:

The process of directly converting solar radiation to electric current was first realized through the use of solar panels. The first success was achieved by Charles Fritts in the 1880s through the photoelectric effect. In his work he used Selenium cells which had an efficiency of less than 1% in converting solar radiation into current. By the 1940s Silicon started to show potential for use in solar cells and in 1954 a group of scientists created the first Silicon based solar cell, achieving 4.5-6% efficiency. By the 1960s solar cells where already being used as a power source on satellites.

These early cells where quiet expensive per energy produced. However the cost of manufacturing solar cells continuously declined and in parallel their inherit efficiency increases steadily. Many different new types of solar panels are now available in the market, however three main types should be highlighted: mono-crystalline, poly-crystalline and thin film (Amorphous).

SOLAR THERMAL:

Solar Thermal is the process of converting solar radiation into thermal energy. This energy can then be used directly or converted into other forms. This type of conversion has been quiet successful and easy to implement without complicated

Figure 5 - Solar Thermal collector

technology. This and the fact that relatively high efficiencies can be achieved has made solar thermal a tempting form of renewable energy.

It is hard to state when man started to look at using the sun's radiation for thermal energy. However the modern use plate collectors for harnessing solar energy has probably started as early 1860s. This remained very limited to solitary experiments in rural areas, till the 1970s when the oil crisis forced people to re-think about using solar thermal devices. There are two main types of solar thermal devices:

- Flat plate collectors: which are commonly used to heat water or a similar liquid to between 90-120oC this water is used directly or used to heat inhabited spaces.
- Concentrated solar collectors: These usually use a series of reflectors or collectors to concentrate solar radiation onto a relatively small area. This method can achieve very high temperatures and pressures for the heated liquid. This liquid can then be used to drive equipment or generate energy through steam turbines.

SOLAR ENERGY INTEGRATION IN BUILDINGS:

Solar systems whether thermal or photovoltaics have been successfully integrated in a large number of buildings around the world. Due to their flat nature, Photovoltaics are easier to install as a replacement to cladding or fixed on flat surfaces. These then are connected to power networks and through inverters, or their power is stored in batteries. Modern types of solar cells can be integrated into glass facades.

Solar Thermal systems are more complicated to integrate due to the need for large collectors, plumbing and storage tanks. However, solar water heaters are commonly used efficiently and with minimal maintenance.

GEOTHERMAL ENERGY

Scientists and geologists have found out long ago that beneath the earth's crust after a certain depth, temperature and pressure increases steadily. This is mainly because of the very hot flowing magma under the Earth's crust. This heat can be tapped fairly easy as a renewable source of energy. Hence there are two main types of geothermal energy systems: *(Allen, S. R., Hammond, G. P., McManus, M. C., 2007)*

GEOTHERMAL POWER PLANTS:

This system consists of relatively long pipes submerged into the ground to a depth that gives them access to rock with the required temperatures. A fluid is then circulated in these pipes to come up again. Depending on the temperature and pressure of the returning fluid, it can be either used directly or indirectly to heat another liquid with a relatively low boiling point. This generated steam is then used to drive a steam turbine.

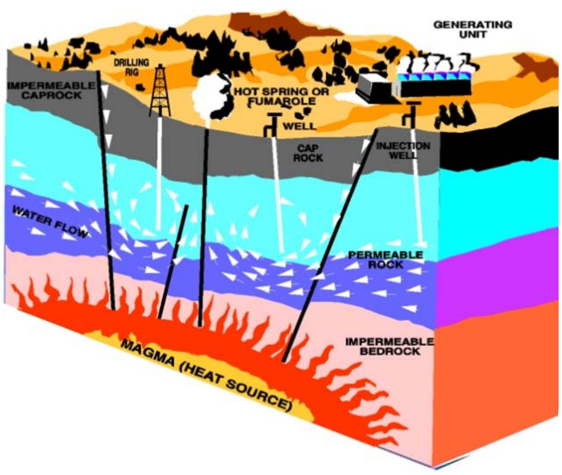

Figure 6 - Geothermal Energy

The major limitation to this technology is the big initial investment for digging deep into the ground with such pipes. Also not all locations have underground temperatures close enough to the top for pipes to reach efficiently.

GROUND COUPLED HEAT PUMPS:

This is a device that benefits from the fact that the upper 3m-8m of the earth's soil remains within a constant temperature most of the year. Hence a network of pipes embedded into the upper layer of the soil, can cool down (or heat in cold climates) a fluid (air or water) to a reasonable temperature. This water or air can then be used to cool down a space.

BUILDING INTEGRATION OF GEOTHERMAL ENERGY:

Several attempts have been done on the integration of geothermal systems in buildings. In these heat pumps have been the more successful, mainly because they are less costly to implement and very simple to operate. Mostly just involving a series of pipes circulating water underground at a level where it can be heated. *(Allen, S. R., Hammond, G. P., McManus, M. C., 2007)*

HYDRO ENERGY

The power of flowing water has always been recognized as an important source of energy. From old water mills, ancient civilizations have used them to grind their grains and lift loads. And when the industrial revolution started, many factories where located near waterfalls and water streams to benefit from the water movement in driving machinery. With the spreading of electricity grids, man started looking at other means of generating power from the flow of water. The first dams were built that utilized large turbines to generate electricity. This was one of the earliest forms of clean energy at a large scale.

Currently Hydroelectric power plants contribute to around 19% of the world's energy use. However, hydropower can only be implemented where there is local high flow of water (river, tide…) hence only very few locations in the world have such privilege. There are a number of different forms of hydro energy, the main types are:

- Hydro power: This is usually associated with damming a naturally occurring water flow (river, stream…) This dam creates a potential difference that can be used to drive fairly large turbines, which in turn drive generators. The main advantage of hydro dams is their ability to start and stop instantly on demand.

- Tidal power: The power of moving currents can also be harnesses through the use of submerged turbines. This approach is fairly new, but recent studies have shown a great potential, in exploiting the power in ocean currents and river flows.
- Wave power: The power of rising and falling waves has been proven to be quiet promising in generating power. Several experiments are underway to convert the movement of waves into useful energy, using floating buoys or pressure difference devices.

Figure 7 - Electric Generating Dam

BUILDING INTEGRATION OF HYDRO POWER:

Because Hydro electric power depends on the availability of a close by flow of water, hydro energy cannot be integrated easily into building. A number of concepts have been visualized showing buildings built on top of flowing rivers or on top of old oil rigs at off-shore sites, however all are at a theoretical level. *(Allen, S. R., Hammond, G. P., McManus, M. C., 2007)*

BIOMASS ENERGY

Is a form of renewable energy where plant or animal material can be used to generate energy. Plant material contains embodied energy from the sun that has been converted through photosynthesis and animals from eating plant material. Usually energy in biomass is released through burning such a fuel, however biomass can also be converted into other forms of fuel like methane.

Figure 8 - Biogas processing tubes

Biomass is a renewable source of energy because we can always grow more plant and animal materials. Biomass can come from sources like: Crops, wood, landfill gas, alcohol fuels and garbage.

Because biomass depends on the availability of a suitable material, biomass energy is location dependent. This limits the potential of biomass in widespread use and integration in urban areas. However new technologies are attempting to provide small scale biomass generators that run on local garbage for instance. These might be promising in building integration.

Another concern with biomass energy has arisen with the steep increase in fossil fuel prices. This has lead to wide use of crops that were originally grown for food in the form of biomass. Concerns over increasing food prices associated with its shortage have grown around such implementation of biomass. *(US Department of Energy, 2009)*

BUILDING INTEGRATION OF BIOMASS TECHNOLOGY:

As explained Biomass energy requires a sustainable local source of plant or animal material suitable for use. Hence this is hardly available urban areas. Another disadvantage of biomass is that usually it's implemented in heating application, hence is more suitable in cold climates.

WIND ENERGY

The kinetic energy in flowing wind is a free and abundant source of clean and sustainable energy. This energy can be harnessed virtually everywhere on earth.

Extracting part of the kinetic energy in the flowing wind or converting it into other forms of energy is the main implementation of wind energy. This has been explored by man as early as 5500BC in the form of sailing boats and later in driving some basic milling machines. However only in the 20th century did the modern implementation of wind energy has been achieved in the form of wind turbines.

These turbines convert the kinetic energy in the wind into rotational torque which can be used. There are two main types of wind turbines:

HORIZONTAL AXIS WIND TURBINES:

These are the more common type. They are differentiated by having their axis parallel to the wind flow. This type is quiet established now in wind power and widely used in wind farms.

The sizes of HAWTs have increased steadily, with the latest models more than 125m in diameter. These models can achieve a power rating of more than 6MW.

HAWTs need to face the incoming wind, hence a yawing mechanism needs is required.

VERTICAL AXIS WIND TURBINES:

The main difference between this type and the later is that the axis of rotation is perpendicular to the air flow; this means that VAWTs can take wind from all directions (Omni-directional).

VAWTs are less common than VAWTs in practical use. Although this type has been found in use by Persians and later Romans, they have dropped out of interest till the 20th century when Finish engineer S.J. Savonius invented the Savonius turbine in 1922 which was a drag type turbine. And later a French engineer in 1931, Georges Darrieus patents his design for a VAWT using lift blades.

There are a number of sub-types of VAWTs based on the two main categories. In practice, VAWTs have lower power conversion efficiency than HAWTs, however with the continuous research being done on VAWTs promising efficiencies are being achieved similar to HAWTs.

BUILDING INTEGRATION OF WIND TURBINES:

Wind turbine integration in buildings are showing promising results, and although this is a new area of research. The few examples that have been realized and researched are showing that with the required knowledge, technology and development great results can be achieved.

The integration of wind turbines into building is the main attention of this research and will be investigated in detail.

1.4 PROBLEM STATEMENT

From the literature review, it has been found that there's a relative increase of interest in wind energy and its extraction using wind turbines. However the issue of integration of wind turbines into buildings (urban environment) is still new. Also because of the domination of HAWT in the market now, not enough studies have been done on the integration of VAWT.

And though a number of studies attempted to compare between VAWT and HAWT, no available study has done this with regards to building integration. This has many different aspects than normal wind farm application. One of those is that though HAWT in wind farms are allowed to yaw to follow the wind direction, studies have proven this to be very difficult in buildings for many reasons that will be detailed later. Also no study has calculated the different generated power from HAWT and VAWT for the same location.

GAPS FOUND IN THE LITERATURE INCLUDE:

- Wind Turbine Integration methods
- Best types of turbines for urban environment and comparison between VAWT and HAWT
- Estimation of power generated in such conditions
- Effect of height of high rise structures on wind power available

1.5 AIM OF DISSERTATION

The aim of this dissertation is to investigate the potentials of integrating VAWT in high rise buildings, focusing on power production and suitability for integration.

1.6 RESEARCH OBJECTIVES

The objectives of this dissertation can be summarized as follows:

- Estimating the available power in the wind
- Study the effect of height on power available
- Study the efficiency of different wind turbine designs
- Estimate the actual power that can be harnessed
- Comparison between HAWT and VAWT in building integration
- Propose optimized integration designs
- CFD analysis of proposed designs

1.7 DISSERTATION STRUCTURE

The structure of the dissertation is as follows:

- Chapter 1: is a background on the problem of Global Warming and the current world Energy Crisis and an introduction to the concept of Renewable Energy as a solution to these problems.
- Chapter 2: explores Wind Energy as a renewable energy source. A literature review of the history of wind energy and its technology is summarized.
- Chapter 3: introduces the concept of wind turbine integration in the urban environment and highlights from literature the different methods of integration.
- Chapter 4: starts with stating the different methods found in literature for studying wind turbine integration and power capture. The mathematical calculations method is chosen as a study approach. The main equations related to power calculations are then highlighted.

- Chapter 5: In this chapter the equations mentioned in the previous chapter are applied to the selected weather data.
- Chapter 6: applies the use of CFD to simulate a number of proposed scenarios based on the previous study on the optimum integration of wind turbines in high rise buildings. These scenarios are then assessed to estimate the available power for harnessing in each scenario.
- Chapter 7: Represents the results of the studies done on chapters 5 and 6
- Chapter 8: States the conclusions of the research, limitations of the work done and the recommendations for future work on the subject.

2.1 OVERVIEW

This chapter concentrates on Wind Energy as a renewable energy source. Starting with a brief explanation of wind motion on earth. Then moves on to a historical study of attempts by man to harness this energy. Next a mention of wind turbines as the technology for harnessing wind and a mention of the different types of turbines. Finally a comparison between the different types of turbines according to various aspects including most importantly the power conversion efficiency.

2.2 WIND ENERGY

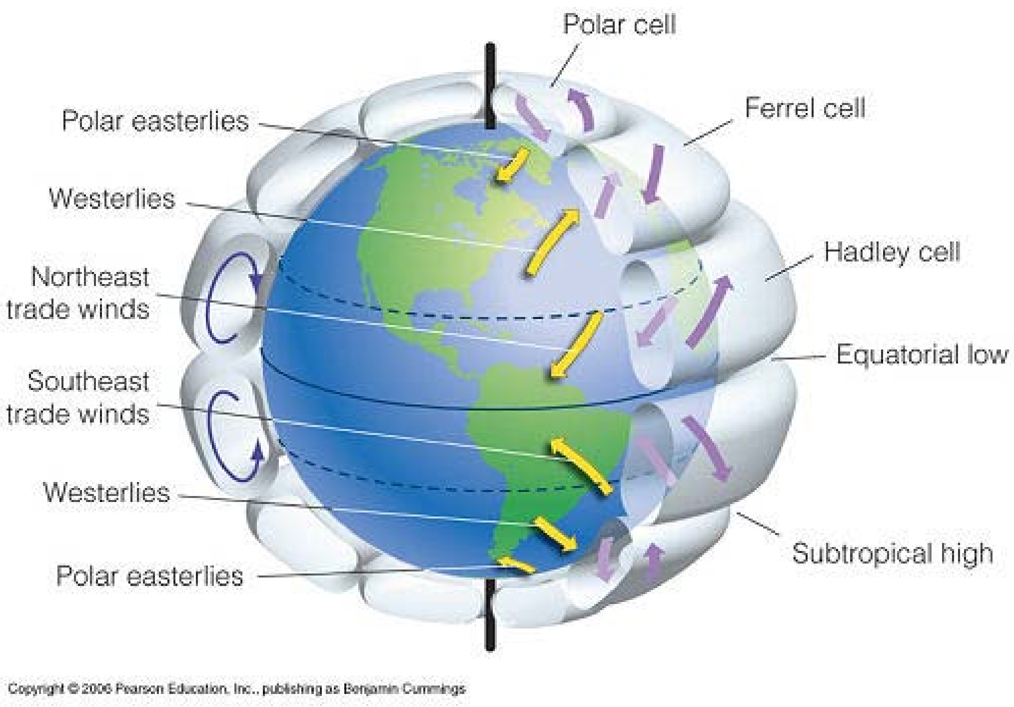

Figure 9 - Wind currents on Earth

When we talk about wind currents, we are usually referring to horizontal movement of the wind parallel to the Earth's surface, this is because vertical wind movement is usually very small compared to horizontal and also because it plays a much smaller role in power generation.

The movement of wind on the earth's surface is due to two main reasons: *(National Weather Service, Jet-Stream Online School for Weather, 2008)*

1. Most of the wind movement on earth is due to temperature differentials. Since the sun radiation falling on earth varies from one area to the other, this as well as other factors cause the air to be heated at different rates. To be more specific, air over the equator receives higher solar radiation than air above the poles. Since colder air is denser and heavier than hot air, cold air sinks towards the ground while hot air rises up. Hence temperature and pressure gradients develop, that force the air to flow from the high pressure zones to the low pressure zones. This happens on a large scale, however local pressure differences develop due to the different heat capacities of land and water bodies, these cause land surfaces to be colder than water bodies at night and warmer in the morning, causing local wind movement.

2. Secondly is the Earth's rotation around its axis. This causes through friction the motion of the wind relative to the earth's surface. This is called the "*Coriolis force*" that affects the direction of wind flow.

2.3 HISTORY OF WIND ENERGY TECHNOLOGY

From ancient times, man has attempted to make use of the power of blowing wind. This force that man has witnessed swaying trees and blowing soil, seemed to offer a great potential for harnessing. This might have began in early civilizations by the sail powered boats and dhows. *(Muller, G., Jentsch, M. F., Stoddart, E., 2008)*

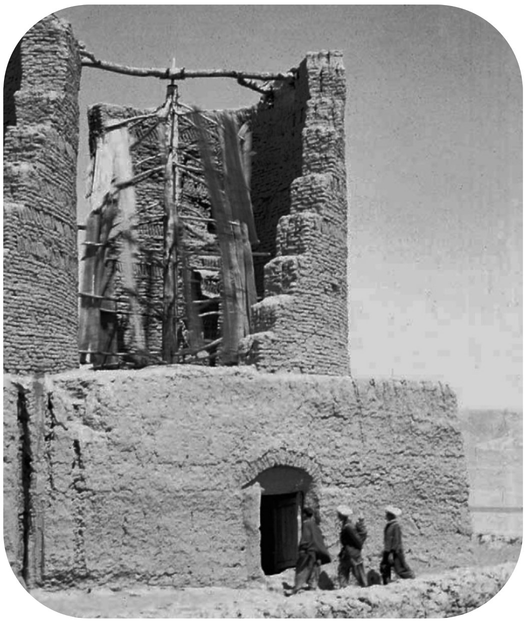

Figure 10 - Persian Wind Turbine

These have been depicted by early paintings on ancient Egyptian temples and manuscripts older than 5500 BC.

The first known examples of wind powered machines appeared in Persia by 200 BC and later at the Roman Empire by 250 AD. These machines where vertical axis windmills with rectangular blades. *(Muller, G., Jentsch, M. F., Stoddart, E., 2008)*

Figure 11 - Dutch Turbine Tower

These machines where used to grind grain or pump water.

The first examples of Horizontal Axis wind turbines appeared in Europe by 11th – 12th Century in England. They were mostly of the same basic design consisting of a 4 bladed rotor turning around a horizontal axis that is supported by a central vertical post. The later allows the rotor to be rotated to face the wind direction. The blade construction was a simple rectangular wooden frame wrapped in canvas. Again these early models where used to grind grain and pump water. Wind turbines spread in most of Europe and countries like Netherlands consider these old mills as their national icon. These turbines remained in service until they were replaced by steam engines. Some of these old models had twisted tapering blades, just like modern types.

After the Industrial Revolution, the use of wind turbines mostly died off to be replaced by fuel powered engines. However during the 1800s small horizontal axis wind turbines became quiet common in the United States rural country side where it was still relatively expensive to provide grid power connection. These small turbines where mostly used to pump water out of wells. They consisted of 6 to 12 blades mounted on a steel or wooden truss tower and allowed to yaw into the wind. A number of manufacturers became famous for such systems. Similarly by the 1900 around 2500 turbines were turning in Denmark mainly to pump water. *(Johnson, G. L., 2001)*

There are a number of claims about who first attempted to generate electricity from the kinetic energy of air through a turbine. Of these the work of Charles Brush in 1888 in the United States, Prof James Blyth of Anderson's College also made an electricity generating turbine on 1887 in Scotland and the Danish Scientist Poul la Cour in the 1890s.

Figure 12 - A Typical wind turbine used in rural USA

Among the most important early turbines was the turbine developed by Marcellus Jacobs. Jacobs' turbine had three airfoil shaped blades, battery storage and a wind vane keeping the turbine against the wind. *(Johnson, G. L., 2001)*

Denmark was the first country to use the wind for generation of electricity. The Danes were using a 23 m diameter wind turbine in 1890 to generate electricity. By 1910, several hundred units with capacities of 5 to 25 kW were in operation in Denmark.

Around 1925, commercial wind-electric plants using two- and three-bladed propellers appeared on the American market. *(Wikipedia Online Encyclopedia, 2009. History of Wind Power)*

The Finish engineer S.J. Savonius invented the Savonius turbine in 1922. This simple design consisted of two semi-cylindrical vanes supported by a central axis. Wind blowing on the vanes created more pressure on the concave face than on the convex one; this made the turbine rotate around its axis. The Savonius turbine was a basic model for a drag type VAWT.

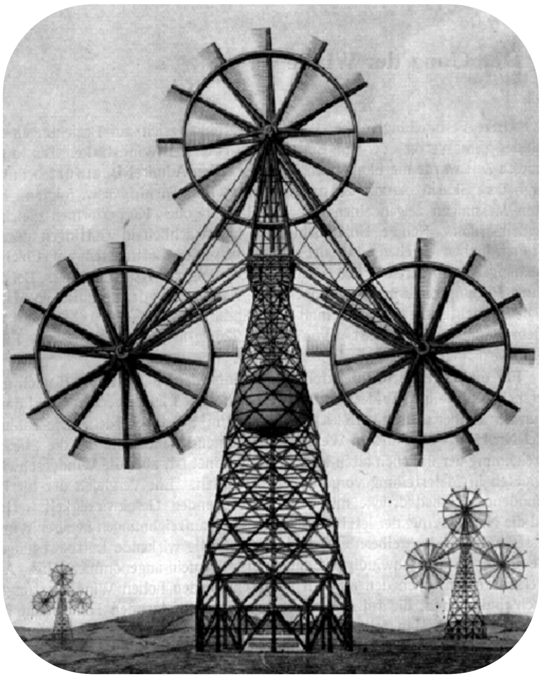

Figure 13 – Old concept for large scale wind turbine tower

In 1931, Georges Darrieus patent his design for a VAWT that uses vertically mounted blades. This design uses lift to induce rotation on the turbine blades which can be straight or twisted. *(Wind Turbine Analysis, 2002)*

During the 20th century, HAWT continued to evolve into bigger and more efficient types. However till the oil crises of the 1970s, the interest in large scale wind power generation was limited.

During the 1970s and 1980s vertical axis machines came back into focus when both Canada and the United States built several prototypes of Darrieus turbines.

The largest wind turbine built before the late 1970's was a 1250 kW machine built on Grandpa's Knob, near Rutland, Vermont, in 1941. The Smith-Putnam machine had a tower which was 34 m high and a rotor 53 m in diameter. The rotor had a chord (the distance from the leading to the trailing edge) of 3.45 m. Each of the two blades was made with stainless steel ribs covered by a stainless steel skin and weighed 7300 kg. The blade pitch (the angle at which the blade passes through the air) was adjustable to maintain a constant rotor speed of 28.7 r/min. This rotational speed was maintained in wind speeds as high as 32 m/s. At higher wind speeds, the blades were feathered and the machine stopped. The rotor turned an AC synchronous. *(Johnson, G. L., 2001)*

Dr. Ulrich Hutter of Germany built a 100 kW machine in 1957. It reached its rated power output at a wind speed of 8 m/s, which is substantially lower than the machines mentioned earlier. This machine used lightweight, 35 m diameter fiberglass blades with a simple hollow pipe tower supported by guy wires. *(Wikipedia Online Encyclopedia, 2009. History of Wind Power)*

The sudden increase in the price of oil stimulated a number of substantial Government-funded programs of research, development and demonstration. In the USA this led to the construction of a series of prototype turbines starting with the 38 m diameter 100 kW Mod-0 in 1975 and culminating in the 97.5 m diameter 2.5 MW Mod-5B in 1987. Similar programs were pursued in the UK, Germany and Sweden. There was considerable uncertainty as to which architecture might prove most cost-effective and several innovative concepts were investigated at full scale. *(Wikipedia Online Encyclopedia, 2009. History of Wind Power)*

The so-called 'Danish' wind turbine concept emerged of a three-bladed, stall-regulated rotor and a fixed-speed, induction machine drive train. This deceptively simple architecture has proved to be remarkably successful and has now been implemented on turbines as large as 60 m in diameter and at ratings of 1.5 MW. *(Wikipedia Online Encyclopedia, 2009. History of Wind Power)*

The development of the VAWT was slower. However, in the 1980s the American company FloWind commercialized the Darrieus turbine and built several wind farms with Darrieus turbines. The Eole, a 96m tall Darrieus turbine built in 1986, was the largest VAWT ever built with a rated maximum power of 3.8MW

The straight-bladed VAWT was also an invention included in the Darrieus patent [9]. This turbine is usually referred to as the straight-bladed Darrieus turbine or the H-rotor, but has also been called giromill or cycloturbine. In the United Kingdom, the H-rotor was investigated by a research team led by Peter Musgrove. The biggest H-rotor built in the UK was a 500kW machine, which was designed in 1989. In the 1990s, the German company Heidelberg Motor GmbH worked with development of H-rotors and they built several 300kW prototypes. *(Johnson, G. L., 2001)*

The modern wind turbine industry started in 1979 by a series of Danish companies that commercialized the construction of wind turbines (Kuriant, Vestas, Nordtank, and Bonus). Though the models first offered were small compared to modern types, they quickly became a successful product and started moving to neighboring countries.

There are now many thousands of wind turbines operating, with a total nameplate capacity of 120,791 MW of which wind power in Europe accounts for 55% (2008). Wind power is the fastest growing energy source. World wind generation capacity more than quadrupled between 2000 and 2006. 81% of wind power installations are in the US and Europe. The share of the top five countries in terms of new installations fell from 71% in 2004 to 62% in 2006, but climbed to 73% by 2008 as those countries - the United States, Germany, Spain, China, and India - have seen substantial capacity growth in the past two years. *(Wikipedia Online Encyclopedia, 2009. History of Wind Power)*

By 2010, the World Wind Energy Association expects 160GW of capacity to be installed worldwide,[58] up from 73.9 GW at the end of 2006, implying an anticipated net growth rate of more than 21% per year.

Denmark generates nearly one-fifth of its electricity from wind turbines -- the highest percentage of any country -- and is ninth in the world in total wind power generation. Denmark is prominent in the manufacturing and use of wind turbines, with a commitment made in the 1970s to eventually produce half of the country's power by wind. *(Wikipedia Online Encyclopedia, 2009. History of Wind Power), (Danish Wind Industry Association, 2002)*

2.4 TYPES OF WIND TURBINES

2.4.1 HORIZONTAL AXIS WIND TURBINES

Figure 14 - A Modern HAWT

The most common type of wind turbines are the HAWTs. These mainly consist of a number of blades (usually airfoils) supported by a central horizontal axis. This axis is the connected to a generator, usually through a gearbox. Most of these components (other than the blades) are usually kept inside an envelope called the Nacelle for protection from weather.

The turbine with the nacelle usually sit on the top of a tall mast. Due to the nature of this turbine, the axis of rotation has to point towards the incoming wind direction. Hence, the turbine with the nacelle must have a yawing mechanism. This can be as simple as a guiding vane on the back of the nacelle in smaller models, or as complex as computer controlled yawing motors in the larger types.

The size of HAWTs have increased greatly since they were first introduced. This is mainly due to the fact that it's usually more efficient to build one turbine with a very big diameter than several ones with an equal sum of area. With the largest models exceeding 120m in diameter swept by the rotors. *(ENERCON, 2007)*

HAWTs have several advantages and disadvantages which can be summarized below:

ADVANTAGES:

- HAWT have been developed over a longer time than other turbine types. Hence modern types can achieve power efficiency close to the theoretical Bletz limit.
- Modern HAWT have the ability to change the pitch of the blades to achieve maximum efficiency at different wind speeds.
- HAWT models have been tried and experimented with for years, hence are fairly reliable and have a safety margin.
- HAWT are widely commercialized and a large number of manufacturers produce various models sizes.

DISADVANTAGES:

- The main disadvantage of HAWT is that they have to face the prevailing wind; hence the turbine has to be yawed to the correct orientation. This not a big problem in standalone installations, however it becomes a difficult issue when integrating into buildings.

- Because of their high rotational speed, HAWT generate higher noise pollution than VAWT. Also HAWT generate even more noise while yawing.
- Because the axis of rotation is horizontal, the generator and all mechanical equipment must be at the turbine level. Hence it is relatively more difficult to maintain or repair the equipment.
- HAWT are very sensitive to turbulence. Turbulence can cause fatigue and over stress the blades. Also if the wind environment where the turbine is installed has a high variation in wind direction, the power output is significantly reduced. This is because the turbine spends most of the time yawing into the wind.
- The turbine blades have to be constructed and moved in one section. Thus the transportation and installation of large scale turbines becomes very problematic and expensive.
- In large scale turbines, the wind speed might vary along the swept area, this causes cyclic stresses that fatigue the blades.

SUBTYPES:

- Large Scale/Small scale: HAWT can be segregated according to size into large scale, small scale and micro turbines. With small scale including all turbines with a diameter less than 10m and micro turbines are the ones smaller than 2m in diameter.
- Up-wind/Down-wind: Another distinction can be made between up-wind and down-wind turbines. With the up-wind turbines having the blades before the generator and mast, while the down-wind turbines have the rotor behind the generator.

DOMINANCE IN MARKET SHARE

Currently HAWT is the dominant technology in the field of wind energy harnessing. This is mainly due to the fact that HAWT technology is much more developed compared to VAWT. Development has been undergone on

HAWT since the beginning of the 20th Century, hence they are much more advanced. Another factor is that for a long time, it was assumed that HAWT are easier to scale up into MW size turbines. However new researches predict that HAWT have reached the limit of size (with the biggest models having a +100m diameter) and assume that larger VAWT might be the way forward.

A number of improvements have been incorporated in modern wind turbines to increase their efficiency and reliability in use, these include:

- Improved materials that have increased strength and lower weight
- Optimized rotors with improved aerodynamic properties for more efficient energy conversion. Many of those are based on NACA profiles.
- Safety brakes that control the speed of rotation or stop the turbine totally when the wind speed exceeds the safety limit.
- Gearless hubs. Those in order to link the turbine to the generator directly to reduce losses.
- Curved turbine rotor tips that decrease the noise caused by the turbines.

2.4.2 VERTICAL AXIS WIND TURBINES

The other major type of wind turbines is the VAWTs. The main difference between this type and HAWTs is that the axis of rotation of the turbine blades is vertical, hence perpendicular to the incoming air flow. This has the advantage of making the turbine Omni-directional in regards to the wind direction. However, this type has a set of advantages and disadvantages as will be described later. Three main types of VAWTs currently exist:

SAVONIUS TURBINE

Figure 15 - Savonius Turbine

The Savonius turbine is a drag type vertical axis wind turbine, which usually consists of two or more bucket shaped surfaces fixed on a vertical axis. Air flowing along the turbine creates more pressure on the concave face than on the convex face; this generates positive torque on the axis causing it to rotate. *(Altan, B. D., Atilgan, M., 2008)*

The Savonius turbine was patented by the Finnish Engineer S. J. Savonius in 1922. Savonius turbines have a relatively low power coefficient mainly due to its poor aerodynamics; however these drag type turbines are characterized by a high starting torque, which means that these turbines are self starting even at low wind speeds. Several studies have been done to improve the efficiency of Savonius wind turbines. *(Irabu, K., Roy, J. N., 2007)*

These measures included using double stepped configurations, which means two Savonius turbines fixed on the same axis but with a 90^o step between the blades. Another measure was twisting the blades. Also the efficiency of the turbine was shown to increase by eliminating or minimizing the negative pressure on the convex surface of the proceeding blade, this has been done using wind vanes or guides. *(Altan, B. D., Atilgan, M., Ozdamar, A., 2008)*

A theoretical efficiency of 32% has been achieved using double stage-twisted-valve assisted rotors. Compared to an efficiency of between 18% in normal Savonius turbines. *(Kamoji, M. A., Kedare, S. B., Prabhu, S. V.)*

This type of wind turbine has a number of advantages and disadvantages, as follows: *(Saha, U. K., Rajkumar, M. J., 2005), (Saha, U. K., Thotla, S., Maity, D., 2008)*

ADVANTAGES:

- Due to the relative simplicity of the turbine assembly, this type of turbine can be constructed easily without complex fabrication and cost effectively.
- Similarly because of the relative simplicity of the design. Savonius wind turbines are very reliable and less prone to damage. This is also due to the relative solidity of the design.
- As explained earlier, the Savonius turbine being a drag type has a very high starting torque and hence can self start even in low wind speeds.
- Like all VAWT, Savonius turbines are omni-directional. And being drag type, they are less affected by air turbulence.

DISADVANTAGES:

- The major drawback of Savonius turbines is them being drag type turbines, which means they are less efficient in converting wind energy than lift type turbines. However recent studies have proved that the efficiency of turbines can be increased by several measures.
- Savonius turbines experience a phenomenon called cyclic torque where the value of the torque on the turbine shaft various considerably with the rotor angles. This effect can be reduced significantly using helical blades, double stepped rotors or guide vanes. *(Saha, U. K., Thotla, S., Maity, D., 2008)*

DARRIEUS TURBINE

Figure 16 - Darrieus Turbine

The Darrieus wind turbine is a type of VAWT that consists of two or more blades fixed around a vertical axis. The blades which are usually aerofoil are fixed in a curved parabolic line around the axis. *(Islam, M., Ting, D. S. –K., Fartaj, A., 2006), (Wind Turbine Analysis, 2002)*

Wind blowing onto the turbine is cut by the blades moving perpendicular to the air flow around the axis; this generates a positive lift on the blade which is translated into a positive torque in the direction of rotation.

This design was patented by the French aeronautical engineer G. J. M. Darrieus in 1931. Later it was re-invented by the National Research Council of Canada in the 1970s. A 4m diameter model was built by Sandia Laboratories in 1974. Several large scale models were built in the 1980s.

In theory, Darrieus turbines have energy conversion efficiency similar to modern HAWT; however this is rarely achieved due to the difficulties associated with building large scale Darrieus models. The characteristics of this design can be summarized as followed: *(Eriksson, S., Bernhoff, H., Leijon, M., 2006)*

ADVANTAGES:

- Being a VAWT the Darrieus wind turbine is omni-directional in regards to wind.
- Darrieus wind turbines have a high theoretical power coefficient similar to modern HAWT.

- Unlike HAWT which use aerofoil blades, Darrieus turbine blades rotate parallel to the axis. Hence no need of altering the cross section or angle of attach relative to the radius. This translates into simple and easy to construct blades.

- Darrieus turbines tend to have parabolic blades fixed from both ends with only centrifugal forces acting on it. Hence thin blades are sufficient.

DISADVANTAGES:

- Blades of Darrieus wind turbines generate maximum torque at two points along their path, hence the wind turbine pulsing torque which can eventually stress the axis and the generator. This can be eliminated by using twisted (helical) blades.

- Due to the nature of the Darrieus turbine, lift is generated on the blades when air is cut by a moving blade. Hence, this type of turbine is not self starting and would not restart itself when wind speed increases. This can be treated in two manners: the first being using the generator as a motor to start the turbine when needed, the other method is by combining the Darrieus turbine with a Savonius turbine on the same axis. *(Wind Turbine Analysis, 2002), (Eggleston, E., et al, 200?)*

- Due to the shape of the blades a big portion of the blade length is close to the ground where air is much slower, this also means that when scaling up the turbine, this problem is exaggerated. This difference in air speed across the length of one blade creates stresses and fatigue.

- Support of the Darrieus turbine requires guy wires fixed between the top of the axis of rotation to the ground. This complicates the installation and consumes a large area

Due to the above mentioned disadvantages of Darrieus turbines, interest in large scale versions of these (egg-beater shaped) have nearly seized, the last manufacturer attempting to commercialize them was Canadian company Sandia in the 1980s. However many still believe that Darrieus turbines have a great potential in wind energy, this is evident in a number of small scale turbines available today. *(Johnson, G. L., 2001)*

Interest in Darrieus turbines has now mainly shifted to their straight bladed derivatives: the H-type and Giromill.

H-TYPE TURBINE

Figure 17 - H-Rotor

H-type turbines are considered a derivative of Darrieus turbines, but differ in using straight blades instead of twisted ones. This has the advantage in having stronger blades. This design was also patented by G. J. Darrieus in 1927. Vertical blades are supported by horizontal supports that create the H-shape. This design is simpler than twisted blades. *(Eriksson, S., Bernhoff, H., Leijon, M., 2006)* However, centrifugal forces can become problematic at high speeds.

GIROMILL / CYCLOTURBINE

Figure 18 - Cycloturbine

This type can be considered as a sub type of H-type turbines and differ in having a mechanical mechanism that alters the angle of attach for individual rotors depending on the wind direction, by rotating the blades around their vertical axis. This significantly increases the performance of the turbine and dramatically increases the starting torque, making the turbine self starting, even at very low wind speeds.

Though this design is relatively complicated compared to other VAWT models due to the pitch mechanism, however the high power conversion efficiency (about 40% efficiency) coupled with very low cut-in speeds (2.2m/s cut-in speed) means that this design is quiet promising for future applications. *(Noll, R. B., et al, 1982)*

CHAPTER 3 WIND ENERGY IN THE URBAN ENVIRONMENT

3.1 OVERVIEW

This chapter introduces the concept of wind turbine integration in the urban environment. Starting with the advantages of integrating wind turbines. Then literature review of the history of wind turbine integration. Later a look at the different methods of integration. And finally a comparison between HAWT and VAWT with regards to integration.

3.2 INTRODUCTION TO WIND TURBINE INTEGRATION INTO BUILDINGS

As a standalone solution, wind turbines now are well established as a form of renewable energy. And as previously highlighted wind farms in isolated un-inhabited areas are becoming a common site now. Wind farms are coming up everywhere, with ever increasing turbine sizes and number of turbines. These farms are usually located in rural areas characterized by steady flow wind with low turbulence and relatively high wind speeds. Moreover, recently wind farms have been located on large water bodies on off-shore locations, to benefit from steady flow, very low turbulence wind and very low terrain roughness. *(Peacock, A. D., et al, 2007), (Dayan, E., 2006)*

The concept of standalone wind turbines for urban power generation started with power generation systems in rural areas, the most famous of which is the multi-bladed wind turbines used in the American farms to pump water or generate electricity where power grids did not reach. These systems though differ from wind farm conditions, still involve wind turbines placed in relatively open terrain with little obstruction.

This is fairly different from the concept of wind turbines integrated within the urban environment. Wind in the urban environment is totally different; the terrain roughness in such context causes the wind flow to be significantly more turbulent than free flowing wind. Also the many obstruction in the form of the built environment causes general decrease of the wind velocity (however local augmentation of wind speed occurs along edges and between pressure differences). Also the complexity of the context complicates the prediction of wind speeds and direction; hence data from a nearby weather station for instance cannot be directly used.

This different wind environment, makes integrating wind turbines onto buildings in an urban environment that much more difficult. The turbulence combined with the small scale wind speed gradient, can quickly fatigue turbine blades. Also this complex wind characteristics makes predicting the power output correctly very intricate.

This requires special measures and techniques to tackle these problems, as well as requires correct understanding of the local wind movement around buildings. These measures include: optimizing wind turbine design to suite the urban wind, selecting the correct location and method for integration on a building.

However, research has revealed that well placed turbines on buildings can benefit from the local acceleration of wind passing around the building geometry to increase the power output. *(Mertens, S., 2002)*

3.3 WHY DO WE INTEGRATE WIND TURBINES INTO BUILDINGS

Having wind turbines as a renewable energy source integrated into the urban environment has several advantages: *(Mertens, S., 2002),*

Figure 19 - One of three turbines installed on the BWTC

- Significantly reduce power losses due to transmission networks. Generated energy is used directly where it is needed.
- Reduce maintenance costs. Instead of doing repairs or maintenance on turbines that might be a few hundred meters up on a mast, the turbine integrated on buildings should have easier access through normal roof cores or access doors. For example the hubs of the turbines fixed on the Bahrain World Trade Centre are accessed through access doors on their respective bridges. *(Smith, R. F., Killa, S., 2007)*
- A major concern with wind farms in some areas is the rural land wasted by these farms. This land which is on most cases prohibited from other use due to safety issues could otherwise be used as farm or agricultural land.

- Also aesthetically, integrating wind turbines in buildings means in most cases that they are less visible or less encroaching on their surroundings. In some designs, it's fairly hard to notice or see the turbines integrated just by looking at the buildings. An example for this is the design for the Pearl River Tower which is proposed for Guangzhou, China. This tower which was designed by SOM, incorporates a number of small scale wind turbines within ducts connecting the windward and leeward sides of the building. These turbines are housed in locations that can hardly be seen from the outside. *(Frechette, R. E., Gilchrist, R., 2008)*

Figure 20 - Turbine location for the proposed Pearl River Tower

- Most Environmental (Green) design rating systems, (like LEED, BREAM, Green Star…) recognize buildings with integrated renewable energy harvesting systems and award points (credits) for such systems. Also as wind turbine systems are considered a new technology, further credits can be achieved in innovation categories.

3.4 WAYS OF INTEGRATION

Different methods have been explored for integrating wind turbines on buildings. These methods can be divided into four main categories as follows:

3.4.1 MOUNTING TURBINES DIRECTLY ON BUILDINGS

The simplest method for wind turbine integration in the urban environment, is mounting standalone turbine systems directly on the building. Usually this happens on the roof top, to provide the turbine with the highest wind speeds. However due to the fact that air hitting the building façade tends to rise upwards along the façade (updraft), this updraft meets the wind moving parallel to the roof and hence creates an area of high turbulence above the building, with the wind direction usually at a 45^o angle.

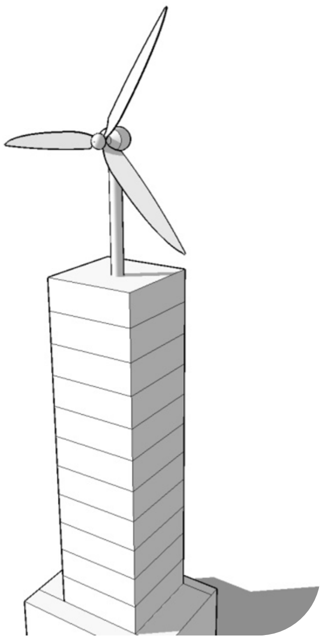

Figure 21 - Turbine mounted on Building

This high turbulence wind flow, coming at an angle is especially undesirable to wind turbines and can cause fatigue to the blades in a short time. An easy remedy for this is to have the turbine mounted on a mast that's long enough to tower over this layer of turbulent wind, however this complicates the design and requires intensive structural measures. Another solution is optimizing the turbines for this turbulent wind coming at an angle, like in the case of the VAWT "Turby" which is manufactured for this exact purpose of integration on roof tops. By twisting the blades the manufacturer claims that the turbine is more suitable to wind coming at an angle.

Never the less, studies on the wind flow around buildings have revealed that local wind acceleration occurs above the roof of the building to multiples of the ambient wind speed. This effect if harnessed effectively promises high power potentials.

3.4.2 DUCT BETWEEN THE WINDWARD AND THE LEEWARD SIDE OF THE BUILDING

Studies on the fluid movement around a solid barrier reveal a big pressure difference between the windward and leeward sides of the barrier. This difference is due to the positive pressure created on the windward side due to the wind blowing on it, and the negative pressure induced on the leeward side due to the wind blowing past it. This pressure difference has great potential, as air moving along the sides of the building from one side to the other experiences local acceleration. *(Frechette, R. E., Gilchrist, R., 2008)*

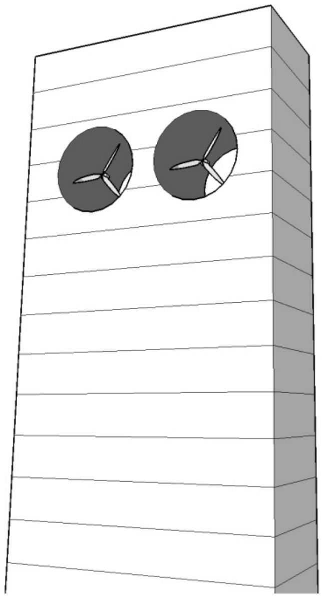

Figure 22 - Ducts connecting windward and leeward building facades

Hence a connection between the two sides of the building in the form of a duct can exploit this phenomenon. As air moving to connect the different pressure points can be accelerated to multiples of the ambient. Also air passing through this duct usually is in laminar flow due to compressing.

The major drawback in this method is its relative directionality. As explained air blowing parallel to the duct is ideal as it creates pressure difference between the two sides. However if the air flow is perpendicular to or at angle to the duct, no pressure difference is induced along the two sides and hence very little air movement occurs.

Some designs claim to have offset this drawback by altering the shape of the building, or by using wind vanes to direct the air into the duct even when the air flow is perpendicular to the duct.

3.4.3 DUCT BETWEEN THE WINDWARD AND THE ROOF OF THE BUILDING

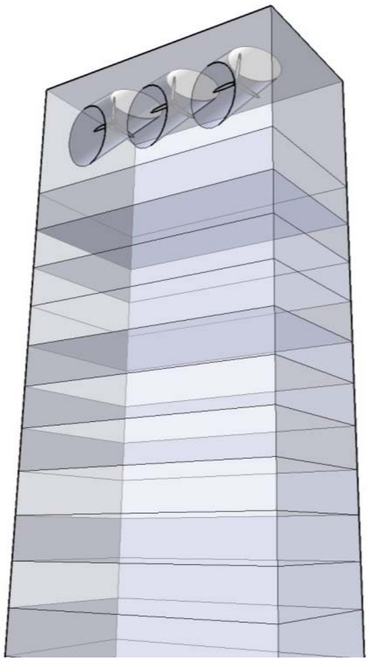

Figure 23 - Ducts connecting windward side and roof

Similar to the previous method, and as mentioned in the first type, air movement around a solid barrier creates positive pressure in front of the barrier (windward side) and negative pressure just above the roof. This is especially true to the separation zone just above the roof. This phenomenon is commonly observed in the form of loose roof tiles getting sucked up due to the negative pressure. *(Grant, A., Johnstone, C. & Kelly, N., 2007)*

Hence this can be similarly exploited by connecting the windward side with the roof through ducts. This pressure difference can be further enhanced using diffusers on the roof similar to a parapet.

3.4.4 AERODYNAMIC SHAPING OF BUILDINGS TO ACT AS CONCENTRATORS (BUWT)

As seen in the previous methods, the shape of the building as a barrier to air flow plays a very important role in determining the characteristics of the flow. Hence this can be used positively by optimizing the shape of the building to enhance the air flow and direct it towards the turbines.

This can have several benefits: optimize the wind approach angles to be more parallel to the turbine axis (very important in HAWT) even with varying prevailing wind and/or accelerate the wind speed by concentrating the incoming wind.

The advantages of the above mentioned effects are numerous as will be detailed later, however, this approach is the most intensive and requires the most alteration to the building form hence cannot be applied to existing buildings. Wind turbines in this arrangement are called BUWTs (Building Augmented Wind Turbines).

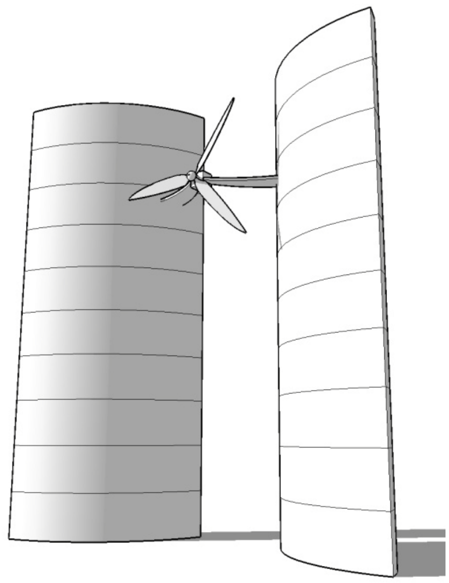

Figure 24 - Aerodynamic shaping of building to act as concentrator

3.5 ADVANTAGES & DISADVANTAGES OF TURBINES IN BUILDING INTEGRATION

As previously mentioned, wind turbines come in two main categories: HAWT and VAWT. In integrating these two types into buildings different considerations are required for each type due to their different approaches to wind harnessing. These considerations are listed in the table below:

(Peacock, A. D., et al, 2007), (Shata, A., Hantisch, R., 2005)

Table 1 - Comparison between HAWT and VAWT in building integration

CRITERIA	HAWT	VAWT
Performance	High power coefficient. Newer models can reach 48-50%.	Lower power coefficient. However, recent studies and developments have measured high power coefficients similar to HAWT especially with lift type turbines.
Directionality	Has to be rotated to face blowing wind	Omni directional in regards to wind
Acoustic performance	Noisy (even more noisy while yawing)	Quieter even at high speed and high turbulence
Building Integration	More difficult to integrate in building's architectural design	Easier to integrate
Turbulent Urban wind	Turbulent air in urban environment causes blade stress and fatigue. This increases as the intensity of the turbulence increase, as the turbine cannot turn quickly enough to face the coming wind and spends most of the time yawing. Decreasing the life span of the turbine and limits the power output significantly.	Less sensitive to turbulence as the turbine has no orientation. Also because of the stronger turbine structure (blades fixed at several points) the blades don't get fatigued easily.
Speed of Rotation	Higher rotational speed, which lead to higher noise levels and make their operation less safe.	VAWT tend to have slower rotational speeds. Meaning they are less noisy and safer to operate.

Location of Equipment	Has to be directly behind Turbine at nacelle level. This results in difficult maintenance and repairs	Generator and gearing can be at the base level. Hence much easier to maintain and repair
Structural Requirement	Because most of the equipment weight has to be at the rotor axis level. Stiffer structural support is required.	Equipment are at a low level, hence less structural support is required. However in some types of large scale VAWT (Darrieus) support at the highest point of the axis is required usually in the form of cables.
Effect of Dust	Studies have shown that dust accumulation in dusty location can reduce the performance of wind turbines due to the reduced aerodynamic efficiency of the blade surfaces.	Blades of VAWTs being normaly vertical are less prone to dust accumulation.

3.6 STUDY OF EXAMPLES FOR BUILDING INTEGRATED WIND TURBINES

The following is a study of the most prominent attempts for integrating wind turbines in theoretical and built examples.

3.6.1 DUTCH WIND MILL

The old Dutch wind mill can be considered one of the first examples of wind turbine incorporation in buildings. This is true as many of these old mills where built on top of buildings that served a specific purpose other than just supporting the turbine. The typical application was to use the turbine to power a grain mill, sawmill or less frequently to pump water. Some of the wind mills where used as residents foe the local miller or grinder.

Figure 25 - Dutch Wind Mill

The old Dutch Wind mill was a HAWT, fixed on a rotating structure to allow it to yaw into the wind. This was done by the means of a wind vane in smaller models but later with the increase in size, a fan tail was introduced. The rotational mechanical power captured by the turbine was transmitted through gears to a vertical mast that could drive machinery at the lower level.

These old turbines usually consisted of canvas wrapped around a wooden frame, with the later models having precision to limit the area of the canvas when strong winds are present. *(The Medieval Technology Pages, 2002)*

3.6.2 THE WORK OF HERMANN HONNEF

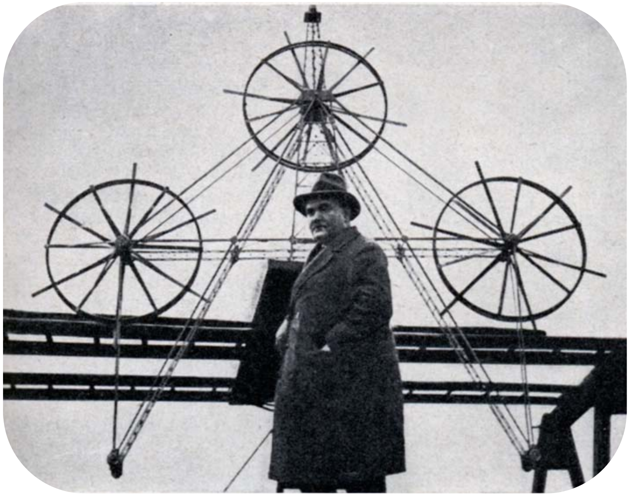

Figure 26 - Hermann Hennof with one of his designs

Hermann Honnef was a German engineer and inventor who pioneered the idea of using large scale wind turbines to harness wind energy. He made a number of designs for wind turbines mounted on tall structures which were usually steal structures.

Having realized that wind speed increases with height, he proposed mounting wind turbines on tall structures up to 600ft tall. He investigated ideas to mount these turbines on tall office or residential towers in urban areas, which can be considered one of the first mentions of such integrations.

His last design was a gigantic structure holding three turbines of 160m diameter each, 800ft above the ground. He estimated that this arrangement can generate 20MWs of power at a 15m/s wind speed.

However, because of the world war, Hennof did not get a chance to investigate his designs further.

(Heymann, M., 1996), (Wikipedia, 2009. Hermann Honnef)

3.6.3 WEB CONFERENCE AND RESEARCH

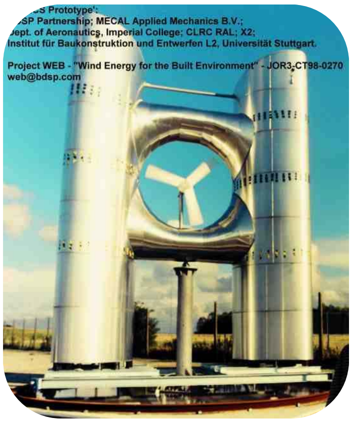

Figure 27 - One of the test model built during the research

The (WEB) "Wind Energy in the Built Environment" was a research program funded by the European Commission to study the potential of wind energy harnessing in the built environment in Europe. The program spanned between September 1998 and August 2000. And at the end of this a conference was held on the 11th of September 2001 to discuss the findings. *(BDSP, 2001), (Campbell, N., et al, 2002)*

The topics investigated included:

- Assessing typical wind regimes around European built-up areas using existing statistical data.
- Development of wind enhancement and integration techniques for low to moderate wind speed areas. With attention to Building form optimization to cause concentration effects.
- Validating the above techniques on a small-scale model in a wind tunnel.
- Development of testing and design specifications for two turbine/concentrator design prototypes.
- Testing of two turbines with concentrators in a moderately windy area. Measurement parameters included site meteorological data, power output, noise emissions and vibration.

A number of models where constructed during this research including two full scale models of wind concentrators. A 2m diameter HAWT and VAWT was experimented with.

The Research Conclusions were as follows:

"Both the HAWT and the VAWT turbines show enhanced performance within the FSM for an incident wind (or concentrator yaw) angle range of ±60°. Power generation generally starts in wind speeds at least 1 m/s below the cut-in wind speed of the stand-alone turbine. This will considerably enhance energy collection in low wind speed sites (typical of urban areas). At the wind speed of 8 m/s the HAWT's performance is enhanced from 155 W to 190 W (from a Ce of 1.8 to 2.8) and the VAWT's performance is enhanced from 40 W to 90 W (from a Ce of 0.33 to 1.1). The electrical power output of both turbines is improved by a large ratio at low wind speeds and a lower ratio at high wind speeds. The performance of the VAWT is enhanced by a factor of more than 2 at 8 m/s, while the HAWT is improved by a factor of between 1.2 and 1.3 (depending on incident wind angle) at the same speed. However the greater enhancement of electrical power, which does take into account energy conversion losses, measured for the VAWT in no way suggests that it is more suited to FSM. After accounting for the VAWT's 15% larger swept area, the HAWT in the FSM produces 2.4 times as much power as the VAWT in the FSM at 8 m/s. The infills further enhance the performance of the HAWT in the concentrator when operating in low wind speeds, but the enhancement appears to become negligible above 6 m/s." (Science and Technology: Facilities Council, 2001), (Campbell, N., et al, 2002)

3.6.4 BAHRAIN WORLD TRADE CENTER

The Bahrain World Trade Center was the first integration of large scale wind turbines on a building. Designed by Architect Shaun Killa of WS Atkins, and involving collaboration with a number of turbine engineering consultants, the building integrates 3 large scale HAWTs.

Figure 28 - Bahrain World Trade Center

Built along the Bahrain's water front this project consists of two 50 storey towers shaped like sails and looking towards each other. These two towers tapper as they rise to reach a height of 240m.

Fixed between these two towers are 3 29m HAWTs, facing the prevailing wind direction. The shape of the building funnels the incoming air onto the turbines, providing two advantages: First is to increase the speed of the approaching air through compression which significantly increases the potential wind energy, Secondly this arrangement helps direct wind coming at different angles onto the turbines, making them operational at a wider approach angle. The turbines are predicted to generate 11-15% of the buildings energy use when operational.

Construction of this complex started in 2004 and completed in 2008. At the time of writing, the turbines were finalizing testing and commissioning.*(Killa, S., Smith, R. F., 2008), (Smith, R. F., Killa, S., 2007)*

3.6.5 DIFC LIGHT HOUSE TOWER

With the experience gained in the BWTC, the second large scale integration of wind turbines was attempted by Shaun Killa of WS Atkins, in the form of the DIFC Light House Tower.

This 400m tall tower is located at the Dubai International Financial City. The design submitted by Atkins represented a highly efficient office tower with integrated renewable energy harnessing systems which include PV panels as well as 3 large scale wind turbines fixed at the top end of the tower.

This design though close to the BWTC, would be the highest integrated wind turbines. And is different in depending less on building form augmentation, but more on vertical louvers to guide the air into the turbines. *(Atkins Middle East and India, 2009)*

Construction on the tower began in April 2007 and is currently under way with expected completion by 2010.

Figure 29 - DIFC Light House Tower

3.6.6 PEARL RIVER TOWER

The Pearl River Tower in Guangzhou, China, is a high rise tower designed by SOM Architects, with the intent to be an energy efficient building. The building is to be of 340m tall with 71 floors and million square feet of usable area.

This tower incorporates renewable energy systems to offset its power demand, these include PV cells, fuel cells and more importantly for this study, the building incorporates VAWTs.

Turbines are integrated within openings that connect high pressure windward facades to low pressure leeward sides. This arrangement benefits from the increased wind speed due to this phenomenon. This is achieved by ducts connecting both sides of the building, as well as the roof. Within these ducts a number of VAWT of the Darrieus type are incorporated.

Figure 31 - Pearl River Tower

The external facades are shaped to funnel the incoming air into these ducts further extending their efficiency. Studies done by SOM claim that this arrangement accelerates air speeds approaching the tower even at angle, except when the wind is perpendicular to the ducts, when there is no pressure difference between two sides. *(Frechette, R. E., Gilchrist, R., 2008)*

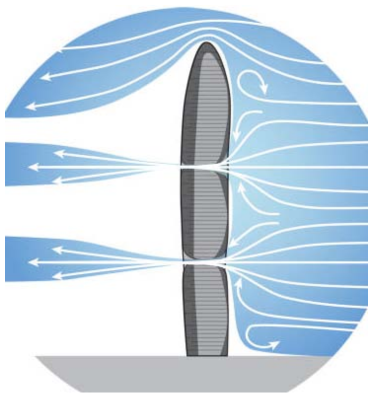

Figure 30 - Diagram showing the ducts

3.6.7 CASTLE HOUSE TOWER

The Castle House Tower was a proposal for a high-rise residential tower, consisting of 43 floors of a total height of 147m.

The design included provision for three 9m diameter HAWTs. The designer of this building: Hamiltons Architects, claim that these turbines are sufficient to power the energy efficient lighting of the building.

The design of the top of the tower is shaped to create a positive pressure at the windward side and negative pressure on the leeward side, also the tower top is carved on the prevailing wind side to funnel the air onto the turbines. *(Coleman, B., Preston, I., 2007)*

Figure 32 - Castle House Tower

3.6.8 DISCOVERY TOWER

The Discovery tower planned for downtown Houston, TX, is another high rise design incorporating wind turbines on the roof. The building is a commercial tower of 30 floors with a total height of about 125m. The building incorporates 10 VAWTs on the roof facing the prominent wind direction. Aerodynamically shaped ducts are built around the turbines to regulate and increase the air flow. *(Cochran, B. C., Damiani, R. R., 2008)*

CHAPTER 4 METHODOLOGY

4.1 OVERVIEW

In this Chapter the focus is put on the means of studying wind data and estimating the power generated in different scenarios from this data. This starts with choosing the appropriate research method. Secondly, defining the equations found in literature that calculate the energy in the air and the power that can be extracted from this energy. Then the Power extraction efficiency of wind turbines and how that affects the extorted power. Then the study moves to the effect of the terrain roughness and height of turbine installation on the available power. Finally a look into the type of wind data relevant to this study, how it is gathered, documented and analyzed.

4.2 TYPES OF THE RESEARCH APPROACHES

From the literature, a number of research methods were found that were used to study the energy in the wind and estimate the power captured by wind turbines in different scenarios. These methods include:

4.2.1 WIND TUNNEL TESTING

A wind tunnel is a very common research tool that is used to assess the behavior and effects of air movement along various objects. The first wind tunnels where probably those primitive instruments used to simulate flight for the first airplanes. However the modern incarnations are complicated devices that can simulate a wide range of scenarios.

The basic operation of the wind tunnel consists of a wind compressor (usually a fan) that blows wind in the desired direction, a test chamber where the air movement is studied and usually a turn table to change the angle of attack or the orientation of the incoming wind. Various measuring devices can then be used to study the phenomena including anemometers, smoke dispensers and powder particles. These wind tunnels can be closed cycle, where the air moved by the compressor is recycled back into the loop, or an open cycle where the air exits at the end of the tunnel and new air is sucked in at the compressor. *(Cochran, B. C., Damiani, R. R., 2008)*

Wind tunnels have been extensively used to study wind turbines as they are very flexible in this regards. The main advantages and disadvantages of using wind tunnels in studying wind turbines are as follows:

ADVANTAGES:

- The main advantage of wind tunnels is their ability to **repeat** different scenarios over and over. This makes it possible to make a number of variables constant and change one variable to measure its effect.
- Wind tunnels have the advantage of being able to simulate different scenarios in a relatively short time, because wind speed for example can be altered quickly and the effects measured in real-time.

DISADVANTAGES:

- Due to the limitation of **Reynolds** number, scaled down models of buildings need multiples of the actual wind speed to correctly simulate air flow. This is not possible in many conventional university wind tunnels.
- Wind tunnels are relatively unable to accurately simulate the **wind shear** caused by rough terrain or an urban environment. This has been addressed to a certain extent in the form of wind shear wind turbines that uses obstacles or other measures to cause wind speed gradients and turbulence.
- Wind tunnels are relatively large and expensive, hence are not usually available in all universities and research facilities.

4.2.2 FIELD TESTING

Open air testing is by far is the most accurate way for testing wind turbines and their performance. Hence, this method is whenever possible, highly preferable. (

Open air testing due to its accuracy of showing realistic performance and behavior is usually done on the final stage of design development. The advantages and disadvantages of open air testing are:

ADVANTAGES:

- The most realistic form of testing and research that can be done on wind turbines in the actual operational context.

DISADVANTAGES:

- Open air testing is costly to compose, requiring fabrication of full scale turbine models as well as any relevant instrument or solid like generators, supports, masts and guide vanes.
- Because testing is done in the real environment, it's theoretically impossible to test specific wind conditions or weather phenomenon. Also test setting cannot be repeated.
- Since this testing is outside laboratory conditions, individual parameters cannot be isolated and hence effects might be due to many different parameters.

4.2.3 COMPUTER SIMULATION (CFD)

Computational Fluid Dynamics (CFD) is a numerical method that utilizes computers to calculate and simulate fluid flow. This operation is a very intensive computational problem; hence even the highest powered super computers cannot perform the calculations with the full detail. Hence a certain level of approximation is required.

CFD used to be only limited to super computers on high level research facilities, however with the rapid increase in personal computer power; it's now highly convenient to have such models run on medium powered personal computers.

This advantage is highly opportune in testing theoretical scenarios for air movement and wind turbine performance.

ADVANTAGES:

- Highly flexible in it's ability to model different scenarios and
- Relatively cost effective compared to other types of simulation.
- Repetition of analysis scenarios is possible.

DISADVANTAGES:

- Accuracy of results are highly disputed due to approximation, however with the increase in computer power and the development of more accurate models, results have been found to be highly comparable to real life testing.
- Commercial CFD packages are relatively expensive to purchase.

4.2.4 MATHEMATICAL CALCULATIONS

This type of analysis involves the use of mathematical equations that define different wind phenomena like speed, energy, power and the effects of height, terrain roughness and turbine power conversion efficiency.

When applied to wind data, this can estimate the energy in the wind and the power available. The advantages and disadvantages of this research technique are as follows:

ADVANTAGES:

- Does not require vast resources as most of the application is applying theories to data and collecting results.
- Results obtained are free from the effect of any parameters outside the scope of interest.
- This type of research can be easily and quickly replicated.

DISADVANTAGES:

- Results obtained might not be very realistic because they are based on mathematical equations that take into consideration only a limited number of parameters that are the most relevant for the case. However when replicating the same experiments in real world situations, the results may vary due to un-apprehended parameters that have an effect.

4.3 SELECTION OF THE RESEARCH APPROACH

The chosen study approach in this thesis is the mathematical calculations with the aim of comparing different wind contexts and calculating the power available in the wind, and the power capture potential of different turbine types and circumstances. This method was used because the resources required for using a wind tunnel or field testing was not available, whether in the actual equipment or time. However mathematical calculations serve the objectives of this research in estimating the wind power available from different cases.

Computational Fluid Dynamics modeling was also used to simulate a number of scenarios based on the findings of the mathematical calculations.

4.4 MATHEMATICAL POWER CALCULATIONS

4.4.1 POWER AVAILABLE IN WIND

Wind turbines are simply devices that capture and convert the kinetic energy in the flowing wind into a mechanical form that can be used, either directly (to drive pumps for example) or indirectly through electrical generators.

Energy in flowing wind is kinetic energy. And the Kinetic Energy "U" in a moving mass of air "m" moving with a velocity "V" in the "x" direction can be calculated as: *(Burton, T. Sharpe, D. Jenkins, N. Bossanyi, E., 2001)*

$$U = \tfrac{1}{2}.m.V^2 = \tfrac{1}{2}(\rho.A.x).V^2 \quad \text{(Joules)} \quad (1)$$

Where:

	U	Kinetic Energy in Joules
	m	mass of air in Kg
	ρ	air density in kg/m^3
	V	velocity of air movement in m/s
	A	area of air mass in m^2
	x	direction of air movement

The Power in the wind "P_w" is the rate of the Kinetic Energy per time in seconds, hence: *(Johnson, G. L., 2001)*

$$P_w = \frac{\Delta U}{\Delta t} = \frac{1}{2}.\rho.A.V^2.\frac{\Delta x}{\Delta t} = \frac{1}{2}.\rho.A.V^3 \quad \text{(Watts)} \quad (2)$$

Where:

	P_w	Wind Power in watts
	ΔU	change in Kinetic Energy
	Δt	change in time

This power is the total wind power approaching the turbine surface; however the actual power extracted from the wind by the turbine is much less. And is calculated as the difference between the power in the air before and after the turbine: *(Johnson, G. L., 2001)*

$$\boldsymbol{P_o = \frac{1}{2}\, mass\ flow\ rate\ per\ second\ .\{V^2 - V_o^2\}} \qquad (3)$$

Where: P_o power extracted by the turbine

V upstream wind velocity in m/s

V_o downstream wind velocity in m/s

The velocity of the air stream changes at the plane of the turbine, hence the mass flow rate of the air through the rotating turbine can be calculated as:

$$\boldsymbol{mass\ flow\ rate = \rho\,.A\,.\frac{V+V_o}{2}} \qquad (4)$$

Hence, the Power extracted equation can be re-written as:

$$\boldsymbol{P_o = \frac{1}{2}\left[\rho\,.A\,.\frac{(V+V_o)}{2}\right].\{V^2 - V_o^2\}} \qquad (5)$$

This can be rearranged as: *(Johnson, G. L., 2001), (Patel, M. R., 1999)*

$$\boldsymbol{P_o = \frac{1}{2}\,\rho\,.A\,.V^3\,\frac{\left[1+\frac{V_o}{V}\right]\left[1-\left(\frac{V_o}{V}\right)^2\right]}{2}} \qquad (6)$$

$\frac{\left[1+\frac{V_o}{V}\right]\left[1-\left(\frac{V_o}{V}\right)^2\right]}{2}$ is described as the Power Coefficient "Cp" which the fraction of the power extracted by the wind turbine from the flowing wind. This represents the turbine's efficiency in the energy conversion. The remaining power is released in the downstream wind.

Hence, the equation becomes: *(Patel, M. R., 1999)*

$$P_o = \frac{1}{2}\,\rho\,.\,A\,.\,V^3.\,C_p \qquad (7)$$

4.4.2 TURBINE POWER COEFFICIENTS

(Patel, M. R., 1999), (Johnson, G. L., 2001), (Burton, T. Sharpe, D. Jenkins, N. Bossanyi, E., 2001) As previously explained the efficiency of the wind turbine in capturing the power in the wind can be represented by the Power Coefficient Cp. This coefficient is the ratio of the power in the downstream wind compared to the upstream wind (Vo / V).

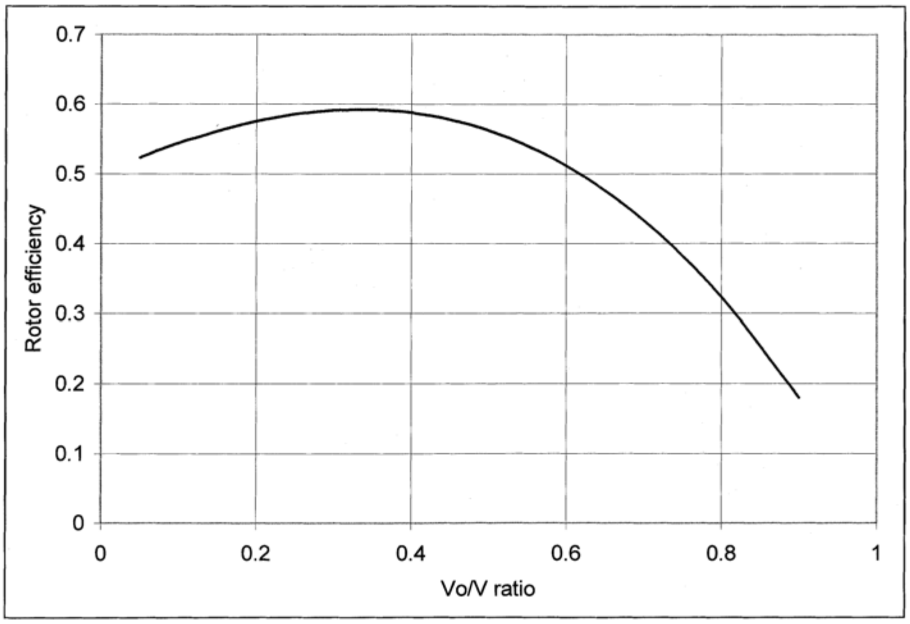

Figure 33 - Power Coefficient plotted against upstream and downstream wind speed

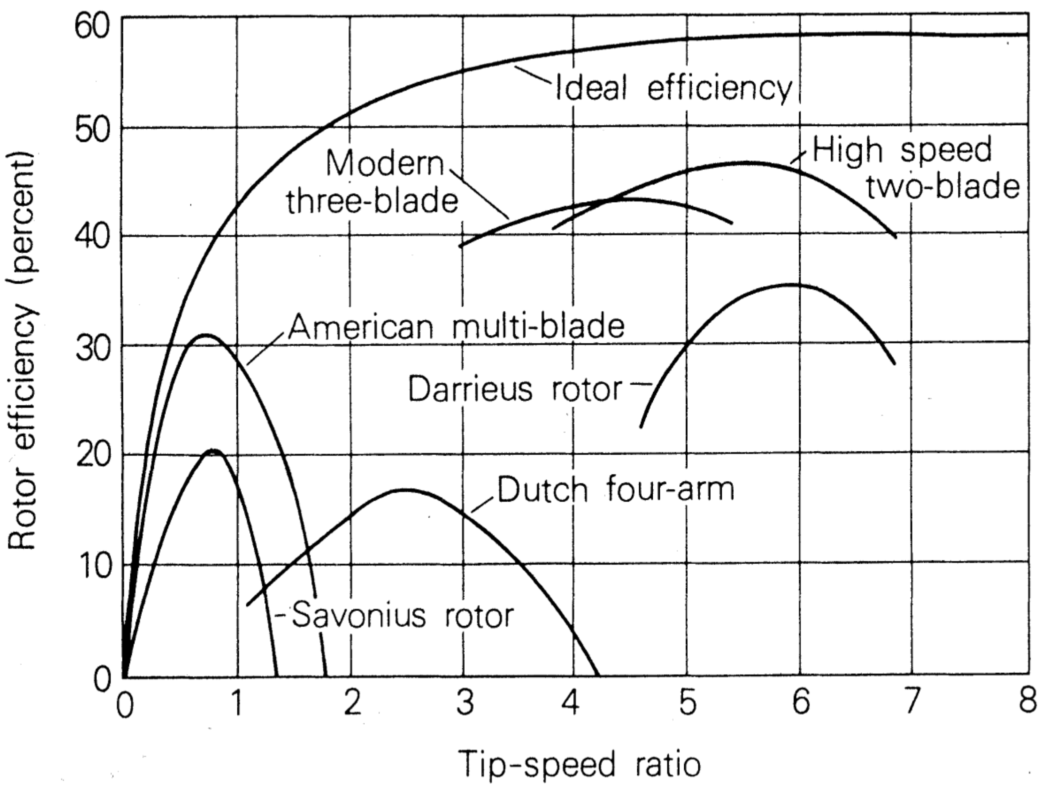

Figure 34 - Power Coefficients of different turbine types

By plotting the power coefficient against the (Vo / V), it's clear that the Cp has a maximum value of 0.593. Which means that the maximum power that can be extracted by a turbine from flowing wind is around 59%.This is called the "Betz Limit" named after the German physicist Albert Betz who developed this theory in 1919.

This is the theoretical limit; however in reality wind turbines rarely achieve this efficiency. Mainly due to mechanical limitations. Modern high speed HAWT achieve a Cp between 0.45 and 0.5, Lift type VAWT can achieve similar efficiencies higher than 0.4, however drag type VAWT rarely achieve more than 0.2 efficiency. *(Patel, M. R., 1999)*

However the Coefficient of power for a turbine is not a constant figure, this figure varies the wind speed, turbine rotational speed, blade angle of attach and pitch. Hence for a given turbine, there's a number of curves that can be plotted for the C_p versus the above mentioned parameters. *(Johnson, G. L., 2001)*

However, for convenience it's common practice to have one C_p curve for a given turbine. This curve usually plots Cp against either the wind speed or the turbine rotational speed. Even better if these two curves can be combined into one, by using a variable that represents the turbine rotational speed versus the wind speed. This variable is called the TSR (Tip Speed Ratio) "λ"and can be represented with the following formula:

$$\lambda = \frac{r_m.\omega_m}{V} \qquad (8)$$

Where: λ Tip Speed Ratio

r_m Maximum radius of the rotating turbine blade in meters

ω_m Angular velocity of the turbine in rad/sec

V Wind speed in m/s

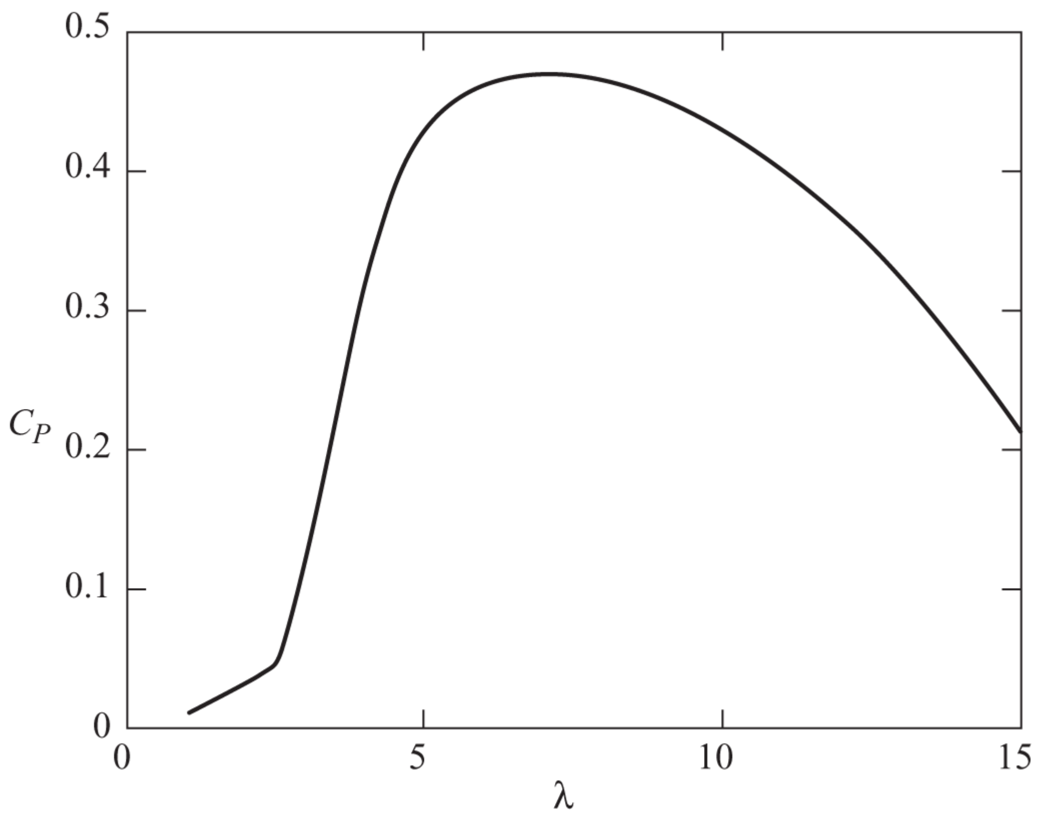

Figure 35 - Curve showing Cp plotted against the TSR for a Darrieus Turbine

4.4.3 EFFECT OF HEIGHT AND TERRAIN ROUGHNESS ON WIND ENERGY

There are two main parameters that have to be taken into account in regards to wind energy, especially in the integration of wind turbines into the urban Environment. Namely the height at which the turbine is installed and secondly the terrain roughness of the site.

The movement of air along the earth's surface suffers from friction between the air layers and the ground surface. Air is slowed down due to this friction, hence a wind speed gradient develops where the bottom layer of air moving just above the ground is the slowest, and each layer above is faster. This is called the *"Wind Shear".* High above the ground, say at a 1km height, the ground has little effect on the wind and the wind speed stabilizes. *(Wind Turbine Energy, 2002)*

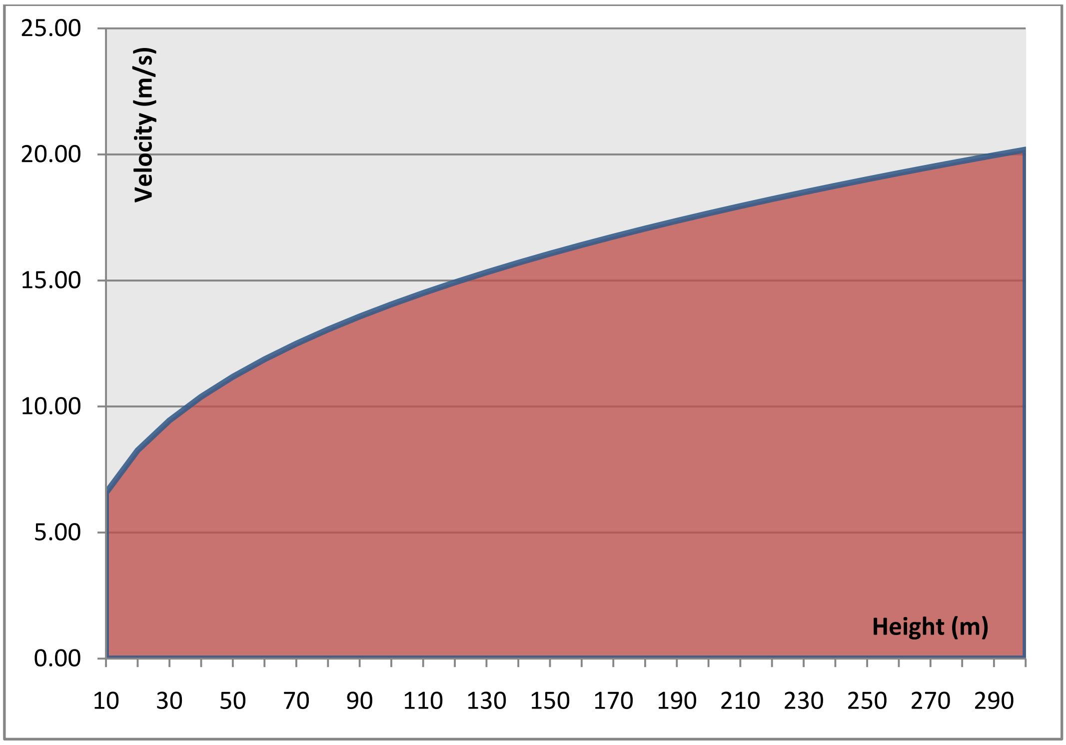

Figure 36 - Chart showing the wind shear caused by terrain roughness

4.4.4 ROUGHNESS CLASSES AND HEIGHT

As explained the friction caused by the terrain slows down wind movement. However this is not consistent, meaning that the rougher the terrain surface is, the higher the friction and hence the slower the wind moves. A large leveled lawn field does not cause as much friction to the passing wind as a hilly tree full forest terrain. In the same sense, a large water body would cause much lower friction than a lawn field, and a dense urban environment with buildings of various heights would have a much higher friction than a forest.

These different terrain types cause different friction levels because they have different roughness. This is called the *"Roughness Class"*. Four roughness classes have been identified: *(Fluent Inc., 2007)*

1. Dense urban areas, with average building height above 21m. These have the highest surface friction.
2. Suburban areas, with small closely located buildings, or dense forests.
3. Open terrain with scattered obstructions which might be small buildings or big trees.
4. Unobstructed terrain, large water bodies.

This roughness classes are then translated into terrain roughness factor "α" for calculating wind speeds at a given site as will be explained later.

The effect of this terrain roughness does not extend indefinitely, as after a certain height, the effect of ground friction diminishes. This is called *"Roughness Height"* and obviously the lower the terrain roughness the smaller the extent of effect extends and vice versa. After this height the effect of the boundary layer seizes.

Before using wind data, the wind speed has to be adjusted from the knowledge of the terrain type where the turbine is to be installed and the height at which it is going to be mounted. And as wind data usually comes from weather stations located in rural or unobstructed areas, and measurements are usually taken at a low height (usually 10m), the wind velocity can be very different if the turbine is to be mounted at an urban location with a different height.

Hence the following equation can be used to estimate the wind speed at a given height and terrain type: *(Fluent Inc., 2007)*

$$V_h = \begin{cases} \boldsymbol{V_{met}} \cdot \left(\frac{d_{met}}{H_{met}}\right)^{a_{met}} \cdot \left(\frac{h}{d}\right)^{a} & \boldsymbol{h} < d \\ \boldsymbol{V_{met}} \cdot \left(\frac{d_{met}}{H_{met}}\right)^{a_{met}} & \boldsymbol{h} \geq \boldsymbol{d} \end{cases} \quad (9)$$

Where:

Where:	V_h	Wind speed at required height in m/s
	$\boldsymbol{V_{met}}$	Measured wind speed at meteorological station in m/s
	$\boldsymbol{d_{met}}$	Boundary layer thickness at meteorological station
	$\boldsymbol{H_{met}}$	Height of the anemometer at the meteorological station
	$\boldsymbol{a_{met}}$	Terrain factor for the meteorological station
	a	Terrain factor for the desired location
	h	The height at which the wind speed is required in meters
	d	Boundary layer thickness at required location

Hence from the above equation, knowing the wind speed, height of anemometer and location of the weather station, the wind speed at any nearby site and height can be calculated.

Table 2 - Terrain Roughness Categories

TERRAIN CATEGORIES	DESCRIPTION	a	d
1	Large city centers, in which at least 50% of buildings are higher than 21m over a distance of at least 2km upwind	0.33	460
2	Urban, Suburban and wooded areas, with small spaced obstructions similar to or larger than single family dwellings, of at least 2km upwind	0.22	370
3	Open Terrain with scattered obstacles generally under 10m in height	0.14	270
4	Flat, unobstructed terrain, like large water bodies	0.10	210

4.4.5 AIR DENSITY VARIATION WITH HEIGHT

Another less relevant factor to wind energy is the effect of height on air density. As explained earlier the power in the wind is proportional to the density of air. The air density on Earth decreases as the altitude increases, however the change in air density within the first 1km is very small compared to other factors, hence is usually disregarded.

Air density change with height can be calculated using the following formula:

$$\rho = \rho_o - (1.194\,E10^{-4}\,.h) \qquad (10)$$

Where: ρ Air density at required height in kg/m^3

ρ_o Standard air density at sea level

h Height at which air density is required

4.4.6 ROTOR SWEPT AREA

The area represented in the power equation, represents the area of mass of air passing through the turbine. *(Burton, T. Sharpe, D. Jenkins, N. Bossanyi, E., 2001)*

HAWT:

$$A = \frac{\pi}{4} . \boldsymbol{r_m}^{\mathbf{2}} \qquad (11)$$

Darrieus:

$$A = \frac{2}{3} . W_m . H_m \qquad (12)$$

Where: W_m Maximum rotor width at center

H_m Maximum height at Axis

4.5 WIND DATA

As explained in Chapter 2, wind movement occurs on earth due to different factors; however no location is similar to another in wind characteristics. Hence wind data needs to be collected and documented for the site of interest to make correct assumptions on the wind energy available.

4.5.1 TYPES OF WIND DATA:

Wind data usually corresponds to measured values for wind speed and direction for specific site. As with most weather data, these measurements can be minute or hourly values, or averaged on longer time intervals. An important association with wind measurements is frequency which represents the probability of a certain wind speed from a specific direction.

Figure 37 - A typical weather station showing an anemometer and wind vane

Wind data can also include measurements of wind temperature and density. However, these latter are less relevant in power calculations, as their tolerances are relatively small for a specific site.

4.5.2 WIND DATA MEASUREMENT:

Wind data is usually measured at weather stations, which are usually located at sites where minimal obstructions are present that might affect the readings. Hence Airport weather stations are the most common. Wind data measured as previously mentioned includes: *(Eriksson, S., Bernhoff, H., Leijon, M., 2006)*

Wind Speed: This is the most important parameter in wind energy as has been highlighted in the power equations. Wind speed is usually measured using anemometers, which can be simple cup type anemometers, or more advanced hot wire, laser or radar anemometers. Readings are usually in m/s.

Wind Direction: Another very important parameter. This is usually measured through wind vanes, which should optimally be located at the same height as the anemometer. Usually direction measurements are taken on 5 degree increments or higher.

Wind Temperature and Pressure: Wind density also plays a role in the wind energy content, hence temperature and pressure measurements are important. However, pressure variations for a specific site have a relatively small effect.

4.6 WIND ROSE

A wind rose is a graphical representation of the speed, direction and frequency of wind at a given site. Usually the wind rose is represented radialy with the top of the diagram pointing towards the north orientation and East, South and West orientation represented accordingly. A number of sub-orientations are added between the mean orientations depending on the data available, but typically lines are drawn at 30 degree increments.

Different variants of the wind roses are used, with the either the wind speed only, wind speed with frequency or frequency only displayed either with text values or graphically (bar length, width and/or color) on concentric circles on their respective orientations. Some less common variants of wind roses might represent wind temperatures or wind humidity. Wind roses can represent yearly, monthly, weekly, daily or seasonal values for wind data.

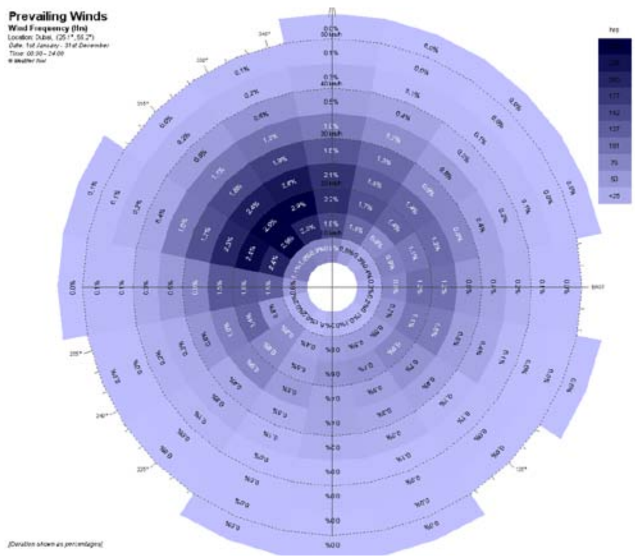

Figure 38 - Example of a yearly wind rose for Dubai

CHAPTER 5 TURBINE POWER CALCULATIONS

5.1 INTRODUCTION

In this chapter the mathematical equations defined in the last chapter are to be applied to actual wind data from meteorological stations. An estimation of the available energy in the wind is then calculated for each orientation independently. The effect of height and terrain roughness is then applied to these estimations. The power coefficient of different turbine types is then taken into the calculations. And finally a statistical comparison is done on the different findings.

5.2 ESTIMATION OF AVAILABLE WIND ENERGY

The quantity of energy that can be captured by a wind turbine depends on two factors: the wind characteristics at the installation site and secondly the turbine's power Coefficient curve for different wind speeds.

Gipe (2004, pp.59-63) states that there are three known ways for estimating the wind power that can be harnessed by a wind turbine at a specific site:

1. Turbine Swept Area method

The Turbine Swept Area method relies on the calculation of the turbine's swept area. This is usually provided by the manufacturer. However it can also be easily calculated as follows:

For a conventional HAWT, the Swept area: *Gipe (2004, pp.59-63)*

$$A = \pi R^2 \qquad (13)$$

Where A: is the rotor's swept area

R: Is the rotor radius

For a Darrieus rotor: *Gipe (2004, pp.59-63)*

$$A = 0.65\ DH \qquad (14)$$

Where A: is the rotor's swept area

D: Is the rotor's largest diameter

H: is the height of the blades

For the H-rotor: *Gipe (2004, pp.59-63)*

$$A = DH \qquad (15)$$

Where A: is the rotor's swept area

D: Is the rotor's largest diameter

H: is the height of the blades

This swept area when multiplied by the site's average power density in W/m2 can estimate the power generated by a turbine in this site. This method is simple and straight forward, hence is used by many turbine consultants as a rule of thumb. However, sometimes it's hard to calculate a site's power density correctly, especially when talking about complex terrain or urban sites, where the power density differs significantly from the weather station's.

2. The Power Curve Method:

The second commonly used method is the power curve method. This technique is the most rigorous, and requires the most information, hence is used by commercial wind farm consultants to accurately estimate the power potential.

This method works by applying the turbines power curve (Turbines power coefficient per wind speed) to the sites wind data (Wind speed frequency curve). Hence this technique requires knowledge of the turbine's Power Coefficient at different wind speeds as well as hourly or at least daily wind speed distribution. Knowing these two parameters it's possible to calculate the number of hours the turbine will be generating various power levels.

3. The Manufacturer's Power Estimates:

This is the third method, and as is clear from the name, this technique relies on estimates provided by the turbine manufacturers' for its performance under different wind speeds. However, these estimates are often unrealistically optimistic and are derived from wind tunnel or lab condition studies, which might differ than real life performance. Hence this method can be used if the later two is not possible and it's recommended to ask for third party verified data, by a trusted verification source. This is very common in medium and large scale turbines, because it's required by costumers of wind farms, however, for smaller scale wind turbines aimed at private use, trusted data is very uncommon.

Hence form the previous; it's clear that the second method (Turbine power curve) is the most accurate measure. This will be implemented in this study as follows: A number of typical urban sites are to be chosen, data for these sites are to be analyzed and a wind speed frequency curve plotted for each. Then a number of turbine models of different types are to be selected (with a trusted source for performance) and the power curve is to be applied to the selected wind speed frequency to estimate the power generation potential of each. *(Gipe, P., 2004), (Wind Power, 2008)*

5.2.1 WIND DATA

As previously explained, wind data comes usually in the form of hourly data of wind speed and direction. This data measured at a weather station is usually collected using data collection devices and later compiled into a data sheet. In this form (hourly values) wind data for a whole year becomes overwhelming and not easy to use to get an idea of the wind characteristics of a specific site.

Hence the data needs to be formulated in a way that can be easily read. This is usually done by dividing the wind data into sets depending on the incoming wind direction, and then these sets are further divided into categories depending on the measured wind speed. This ends up with a table that shows the wind direction versus wind speeds. The final thing that remains is to know how often each category of wind speed happens from each wind direction. This is called the wind frequency.

The wind rose, as explained earlier is a representation of the above mentioned data that is arranged in a radial manner according to the wind direction to facilitate reading the data.

SELECTED WIND DATA

For the sake of this study, wind data has been selected for a number of cities showing different wind characteristics. The wind data was acquired mainly from the Weather Tool software interface which is supplied as part of the Ecotect Environmental software package. *(Ecotect Weather Tool, 2008)*

The selected cities where based on wind characteristics, mainly wind directionality as follows:

1. Camborne, UK: is a city located in the south of the UK. This city was selected because it represents an example for a wind rose with wide dispersion; no prevailing wind direction seems unidentifiable.

2. Dubai, UAE: Dubai is the biggest city in the UAE, located along the Persian Gulf. Dubai's wind rose represents a wide spread wind orientation, however a prevailing wind direction from the north west can be identified.

3. Cairo, Egypt: is the capital of Egypt, located along the Nile delta. Cairo's wind rose is relatively more concentrated than Dubai. Wind is measured from other orientation, but the prevailing wind direction is much more frequent.

4. Hong Kong, China: located in the south east of China. This city is an example of a wind rose with a highly concentrated prevailing wind direction.

CAMBORNE, UK

Camborne is an x-industrial town located in north Kerrier, Cornwall in the United Kingdom, forming the western end of the greater Camborne. The city currently has a population of approx. 23,000.

Figure 39 - Camborne Location, Google Maps

Camborne is located at these coordinates: 50° 12′ 46.91″ N, 5° 18′ 7.99″ W

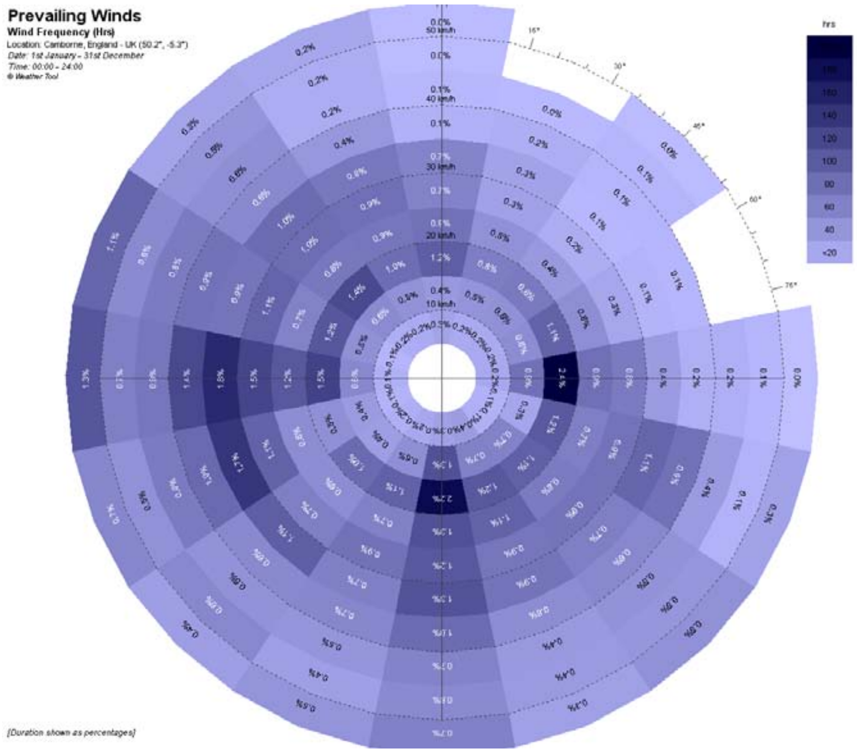

Figure 40 - Yearly Wind Rose for Camborne, UK

DUBAI, UAE

Dubai is one of the seven emirates that make up the United Arab Emirates. It's also the country's most populated city and is considered the major business and financial hub for the region. Dubai is located along the coast of the Persian Gulf on the Arabian Peninsula. 25° 12′ 0″ N, 55° 18′ 0″ E

Figure 41 - Dubai Location, Google Maps

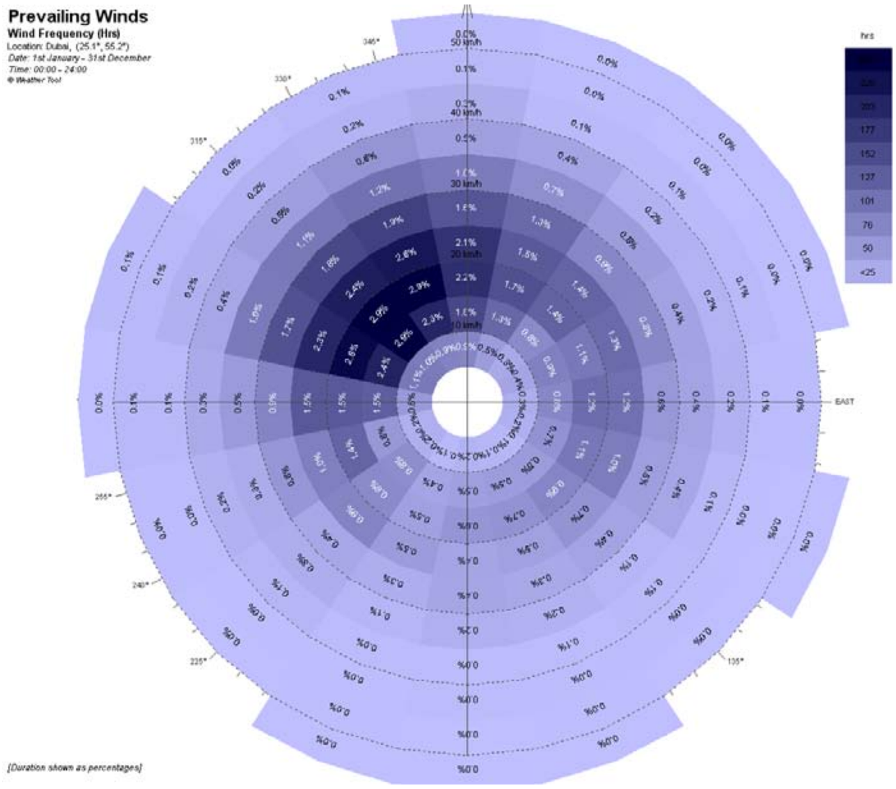

Figure 42 - Yearly Wind Rose for Dubai, UAE

CAIRO, EGYPT

Cairo is the capital of Egypt and both the largest and most populated city. The city is located on the Nile valley in the northern part of the country. With its suburban areas, Cairo is considered one of the most populated metropoltian areas with approx. 17.8 million inhabitants.

Figure 43 - Cairo Location, Google Maps

Cairo is located at these coordinates: 30° 3′ 28.8″ N, 31° 13′ 44.4″ E

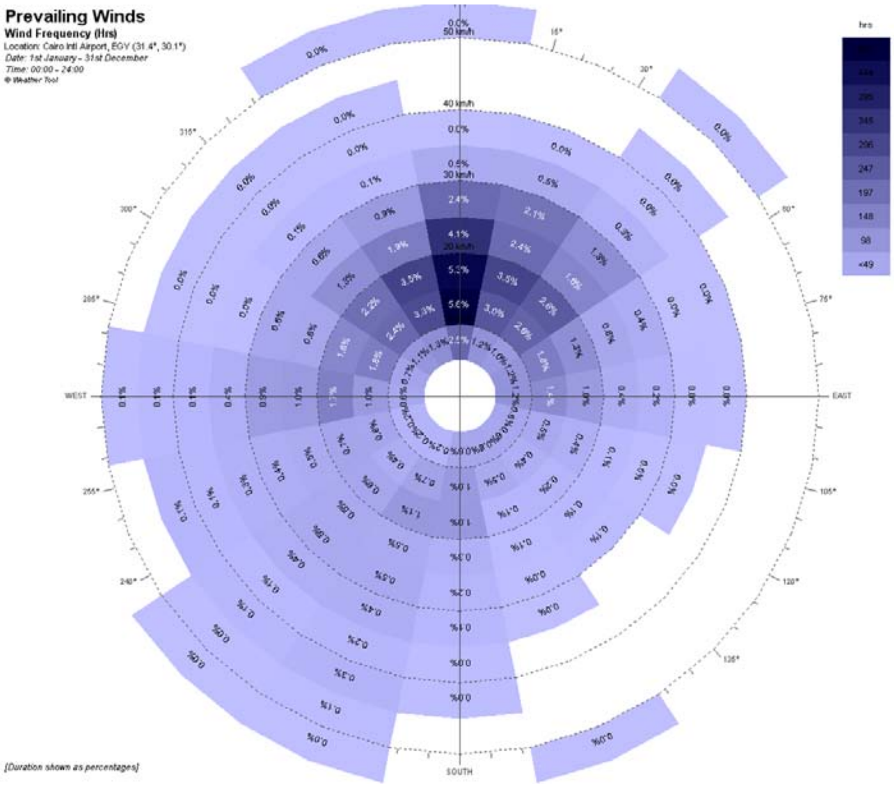

Figure 44 - Yearly Wind Rose for Cairo, Egypt

HONG KONG, CHINA

Hong Kong is located in Southern China in East Asia, bordering the province of Guangdong to the north and facing the South China Sea to the east, west and south. It has a population of 7 million people, making it one of the most densely populated areas in the world.

Hong Kong is located at these coordinates:

22° 18′ 0″ N, 114° 12′ 0″ E

Figure 45 - Hong Kong Location, Google Maps

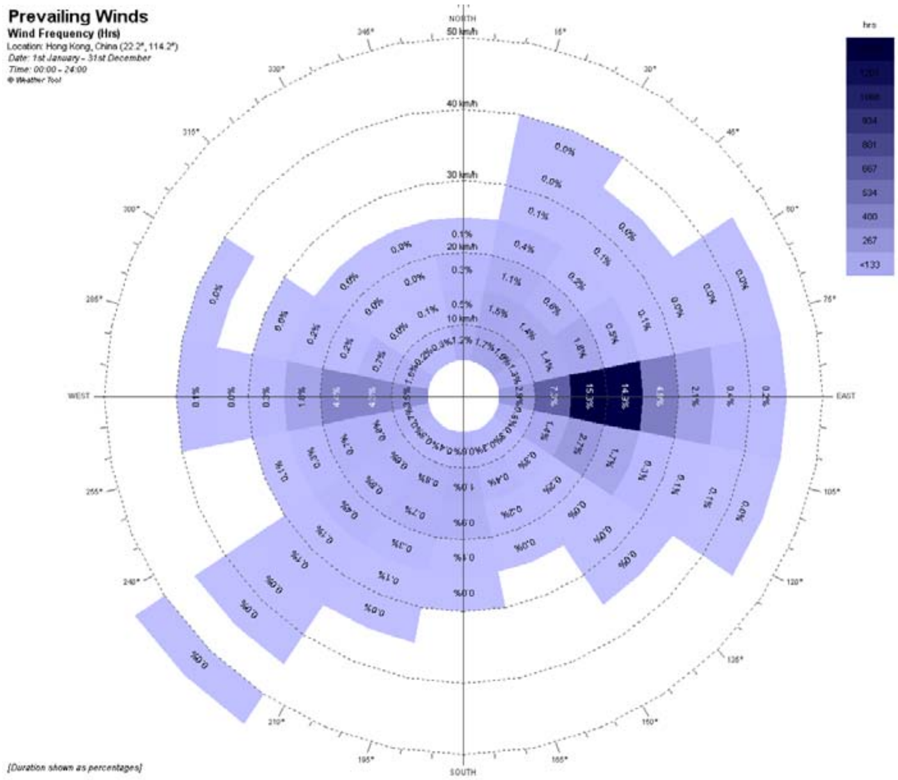

Figure 46 - Yearly Wind Rose for Hong Kong, China

WIND DIRECTIONALITY CHARACTERISTICS:

Hence according to directionality, four wind characteristics can be defined:

1. Highly Concentrated: when more than 35% of wind comes from one prevailing direction and no other secondary prevailing wind direction can be identified.

2. Concentrated: when more than 18% of the wind come from one prevailing wind direction. Another secondary wind direction may or may not exist.

3. Dispersed: when the prevailing wind direction contributes to less than 10% of the wind frequency and wind is relatively frequent from orientations within a 70 degree window from the maximum.

4. Widely dispersed: when no prevailing wind direction can be clearly defined. Most of the wind directions are near to the average frequency. This does not mean that in specific months wind prevails from a certain direction.

WIND DATA

Table 3 - Camborne Wind Speed Frequency Data

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s)	2.78	0.30	0.20	0.20	0.20	0.20	0.10	0.10	0.40	0.30	0.20	0.20	0.10	0.10	0.10	0.20	0.20
	4.17	0.40	0.50	0.50	0.60	0.90	0.30	0.70	0.70	1.30	0.60	0.40	0.40	0.60	0.50	0.60	0.50
	5.56	1.20	0.80	0.80	1.10	2.40	1.20	1.10	1.20	2.20	1.10	1.00	0.50	1.50	1.20	1.40	1.00
	6.95	0.90	0.50	0.40	0.60	0.90	0.70	0.80	1.10	1.30	0.70	0.60	0.60	1.20	0.70	0.80	0.90
	8.33	0.70	0.30	0.20	0.30	0.80	0.90	0.90	0.90	1.20	0.90	0.70	1.10	1.50	1.10	1.00	0.90
	9.72	0.70	0.30	0.10	0.10	0.40	1.10	0.70	0.90	1.30	0.70	1.10	1.70	1.80	0.90	1.00	0.80
	11.11	0.10	0.20	0.10	0.10	0.20	0.90	0.60	0.60	1.00	0.70	0.60	1.00	1.40	0.90	0.60	0.40
	12.50	0.10	0.02	0.10	0.00	0.20	0.40	0.50	0.40	0.70	0.50	0.50	0.80	0.90	0.80	0.60	0.20
	13.89	0.02	0.00	0.02	0.00	0.10	0.10	0.50	0.40	0.60	0.40	0.60	0.50	0.70	0.60	0.50	0.20
	15.28	0.02	0.00	0.00	0.00	0.02	0.30	0.50	0.30	0.70	0.50	0.40	0.70	1.30	1.10	0.30	0.20
	16.67																
	18.06																
Total	%	4.44	2.82	2.42	3.00	6.12	6.00	6.40	6.90	10.60	6.30	6.10	7.40	11.00	7.90	7.00	5.30

The wind data for Camborne shows a fairly uniform wind distribution, with peaks at angles 270^{o} and 180^{o}, however even at those two peaks the concentration is no more than 11% of the total.

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s)	2.78	0.90	0.50	0.30	0.40	0.30	0.20	0.10	0.10	0.20	0.10	0.20	0.20	0.60	1.10	1.00	0.90
	4.17	1.80	1.30	0.80	0.90	0.80	0.70	0.50	0.50	0.50	0.40	0.80	0.60	1.50	2.40	2.90	2.30
	5.56	2.20	1.70	1.40	1.10	1.20	1.10	0.90	0.70	0.60	0.50	0.80	1.40	1.50	2.80	2.90	2.90
	6.95	2.10	1.50	1.40	1.30	1.20	1.00	0.70	0.50	0.40	0.50	0.90	1.00	1.50	2.30	2.40	2.60
	8.33	1.60	1.30	0.90	0.80	0.60	0.50	0.40	0.30	0.40	0.30	0.40	0.60	0.90	1.70	1.80	1.90
	9.72	1.00	0.70	0.50	0.40	0.40	0.40	0.10	0.20	0.20	0.10	0.30	0.30	0.50	1.00	1.10	1.20
	11.11	0.50	0.40	0.20	0.20	0.20	0.10	0.10	0.10	0.02	0.02	0.10	0.20	0.30	0.40	0.50	0.60
	12.50	0.30	0.10	0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.20	0.20	0.20
	13.89	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.10	0.02	0.10
	15.28	0.02	0.02	0.02	0.02	0.00	0.02	0.00	0.02	0.02	0.02	0.00	0.00	0.02	0.10	0.00	0.00
	16.67																
	18.06																
Total	%	10.52	7.54	5.64	5.24	4.82	4.06	2.84	2.46	2.38	1.98	3.54	4.34	7.02	12.10	12.82	12.70

Table 4 - Dubai Wind Speed Frequency Data

The Dubai wind data shows a peak in wind frequency between angles 292.5^o and 0^o. However, the maximum concentration at angle 315^o is no more than 13% of the total.

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s)	2.78	2.50	1.20	1.00	1.20	1.20	0.60	0.60	0.60	0.60	0.20	0.20	0.20	0.60	0.70	1.10	1.30
	4.17	5.60	3.00	2.60	1.80	1.40	0.50	0.40	0.50	1.00	0.70	0.40	0.60	1.00	1.80	2.40	3.30
	5.56	5.30	3.50	2.80	1.30	1.00	0.40	0.20	0.10	1.00	1.10	0.60	0.70	1.70	1.60	2.20	3.50
	6.95	4.10	2.40	1.60	0.60	0.40	0.10	0.10	0.10	0.30	0.50	0.50	0.50	1.00	0.60	1.30	1.90
	8.33	2.40	2.10	1.30	0.40	0.20	0.04	0.10	0.02	0.20	0.50	0.50	0.40	0.90	0.60	0.60	0.90
	9.72	0.50	0.50	0.30	0.04	0.04	0.02	0.00	0.02	0.10	0.40	0.40	0.30	0.40	0.02	0.10	0.10
	11.11	0.02	0.04	0.04	0.02	0.02	0.00	0.00	0.00	0.02	0.20	0.10	0.10	0.10	0.02	0.02	0.02
	12.50	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.02	0.30	0.10	0.10	0.10	0.02	0.02	0.02
	13.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.02	0.00	0.10	0.00	0.00	0.02
	15.28	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.02
	16.67																
	18.06																
Total	%	20.44	12.76	9.68	5.36	4.26	1.66	1.40	1.36	3.24	4.02	2.84	2.90	5.90	5.36	7.74	11.08

Table 5 - Cairo Wind Speed Frequency Data

For Cairo, Wind peaks between angles 337.5^o and 22.5^o. With the maximum frequency at 0^o of more than 20% of the total.

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s)	2.78	1.20	1.70	1.90	1.30	2.90	0.80	0.30	0.30	0.60	0.40	0.30	0.70	3.50	1.00	0.20	0.30
	4.17	0.50	1.50	1.40	1.40	7.30	1.40	0.30	0.40	1.00	0.80	0.60	0.80	4.30	0.70	0.02	0.10
	5.56	0.30	1.10	0.80	1.60	15.30	2.70	0.20	0.20	0.90	0.70	0.50	0.70	4.40	0.20	0.02	0.02
	6.95	0.10	0.40	0.20	0.50	14.90	1.70	0.02	0.02	0.10	0.30	0.40	0.30	1.80	0.20	0.01	0.01
	8.33	0.00	0.10	0.10	0.10	4.90	0.30	0.02	0.00	0.02	0.10	0.10	0.10	0.30	0.02	0.00	0.00
	9.72	0.00	0.02	0.02	0.02	2.10	0.10	0.01	0.00	0.00	0.02	0.10	0.00	0.01	0.00	0.00	0.00
	11.11	0.00	0.01	0.00	0.01	0.40	0.10	0.00	0.00	0.00	0.00	0.02	0.00	0.10	0.01	0.00	0.00
	12.50	0.00	0.00	0.00	0.01	0.20	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
	13.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	15.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
	16.67																
	18.06																
Total	%	2.10	4.83	4.42	4.94	48.00	7.12	0.85	0.92	2.62	2.32	2.06	2.60	14.41	2.13	0.25	0.43

Table 6 - Hong Kong Wind Speed Frequency Data

Hong Kong wind data shows very high wind concentration, with more than 48% of the wind coming from the 90^o angle. This is a fairly rare occurrence. However a secondary prevailing wind direction is at angle 270^o, but does not exceed 14.5%

5.2.2 POWER ESTIMATION FROM WIND DATA

From the above wind data an assumption for the power in the wind for each orientation and frequency can be calculated according to the assumption that $\rho = V^3$

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Power Generated	2.78	6	4	4	4	4	2	2	9	6	4	4	2	2	2	4	4
	4.17	29	36	36	43	65	22	51	51	94	43	29	29	43	36	43	36
	5.56	206	137	137	189	412	206	189	206	377	189	172	86	257	206	240	172
	6.95	301	167	134	201	301	234	268	368	435	234	201	201	402	234	268	301
	8.33	405	174	116	174	463	521	521	521	695	521	405	637	868	637	579	521
	9.72	643	276	92	92	368	1,011	643	827	1,195	643	1,011	1,563	1,655	827	919	735
	11.11	137	274	137	137	274	1,235	823	823	1,372	960	823	1,372	1,921	1,235	823	549
	12.50	195	39	195	0	391	781	977	781	1,368	977	977	1,563	1,758	1,563	1,172	391
	13.89	54	0	54	0	268	268	1,340	1,072	1,608	1,072	1,608	1,340	1,876	1,608	1,340	536
	15.28	71	0	0	0	71	1,070	1,783	1,070	2,497	1,783	1,427	2,497	4,637	3,924	1,070	713
Total		2,049	1,108	906	840	2,618	5,351	6,597	5,728	9,647	6,428	6,657	9,289	13,420	10,272	6,459	3,959

Table 7 - Camborne Yearly Power Calculation (Watts)

Applying the Power equation to the wind data for Camborne reconfirms the wide spread wind approach direction, however angle 270^o still provides the highest power potential.

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Power Generated at 10m Height	2.78	19	11	6	9	6	4	2	2	4	2	4	4	13	24	21	19
	4.17	130	94	58	65	58	51	36	36	36	29	58	43	109	174	210	166
	5.56	377	292	240	189	206	189	154	120	103	86	137	240	257	480	497	497
	6.95	703	502	469	435	402	335	234	167	134	167	301	335	502	770	804	871
	8.33	926	752	521	463	347	289	232	174	232	174	232	347	521	984	1,042	1,100
	9.72	919	643	460	368	368	368	92	184	184	92	276	276	460	919	1,011	1,103
	11.11	686	549	274	274	274	137	137	137	27	27	137	274	412	549	686	823
	12.50	586	195	195	195	195	39	39	39	39	39	39	39	195	391	391	391
	13.89	268	54	54	54	54	54	54	54	54	54	54	54	268	268	54	268
	15.28	71	71	71	71	0	71	0	71	71	71	0	0	71	357	0	0
Total		4,687	3,164	2,349	2,123	1,910	1,537	980	985	884	741	1,238	1,613	2,808	4,915	4,716	5,239

Table 8 - Dubai Yearly Power Calculation (Watts)

Directional Power Calculations for Dubai's wind data shows a peak power potential at angle 337.5^{o} which is different from the prevailing wind frequency angle of 315^{o}. This is due to the higher wind speeds at this approach angle.

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Power Generated	2.78	54	26	21	26	26	13	13	13	13	4	4	4	13	15	24	28
	4.17	405	217	188	130	101	36	29	36	72	51	29	43	72	130	174	239
	5.56	909	600	480	223	172	69	34	17	172	189	103	120	292	274	377	600
	6.95	1,373	804	536	201	134	33	33	33	100	167	167	167	335	201	435	636
	8.33	1,389	1,216	752	232	116	23	58	12	116	289	289	232	521	347	347	521
	9.72	460	460	276	37	37	18	0	18	92	368	368	276	368	18	92	92
	11.11	27	55	55	27	27	0	0	0	27	274	137	137	137	27	27	27
	12.50	0	39	39	0	0	0	0	0	39	586	195	195	195	39	39	39
	13.89	0	0	0	0	0	0	0	0	0	268	54	0	268	0	0	54
	15.28	71	0	71	0	0	0	0	71	0	71	71	0	0	0	0	71
Total		4,689	3,416	2,419	876	613	193	167	201	631	2,268	1,418	1,175	2,201	1,053	1,516	2,308

Table 9 - Cairo Yearly Power Calculation (Watts)

For Cairo wind power potential peaks at an approach angle of 0^{o}. However a secondary power peak is at an approach angle of 202.5^{o}. This is probably the effect of seasonal wind storms "Khamasein" during spring when relatively high wind speeds prevail for a number of days (Table shows that most of the energy at this orientation is from wind blowing at 12.5m/s in contrast to the rest of the year).

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Power Generated	2.78	26	36	41	28	62	17	6	6	13	9	6	15	75	21	4	6
	4.17	36	109	101	101	528	101	22	29	72	58	43	58	311	51	1	7
	5.56	51	189	137	274	2,624	463	34	34	154	120	86	120	755	34	3	3
	6.95	33	134	67	167	4,991	569	7	7	33	100	134	100	603	67	3	3
	8.33	0	58	58	58	2,836	174	12	0	12	58	58	58	174	12	0	0
	9.72	0	18	18	18	1,930	92	9	0	0	18	92	0	9	0	0	0
	11.11	0	14	0	14	549	137	0	0	0	0	27	0	137	14	0	0
	12.50	0	0	0	20	391	39	0	0	0	0	39	0	0	0	0	0
	13.89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	15.28	0	0	0	0	0	0	0	0	0	0	71	0	0	0	0	0
Total		147	558	423	681	13,912	1,593	90	76	285	363	557	351	2,064	199	13	20

Table 10 - Hong Kong Yearly Power Calculation (Watts)

Hong Kong's power estimation confirms very high wind concentration from an approach angle 90^{o}. Power available from this orientation is more than thrice that available from all the other orientations.

From the above tables, a comparison of the power for each location is as follows:

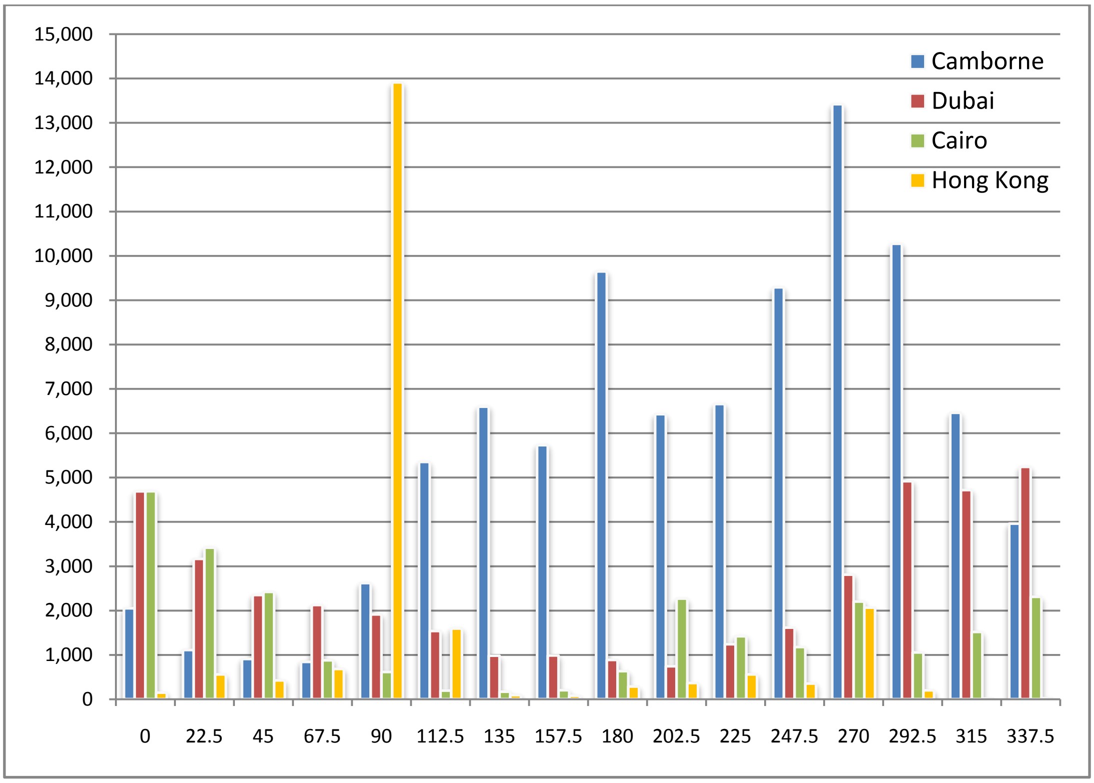

Figure 47 - Comparison between different sites with regards to power potential from each orientation

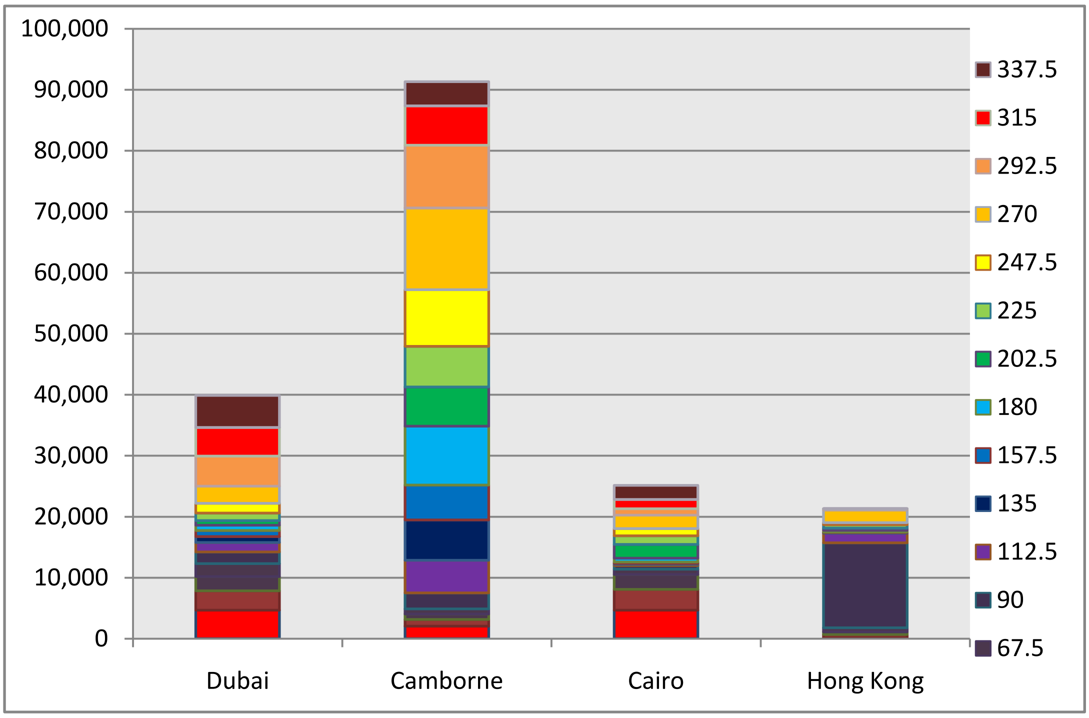

Figure 48 - Power Available at different sites

Figure 48, Shows the difference between the wind power estimates from each direction for each site. Figure 49, compares the wind energy at each site, Camborne shows the highest wind potential though the wind directions are quiet dispersed.

5.2.3 WIND SPEED FREQUENCY DISTRIBUTION

Wind speed frequency distribution is a description of the rate of recurrence of different wind speeds for a specific site. This can be done for various wind orientations or for the over-all wind regardless of the direction. *(Muller, G., Jentsch, M. F., Stoddart, E., 2008), (*Gipe, P., 2004)

For the sake of this study, both approaches will be attempted for the selected wind data. First the wind frequency from all orientations, and then for the prevailing wind direction.

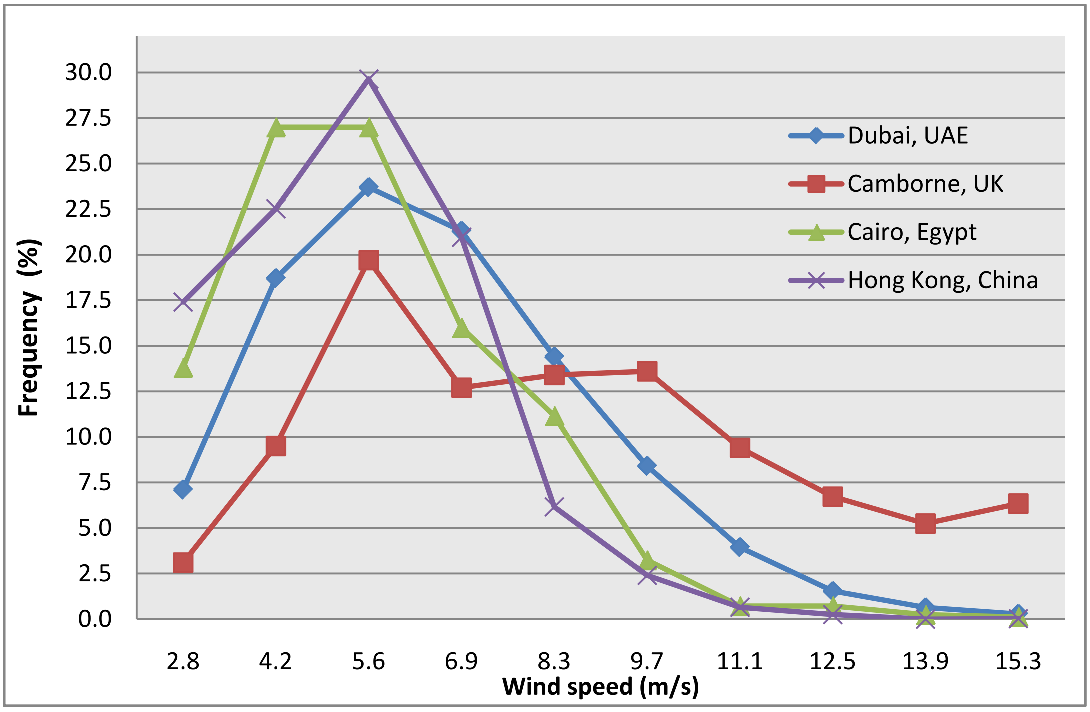

Figure 49 - Wind Frequency Distribution for all wind directions

The diagram in Figure 50 shows that the wind speed of 5.6m/s is the most frequent for all sites, however with different values, Hong Kong Being the highest and Camborne the lowest for this wind speed. The frequency curves for all sites seem relatively similar, with the exception of Camborne which experiences a higher frequency for wind speeds between 8.3 and 9.7m/s. This would have a significant in increasing the wind power potential.

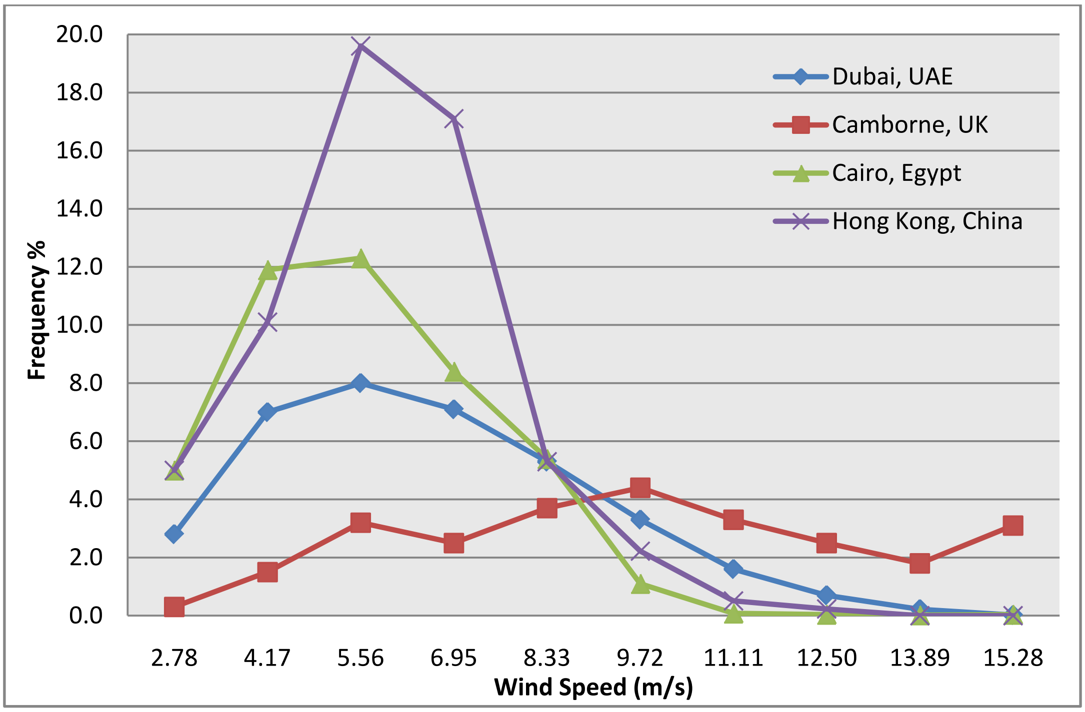

Figure 50 - Wind Frequency Distribution for prevailing wind direction

Isolating the prevailing wind direction reveals a different wind frequency distribution. Hong Kong has the highest wind frequency concentration at the wind speed range of 5.6m/s, however this doesn't tell the whole story as again Camborne shows the highest frequency at a higher wind speed range of about 9.7m/s. This has a significant effect on the power potential.

By multiplying these frequency percentages by the number of days in a year (365) and the number of hours per day (24), we can calculate the number of hours per year were these wind speeds occur. The diagrams become as follows:

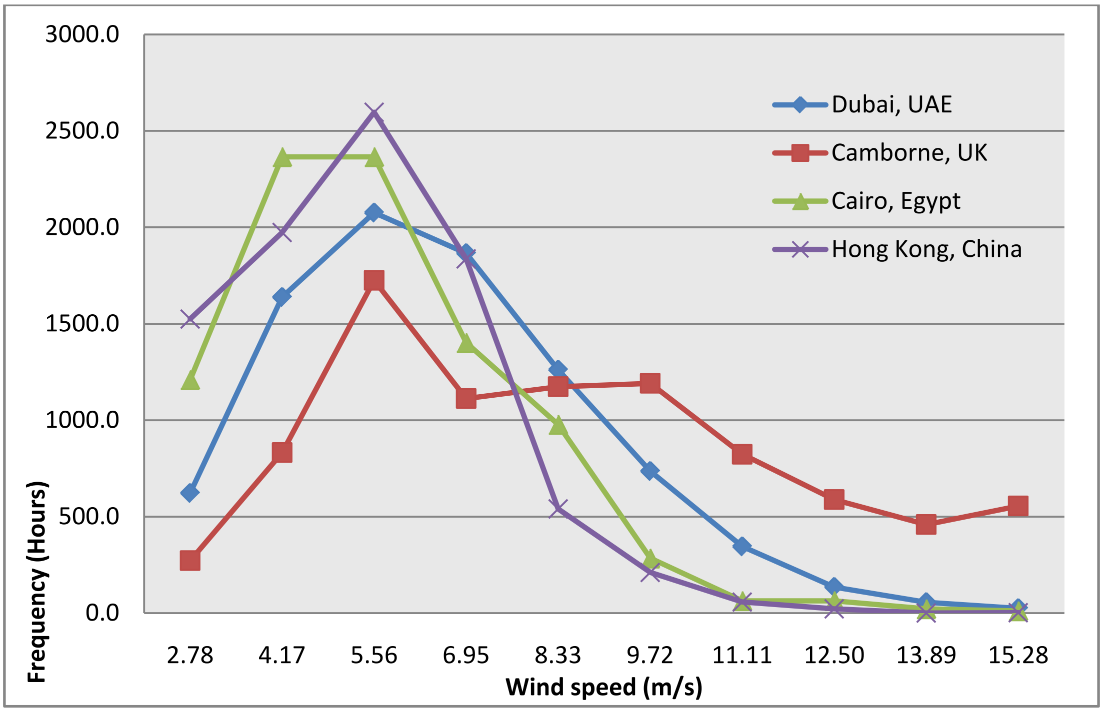

Figure 51 - Wind Frequency Distribution for all wind directions in hourly occurrence

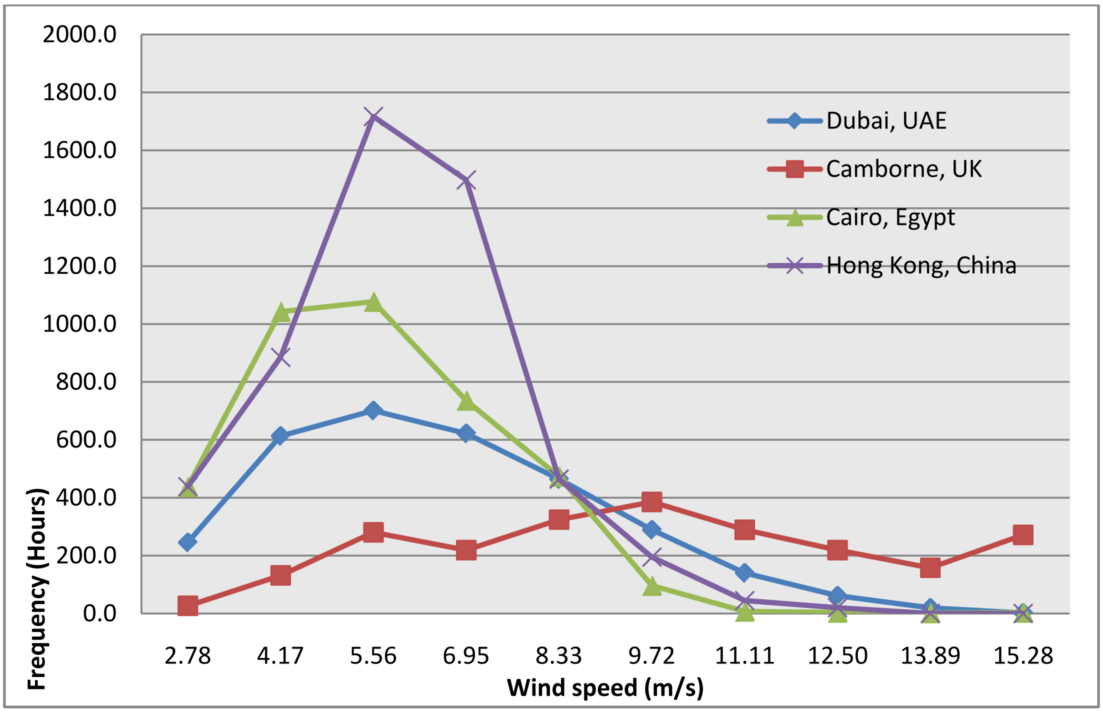

Figure 52 - Wind Frequency Distribution for prevailing wind direction in hours

Table 11 - Hourly frequency for different sites

	DUBAI		CAMBORNE		CAIRO		HONG KONG	
	Total	Prevailing	Total	Prevailing	Total	Prevailing	Total	Prevailing
2.78	622.0	245.3	271.6	26.3	1208.9	438.0	1524.2	438.0
4.17	1638.1	613.2	832.2	131.4	2365.2	1042.4	1972.8	884.8
5.56	2076.1	700.8	1725.7	280.3	2365.2	1077.5	2596.5	1717.0
6.95	1865.9	622.0	1112.5	219.0	1401.6	735.8	1836.1	1498.0
8.33	1261.4	464.3	1173.8	324.1	977.6	473.0	539.6	464.3
9.72	735.8	289.1	1191.4	385.4	283.8	96.4	210.2	194.5
11.11	345.1	140.2	823.4	289.1	63.1	7.0	56.9	44.7
12.50	134.9	61.3	588.7	219.0	63.1	3.5	21.9	20.1
13.89	56.1	19.3	459.0	157.7	21.0	1.8	0.0	0.0
15.28	24.5	1.8	555.4	271.6	10.5	3.5	1.8	0.0

5.2.4 EFFECT OF WIND DIRECTION ON AVAILABLE POWER

As explained earlier (3.4) wind turbine integration into buildings, requires special considerations and have specific advantages and limitations.

The most significant difference between HAWT and VAWT, is the ability of VAWT to receive wind from all directions (Omni directional). As explained earlier, HAWT in free standing wind farms are allowed to yaw to follow the wind direction. This is not a problem in free standing operation. However, when integrated into buildings yawing becomes a real challenge for many reasons:

1. HAWT become even noisier when yawing due to blade vibrations.
2. HAWT especially large scale types vibrate excessively while yawing due to the gyro-effect and would require substantial structural measures to accommodate these forces.
3. The mechanical mechanisms required to yaw large scale wind turbines would difficult to incorporate in buildings.
4. HAWT that are allowed to yaw, would take up a significant volume. And would require safety measures in the case of rotor failing.

5. The highly turbulent wind characteristics in urban environments might result in the turbine constantly yawing to follow the frequently changing wind direction.

Hence, it's correct to assume that in most cases HAWT will be integrated on buildings fixed to a specific orientation that is to be aligned to the prevailing wind direction according to wind data. However from the previous study into wind data for different locations, it's clear that even in locations with high wind concentration, wind coming from other directions other than the prevailing wind direction contribute to a significant percentage of the wind power potential.

This means that for such a fixed orientation turbine, wind will be relatively often blowing from an angle not contributing to energy generation (Most HAWT work only when wind is blowing perpendicular to the turbine and in the best assumptions at an angle not more than 12.5^o from the perpendicular).

The following study was done on the chosen wind data, to calculate and compare the total power available in the wind from all directions, compared to power available from the optimum orientation plus the perpendicular component of wind at ±12^o from the optimum.

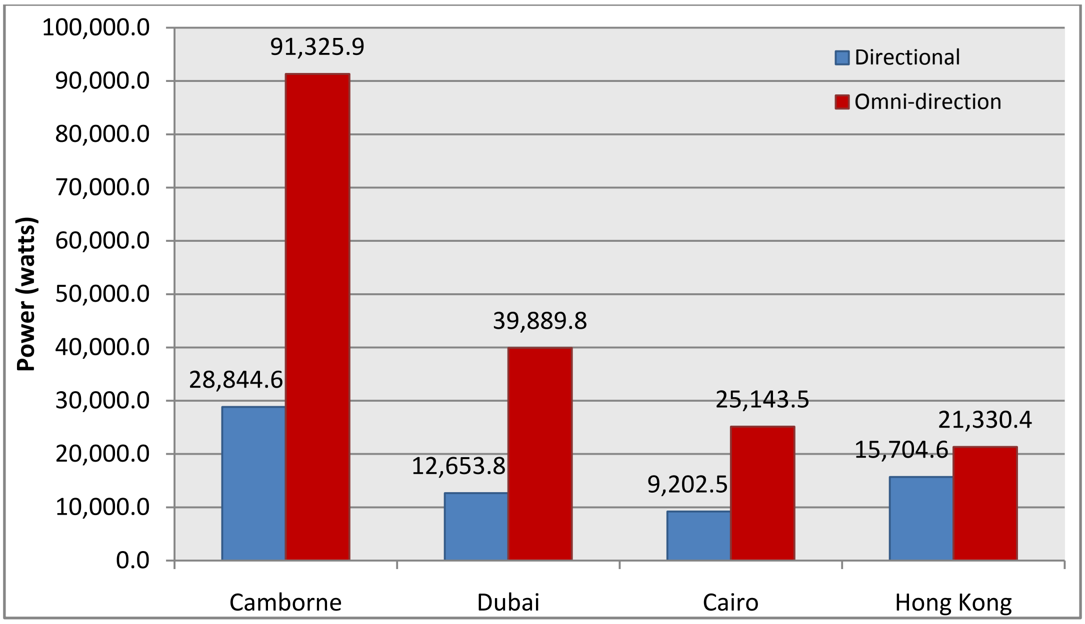

Figure 53 - Comparison between Directional and Omni-directional available wind power

In Figure 54, it's clear that limiting the power harnessing to the prevailing wind orientation, like in the case of fixed HAWTs, significantly reduces the potential wind power available. The more dispersed the wind rose, the higher the difference. From the previous study, the results were as follows: For Camborne, the power available from all directions is more than 3 times that from the prevailing wind direction. For Dubai, again the difference is more than 3 times. For Cairo, the difference is about 2.5 times. In the case of Hong Kong, because the wind directions are already highly concentrated, the difference is very small approx. 1.3 times.

5.2.5 APPLYING THE POWER CURVES OF DIFFERENT TURBINES

Knowing the number of hours per year that wind blows from a specific orientation at a specific speed one can estimate the power captured by a specific turbine. This can be done by applying the power curve of that turbine, which shows the power generated at each wind speed. Multiplying those two together gives us the total yearly power potential for that turbine.

For the sake of comparing HAWTs and VAWTs in this study, a typical modern HAWT is selected and a typical modern VAWT. Power is calculated from the wind data for both for comparison.

The turbines selected for study are:

- HAWT: the NORWIN 29-STALL-225

This is a 29m diameter, three bladed wind turbine rated at 225kW at a wind speed of 19m/s. It features stall speed regulation, meaning that when wind speeds exceeds the allowed limit, the blades aerodynamically stall to reduce the rotational speed without stopping all together, and this allows the wind turbine to operate at a wide range of wind speeds.

This turbine was chosen because it has been proven suitable for urban integration as has been implemented at the Bahrain World Trade Center. Three of such turbines were installed there with fixed yaw towards the optimum orientation.

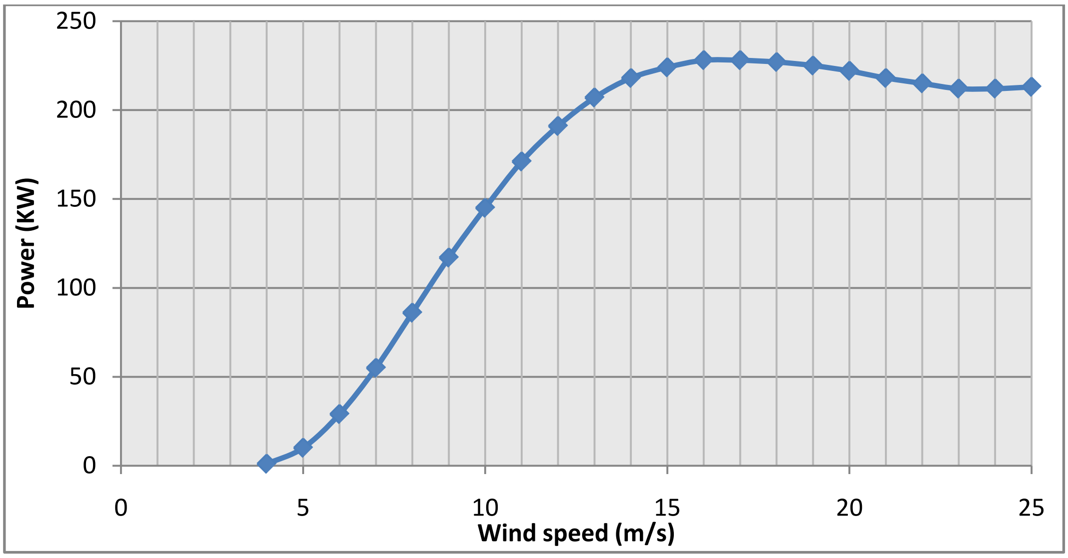

Figure 54 - Power curve for Norwin 29-stall-225 HAWT

- VAWT: the Ropatec Windrotor – Big Star Vertical

This is an H-type Vertical Axis wind turbine, with a diameter of 8.5m and a blade height of 4.3m. The Big star has five blades and is rated at 20KW at a wind speed of 14m/s. Like the previous turbine, this VAWT is stall speed regulated.

As the previous, this turbine was chosen to because of its potential for urban integration.

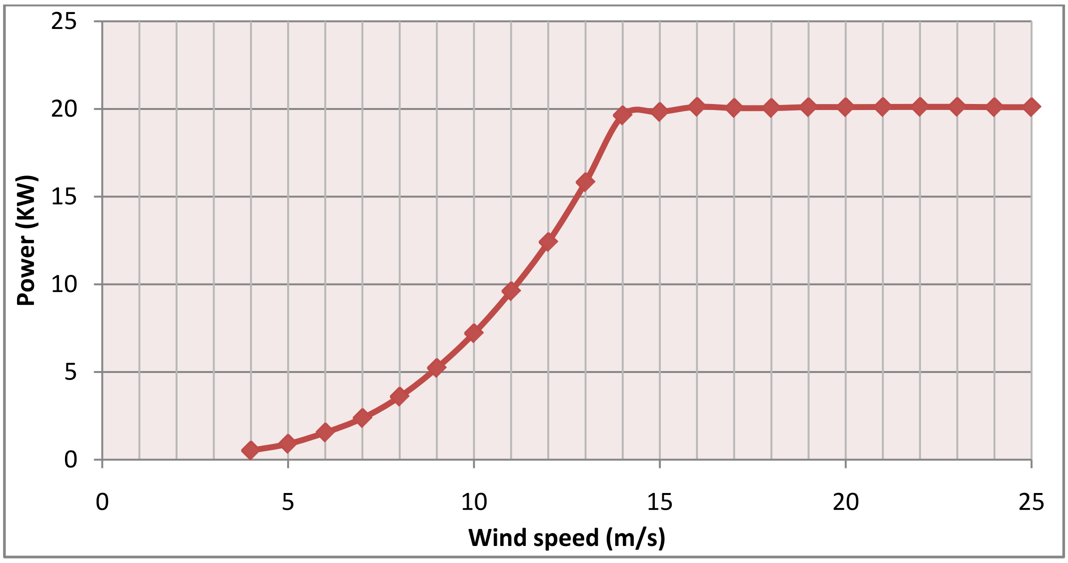

Figure 55 – Power Curve for Ropatec Windrotor – Big star Vertical

Figure 56 - Left: Ropatec - Big Star Vertical   Right: Norwin 29-S-225

Comparing these two turbine models would be very inaccurate, as they vary greatly in size (no medium or large scale VAWTs are currently manufactured) The chosen HAWT is around 29m in diameter which gives it a swept area of around 660m^2, while the H-type VAWT chosen has a dimensions of 8.5m x 4.3m, which gives it an effective swept area of about 36.5m^2. And since the power harnessed by a turbine is directly related to its swept area, this factor has to be equalized.

This can be done theoretically by multiplying the power output of the smaller turbine by the difference in area, however, this is not realistic, because the different engineering of the two turbines, requires different building integration approaches.

Figure 58, shows that the same area that accommodates one 29m HAWT, can possibly accommodate 12x 8.5m VAWTs. Multiplying the power output of the VAWT by this number gives us a more correct comparison. Adjusting the power curves is shown in Figure 59.

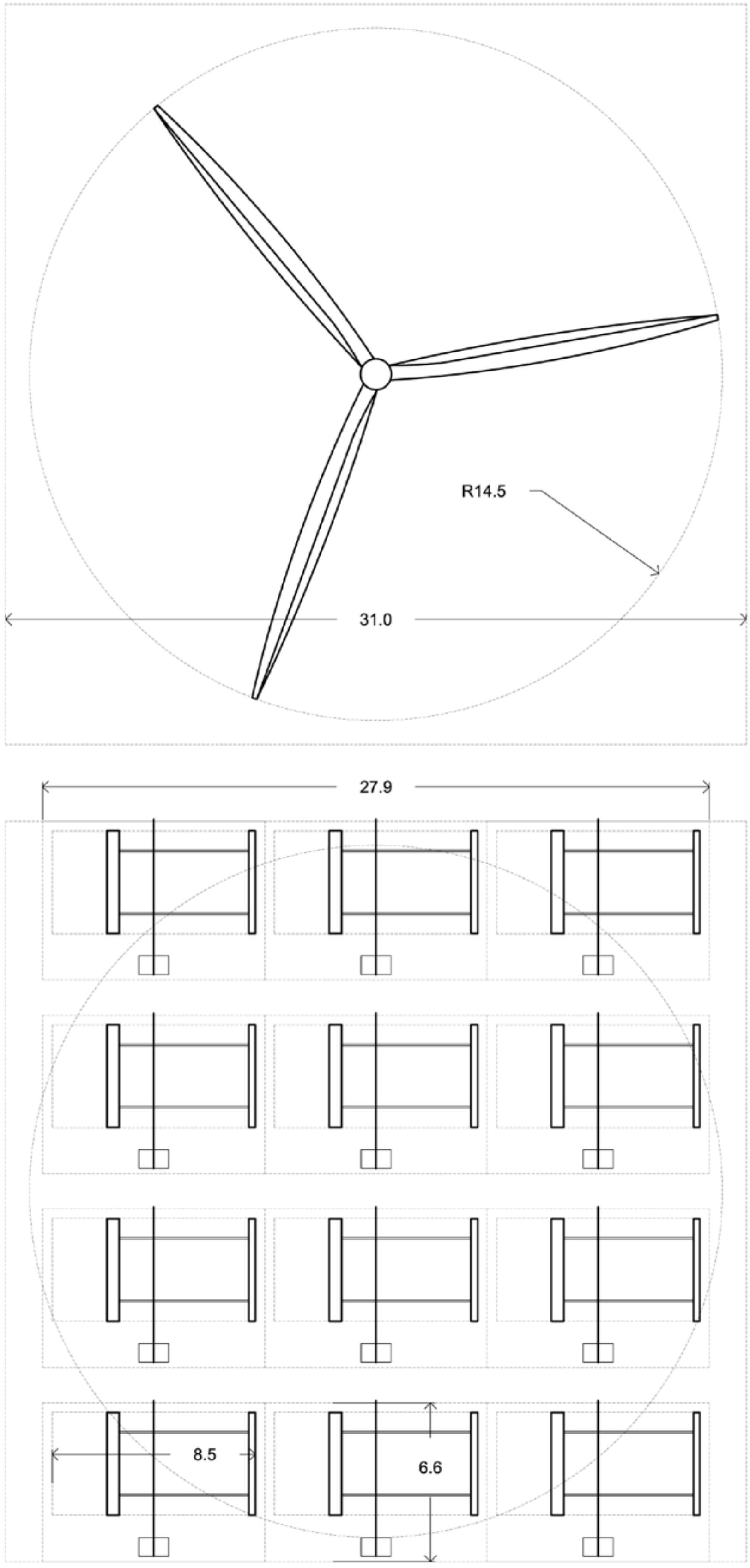

Figure 57 - Comparison between the size of a 29m HAWT and 8.5m VAWT

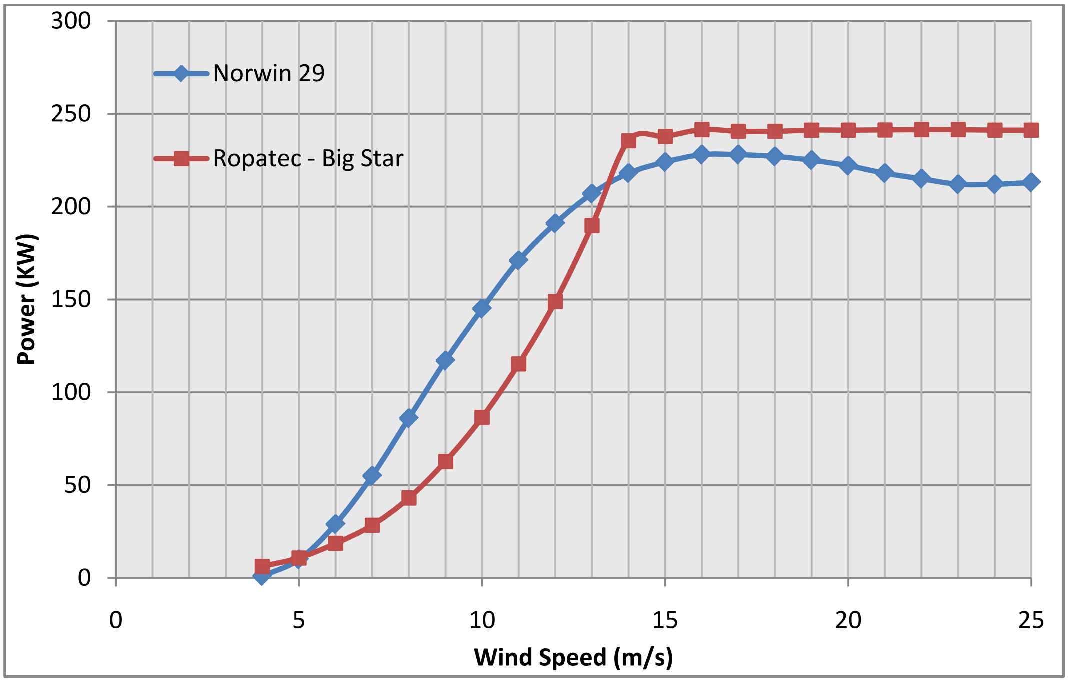

Figure 58 - Comparison between Power Curves of the VAWT and HAWT

5.2.6 POWER CALCULATION

By applying the power curves to the wind data:

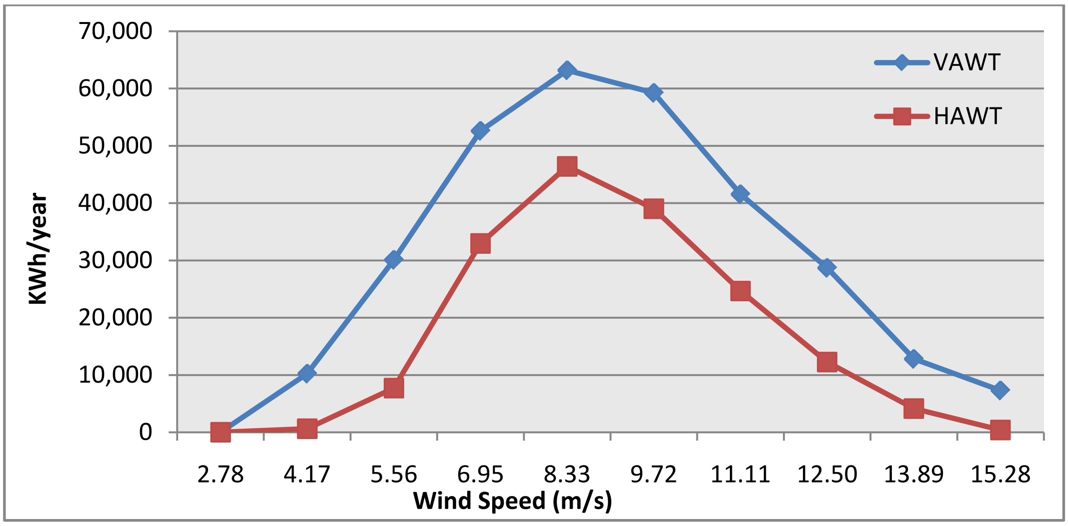

Figure 59 - HAWT vs VAWT power potential for Dubai Wind Data

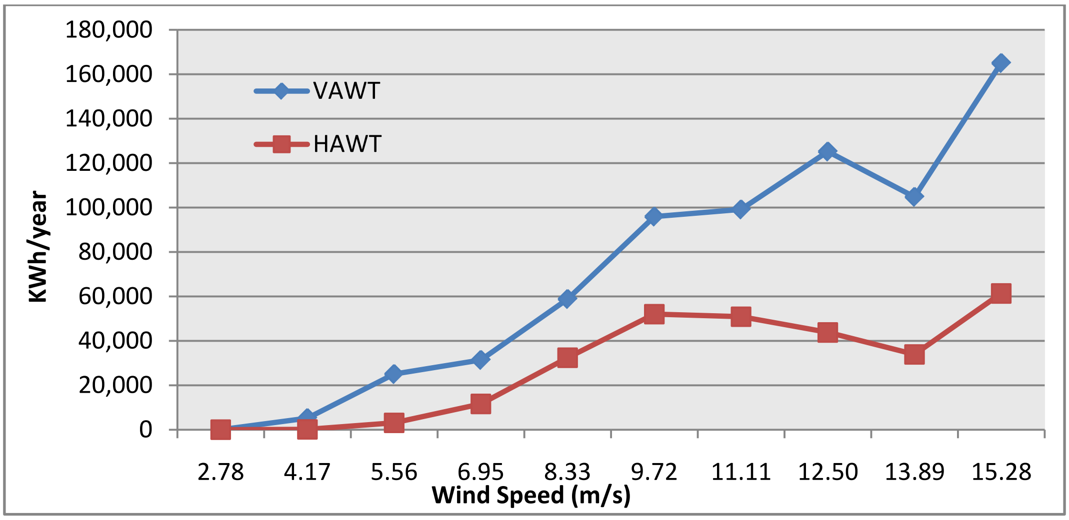

Figure 60 - HAWT vs VAWT power potential for Camborne Wind Data

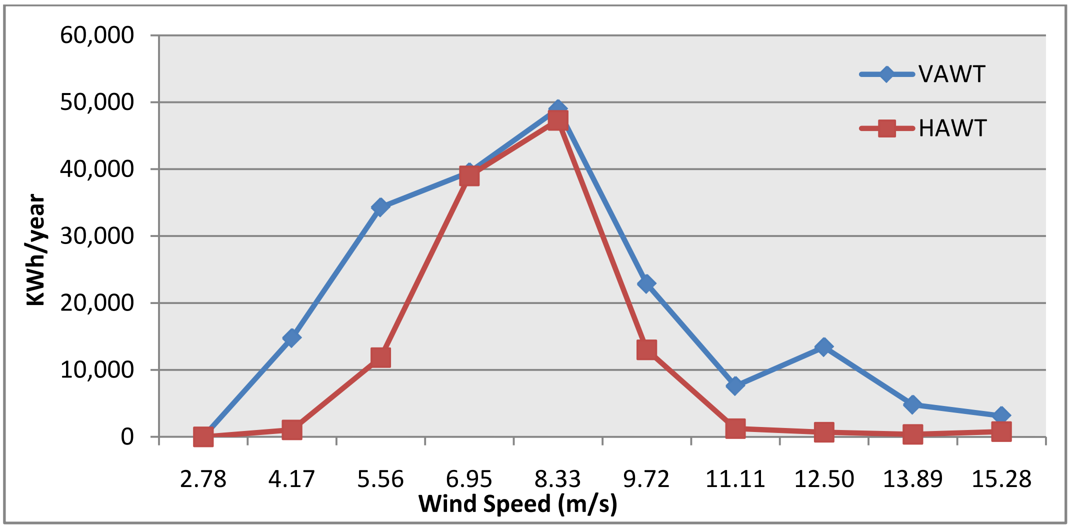

Figure 61 - HAWT vs VAWT power potential for Cairo Wind Data

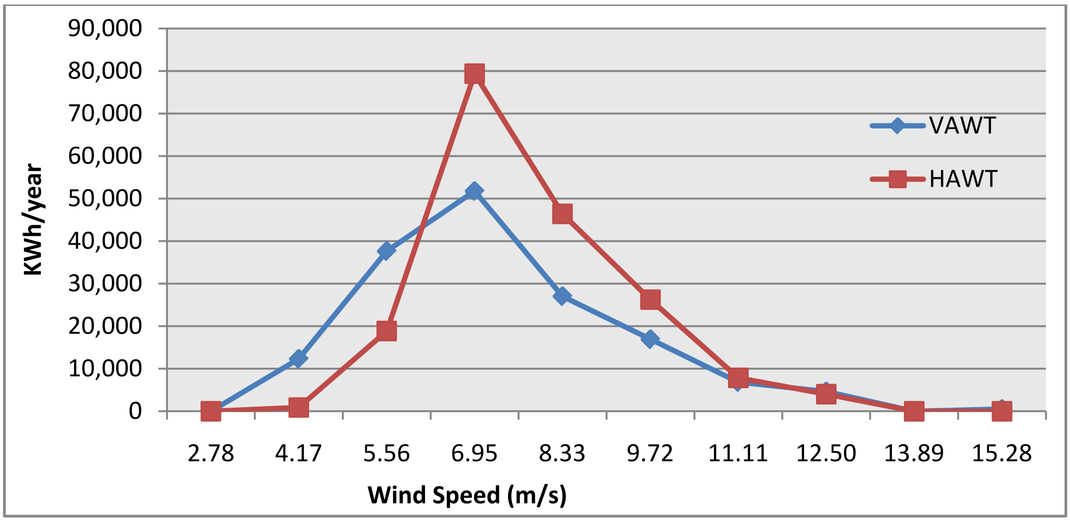

Figure 62 - HAWT vs VAWT power potential for Hong Kong Wind Data

Figure 60, 61, 62 and 63, show the potential power output from a HAWT oriented to the prevailing wind direction compared to that from a VAWT with omni-directional wind input.

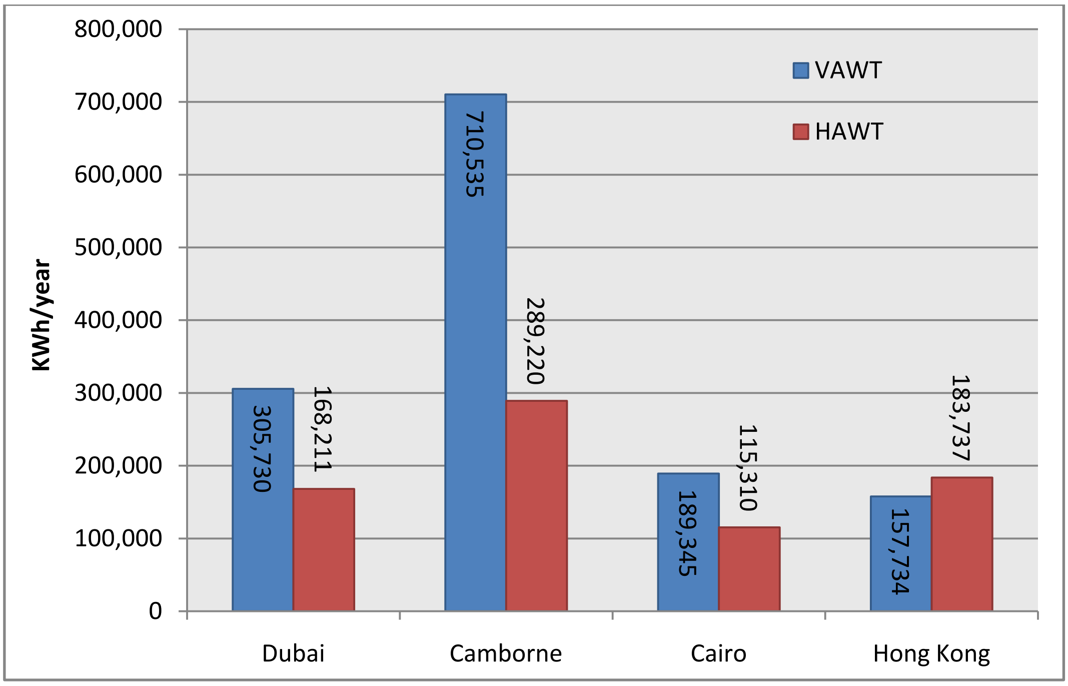

Figure 63 - Comparison between Total Power Outputs for each site

From the previous diagrams it's clear that VAWTs have an advantage in being able to capture energy from all directions, this is true in most cases except when the wind characteristics for a site are highly concentrated like the case for Hong Kong. In this situation the higher power conversion efficiency of HAWTs accounts for the lower wind frequency from one orientation.

5.2.7 APPLYING THE EFFECT OF HEIGHT

As explained earlier, wind speeds increases with height due to decreased friction with the ground. And because the power in the wind is proportional to the cube of the wind speed, any increase in wind speed because of height can yield a significant increase in wind power available for extraction.

And with the increase in the popularity of high rise buildings, in new construction especially in the Middle East and China, this represents a huge potential that needs attention. In the next part, the effect of height on wind power available is to be studied to evaluate the increase in power, in regards to the two turbine types.

To calculate the effect of the height on the wind speed at a certain location, it's essential to know the terrain roughness class for the site and the same for the wind data source. From these using the previously mentioned equation, the corrected wind speed at the required height can be calculated. (Page 65)

This calculation is to be applied to Dubai and Hong Kong's wind data to study the effect of height on the increase in wind speed frequency and hence on the wind power available from each turbine type.

Off course the effect of increase in wind speed is not the only factor affecting the power in this case. However, the power curve of the different turbine types as well as their different abilities to take wind from different directions is equally as important in determining the power output at these heights

DUBAI WIND DATA

The wind data for Dubai is gathered at the Airport weather station, and though the Dubai Airport lies within the city, it's vast open spaces typical for an airport moves the site to the roughness category: "2" for suburban zones compared to "1" assumed for a turbine integrated in a dense urban context.

Hence the wind data for Dubai needs to be optimized using the equation explained earlier. The effect of height on wind speed frequency is studied at reference heights: 50, 100, 200, 300, 400 and 500m above the ground. This accounts for turbines mounted on buildings at this height. Above 500m the increase in wind speed with height becomes minimal. Also with the exception of a number of super high towers like Burj Dubai, Most high rise buildings currently planned or under construction do not rise beyond 500m.

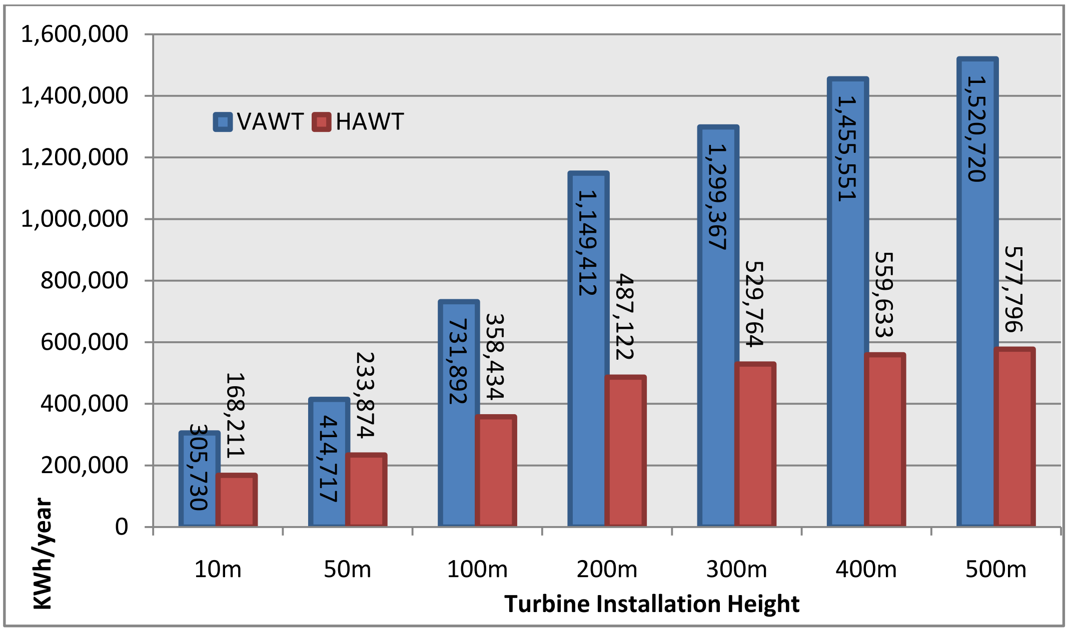

Figure 64 - Wind Power at different heights from HAWT and VAWT for Dubai

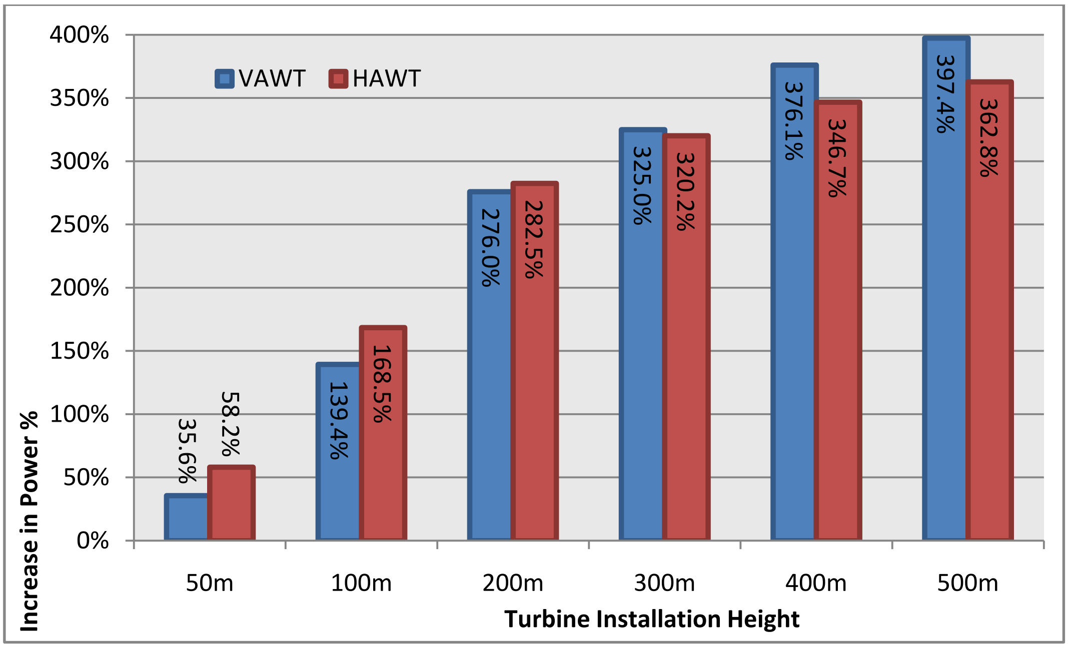

Figure 65 - Increase in power with height compared to wind power at 10m, for Dubai

As previously confirmed, wind power harnessed from all directions using a HAWT exceeds that available from a HAWT oriented to the prevailing wind. By increasing the installation height of the wind turbine, the air velocity increases, which in turn increases the power available in the wind. Applying the power coefficient of the two turbine types gives us a more realistic idea of the power generated, as follows:

At 50m above the ground the power available, increases by 35.6% for the VAWT, while a 58.2% increase is calculated for the HAWT.

At 100m, the power from the VAWT increases by 139.4%, compared to an increase of 168.5% for the HAWT.

At 200m, the power from the VAWT increases by 276.2%, compared to 282.5% for the HAWT.

At 300m, the power from the VAWT increases by 325%, compared to 320% for the HAWT.

At 400m, the power from the VAWT increases by 376.2%, compared to 346.7% for the HAWT.

At 500m, the power from the VAWT increases by 397.4%, compared to 362.8% for the HAWT.

Hence HAWTs benefit more from the increased installation height till about 200m when VAWTs start seeing more gains, however, in both cases, it's clear that the increase in wind speeds with height, wields considerable gains. To the extent that it might transform an unfeasible site in regards to average wind speeds into a highly productive one. In the case of Dubai, it has been shown that the same type of VAWT would generate more than 5 times the power at 500m above the ground from the same site.

HONG KONG WIND DATA

Hong Kong was chosen to study the effect of height because it represents a site with highly concentrated prevailing wind direction. And similar to Dubai, the wind data for Hong Kong, is collected from a weather station in a suburban area. This requires applying the wind height formula to calculate the wind speeds and frequency for different installation heights. Again the study was done for the installation heights: 50, 100, 200, 300, 400 and 500m above the ground.

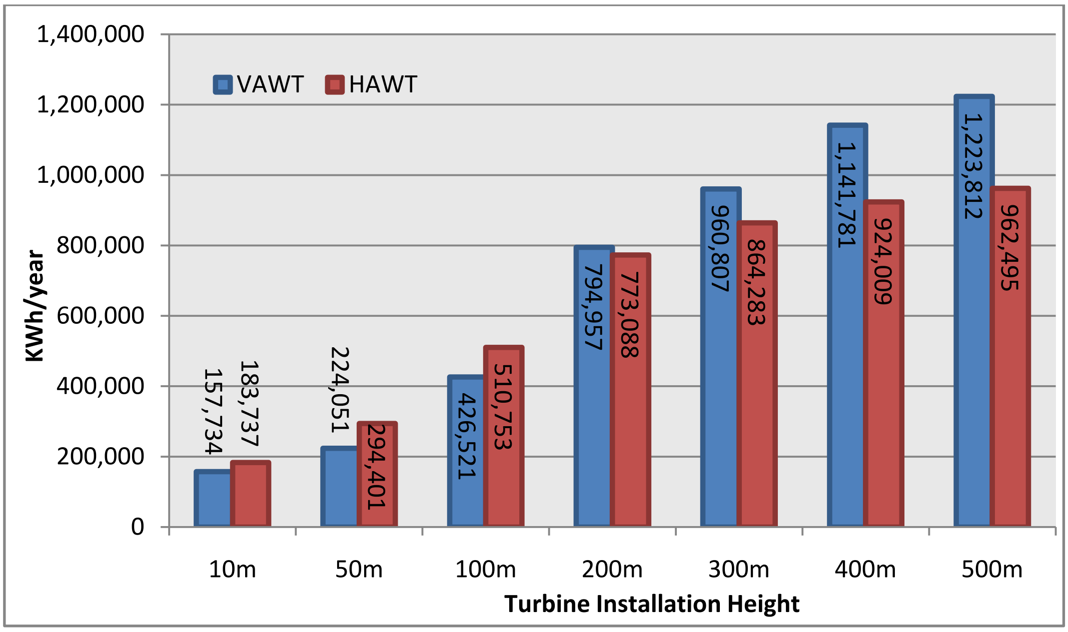

Figure 66 - Wind Power at different heights from HAWT and VAWT for Hong Kong

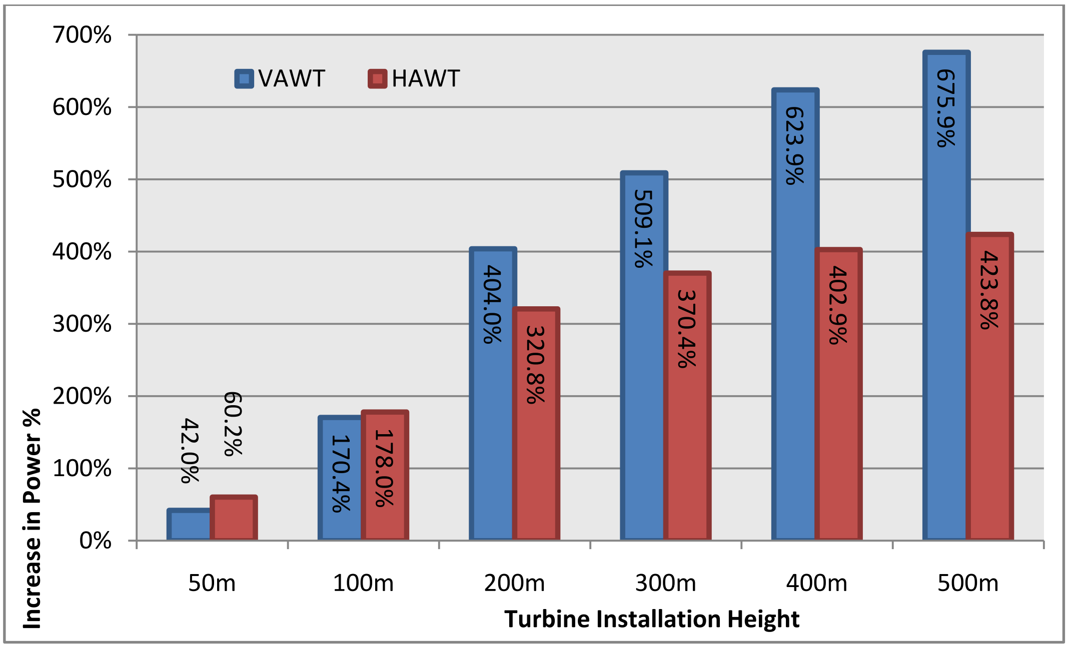

Figure 67 - Increase in power with height compared to wind power at 10m, for Hong Kong

For the Hong Kong site, the results were as follows:

At 50m above the ground the power available, increases by 42.0% for the VAWT, while a 60.2% increase is calculated for the HAWT.

At 100m, the power from the VAWT increases by 170.4%, compared to an increase of 178.0% for the HAWT.

At 200m, the power from the VAWT increases by 404%, compared to 320.8% for the HAWT.

At 300m, the power from the VAWT increases by 509.1%, compared to 370.4% for the HAWT.

At 400m, the power from the VAWT increases by 623.9%, compared to 402.9% for the HAWT.

At 500m, the power from the VAWT increases by 675.9%, compared to 423.8% for the HAWT.

Due to the high concentration of the wind direction in Hong Kong, HAWT yields more power till an installation height of 200m afterwards the VAWT benefits from a higher efficiency at higher speeds, as well as a higher cut-out speed.

6.1 INTRODUCTION

As observed in the previous chapters, there is great potential in harnessing wind power in the urban environment especially through integrating wind turbines into high rise buildings, where the turbine can have an increase yield due to the higher wind velocities and effect of building wind concentration.

The mathematical studies have also revealed the better suitability of VAWT for such integration. In this chapter, CFD is used to simulate a number of scenarios of such turbine integration, in order to study the potential of energy gains through building integration as well as the best morphology.

6.2 COMPUTATIONAL FLUID DYNAMICS SIMULATION

6.2.1 INTRODUCTION

CFD or Computational Fluid Dynamics is a method for solving problems involving the flow of fluids using numerical methods. Usually this is done using computers. The use of CFD was very limited because of the fact that it was very demanding in computational power and time, only super computers had the power to run such simulations and achieve acceptable results. However with the rapid increase in computer power, the ability to run CFD packages on personal computers is now available and a number of commercial packages are offered to fill this role. *(Abe, K., Ohya, Y., 2003), (Aguilo, A., et al, 200-), (Lu, L., Ip, K. Y., 2007), (Chen, Q., 2003)*

6.2.2 PHOENICS

For the sake of this study, the CFD package used was PHOENICS 2008, provided by CHAM Ltd. Phoenics is a general purpose CFD package, that was offered for sale since 1981, hence is one of the oldest commercial CFD packages.

This CFD package was provided by the BUiD computer lab in the form of educational versions.

6.2.3 PROPOSED SCENARIOS

From the findings in the previous chapters, VAWTs offered a promising potential in wind power harnessing in urban environments. This was also proved to be more valid in the case of high rise buildings which experience a higher wind speed at height.

In this study, a number of models where created, representing different options for integration of a VAWT on high rise building. To limit the parameters involved, the scenario was set-up for a 200m high tower, with a cylindrical plan cross-section. The wind turbine was assumed to be installed on the roof of the tower. Several options for the tower ending were explored to find out the optimum integration geometry for such a turbine.

6.2.4 SIMULATION SETUP

For the sake of this study, a CFD model was developed using the software's Data-enter module: "SATELLITE", this was done through the VR-Editor interface. The problem was then run through the equation solving module: "EARTH". And later results where visualized and analyzed using the "Viewer" and "PHOTON" modules.

6.2.5 DOMAIN SETUP

The Domain setup for this exercise was as follows:

A rectangular domain of the Dimensions: 2000m in length “X”, 2000m width “Y” and a height of 1000m “Z”.

A building model of the dimensions: 40mx40mx200m was used as the blockage. With the standard wall material. This blockage was placed at the following coordinates relative to the Domain: x:400, y:400 and z:0. This allows enough spacing between the building and the Domain, assuming that air is entering the domain from the left (x=0).

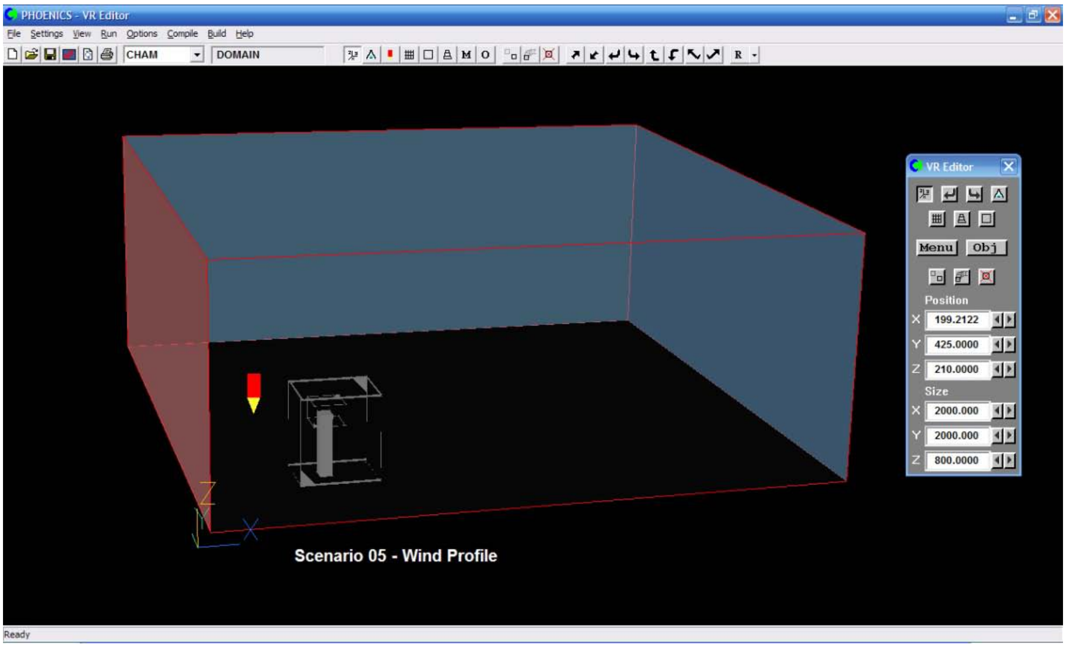

Figure 68 - Phoenics-VR Editor interface showing the simulation Domain

The grids where setup as follows: 52 grids in the X axis, 46 grids in the Y axis and 33 in the Z.

An air inlet was placed at the left face of the domain at 0,0. This inlet was a “Wind-Profile” Inlet that simulates boundary conditions. The parameters for the inlet were as follows:

- Wind velocity: 4.5m/s at a reference height of 8m. moving in the “x” direction
- The effective roughness height: 1m, representing a dense urban terrain roughness.

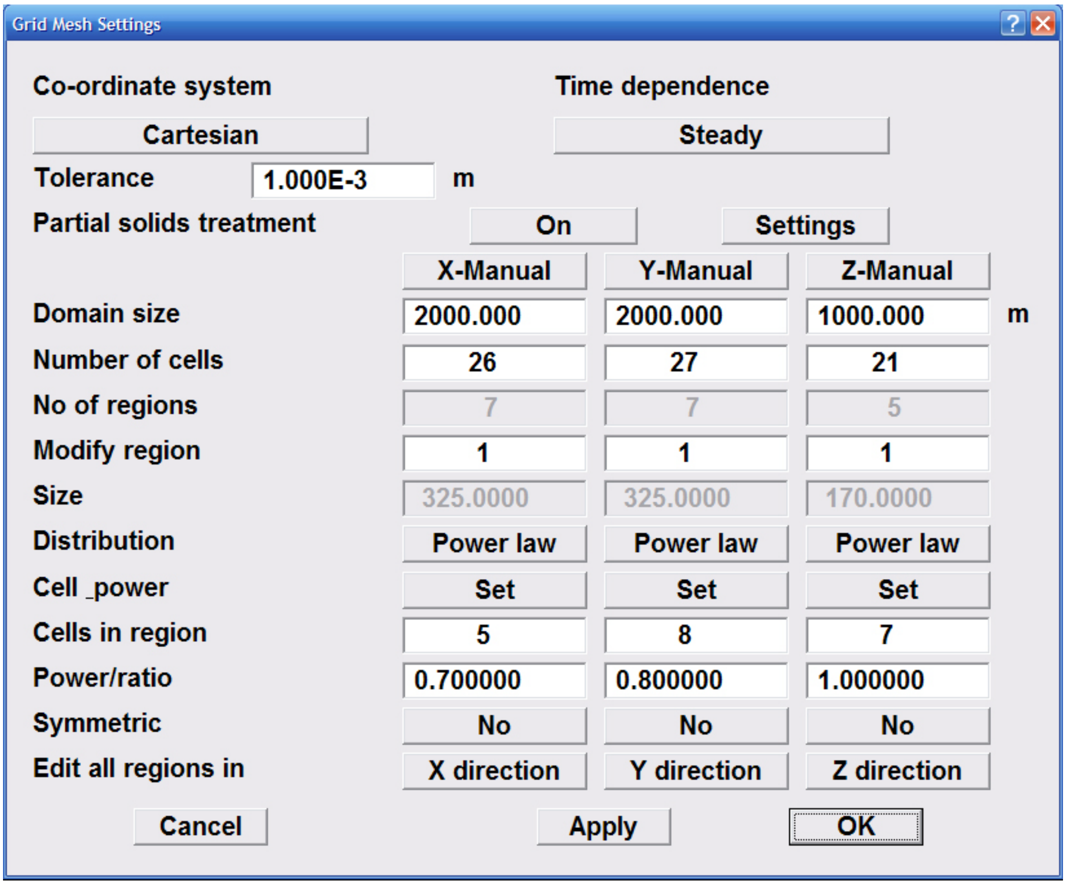

Figure 69 - Settings for the used Domain

Four Outlets where used as follows: 3 outlet along the other 3 faces of the domain, and one horizontally at the top of the Domain representing the sky outlet. All are constant pressure outlets, however the sky outlet was given an external conditions depicting wind speed at this height and kinetic energy.

A ground plane was used with a roughness factor: 1m, similar to that in the Wind-profile inlet. A “fully rough” wall function law was used.

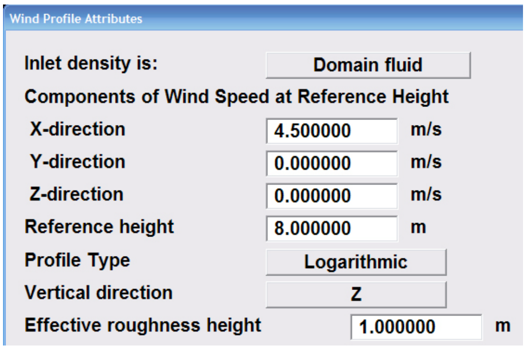

Figure 70 - Wind-profile inlet settings

A first run was done to evaluate the Domain, with 10,000 Iterations. After this first, the domain was confirmed to run correctly as expected and the wind speed profile was accurate. However it was observed that the grid sizes used where to big to show detailed air movement around the building geometry. But increasing the grid numbers further would increase the running time beyond the available to run a number of scenarios and options within this research.

Hence a solution was implemented, which involved adding "Grid-Multiplier volumes" to the domain. These are objects in Phoenics that have no effect on the domain except multiplying the number of grids within their volume. Two of these objects were used as follows:

- A primary grid multiplier was used around the building's geometry, with the following dimensions: x:250, y:200, z:280.
- A secondary grid multiplier object was inserted inside the first one around the building's roof area, where the turbine was to be installed. The secondary grid multiplier had the following dimensions: x:100, y:100 and z:70.

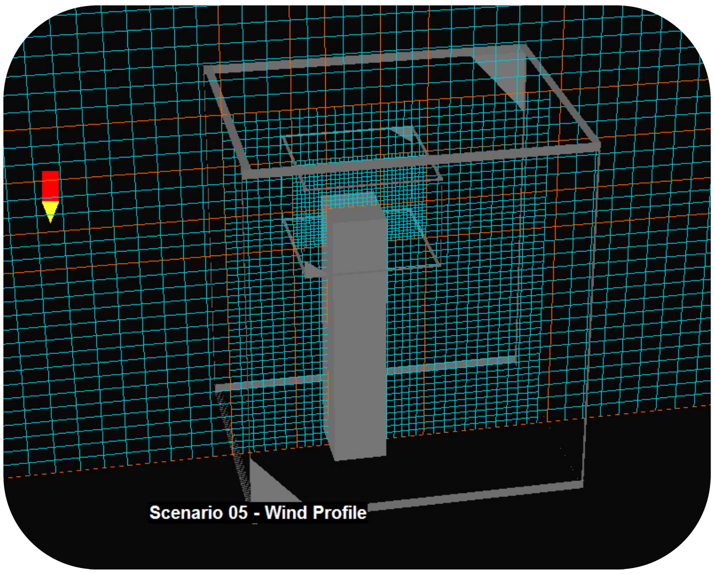

Figure 71 - Grid multipliers

6.2.6 RUNNING THE SIMULATION

With the previously mentioned parameters and settings, the main exercise was run on the solver with 10,000 iterations. This time the results of the previous first run was used to initialize the domain.

The following scenarios were run:

1. A 200m tall building with a flat roof.
2. The same building with a cone shaped roof.
3. Same building with a hemisphere roof.
4. Same building with a cone shaped roof and an inverted cone diffuser to concentrate the air flow.
5. Same building with a hemisphere roof and an inverted hemisphere diffuser to concentrate air flow.

6.2.7 SIMULATION RESULTS

The main aim of this CFD exercise was to explore some options for the integration of VAWTs on a high-rise building. The results required were: flow patterns around different tower ending options and the mass flow rate of air within those to estimate the enhancement of the power harnessing potential.

The results were as follows:

Accelerated wind speeds are experienced for all options. However, with a more streamlined transition between the roof and the windward façade, the air movement is less turbulent and the speed gradient is milder.

Adding a diffuser further accelerates the air movement approaching the turbine, again with the hemispherical roof and diffuser yielding the best results.

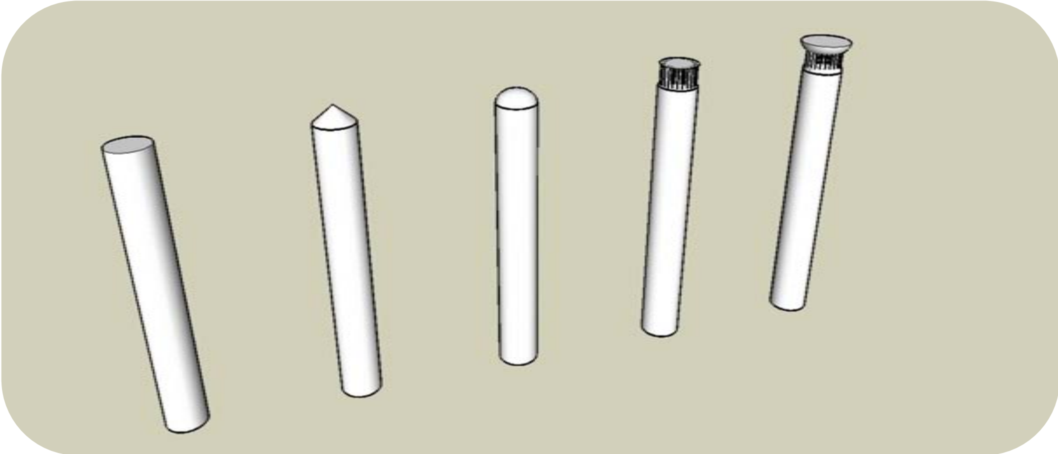

Figure 72 - Tower end options simulated in CFD

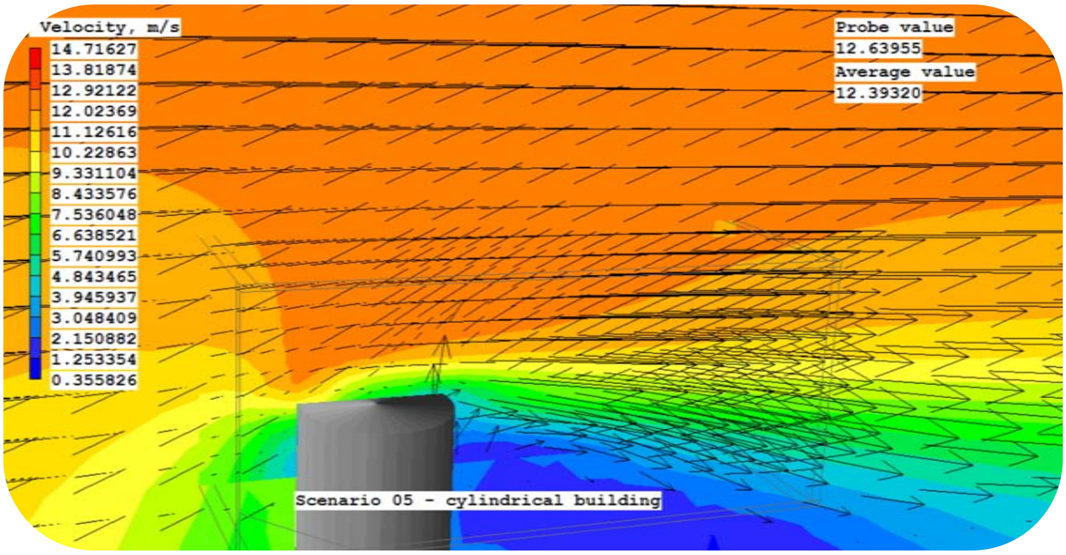

Figure 73 - Cylindrical Building

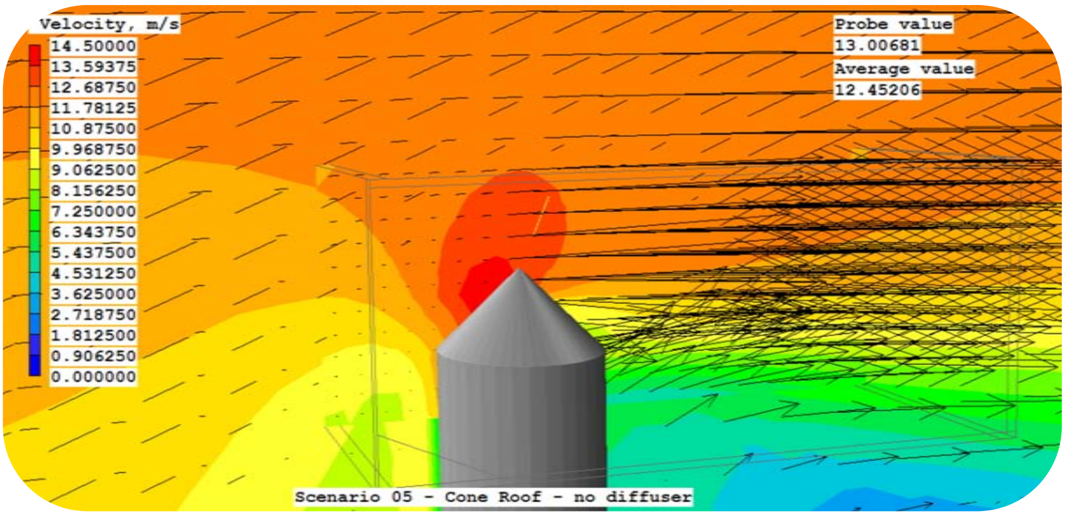

Figure 74 - Cone Roof

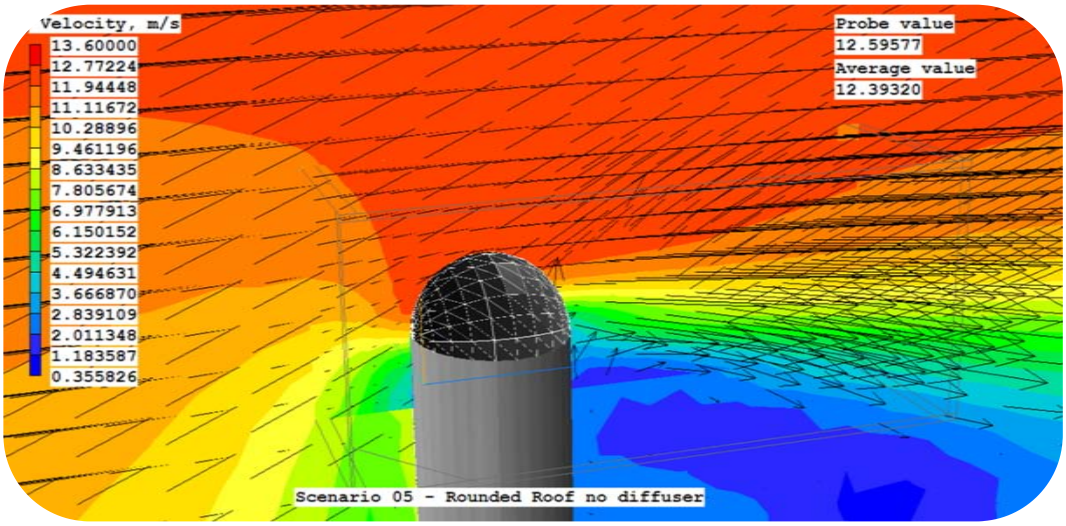

Figure 75 - Hemisphere roof

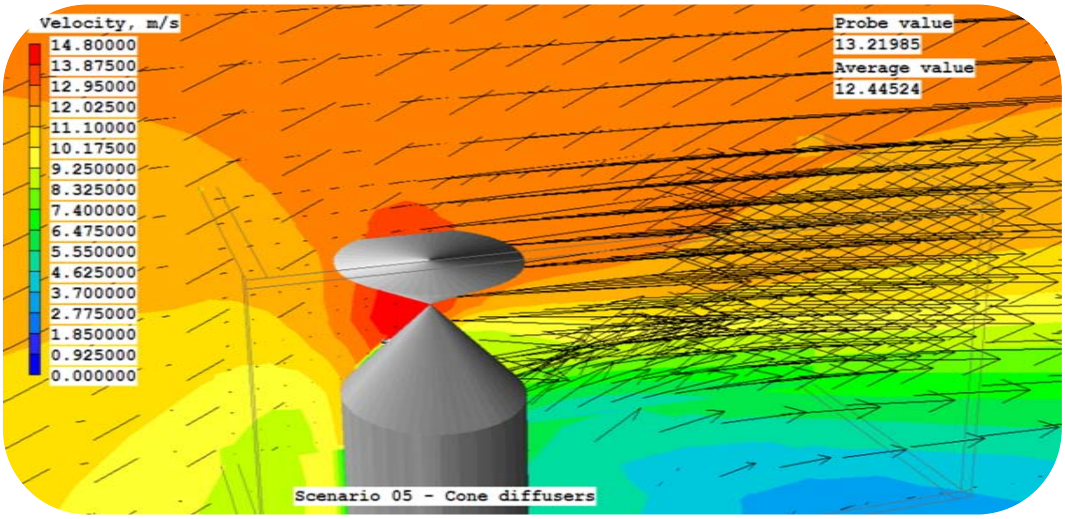

Figure 76 - Cone roof and diffuser

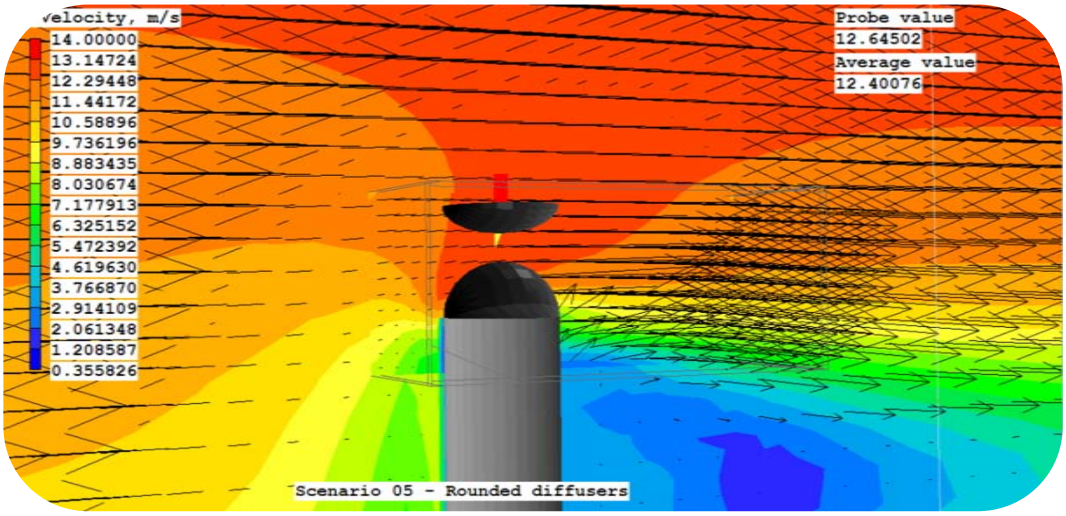

Figure 77 - Spherical diffuser

The calculated mass flow rate for each scenario was as follows:

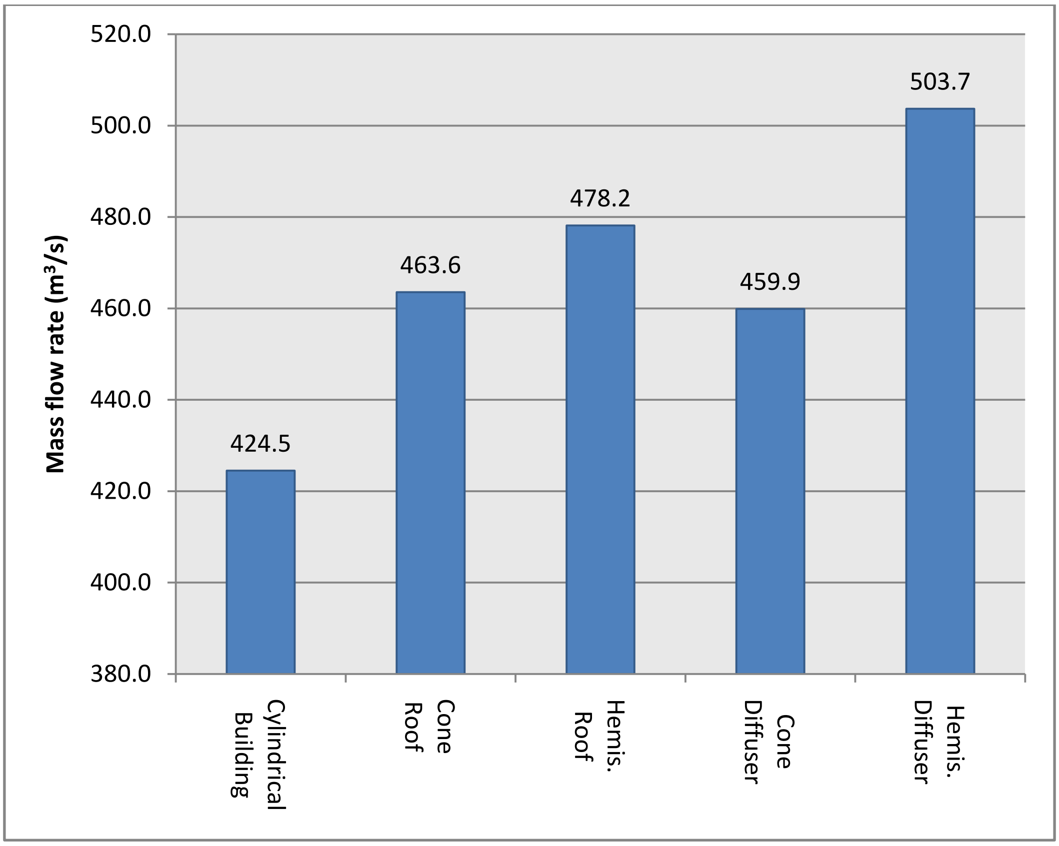

Figure 78 - Estimated mass flow rate for each option

All the results show the benefits of aerodynamically shaping the top of the tower in increasing the speed of air flow and decreasing the turbulence.

However, the hemispherical top shows the best results especially with the addition of a hemispherical diffuser to further concentrate and streamline the air flow.

The simulation also shows that these methode can accelerate the air flow along the top of the building by up to 1.4 times the ambient. And at a height of 200m, the air velocity approaching the turbine can be 3.2 times the wind speed at 10m height.

CHAPTER 7 RESULTS AND DISCUSSION

7.1 INTRODUCTION

Two series of studies were conducted in this thesis; the first was a mathematical study of the wind power potential for a number of sites and the different characteristics of turbine types in these sites. The aim of this first part is to compare the power extraction potential of a VAWT installed on a building, compared to a similarly sized HAWT fixed to face the optimum wind direction.

The second study was done using CFD simulation to test a number of wind turbine integration scenarios in order to assess the best incorporation techniques.

In this chapter the results of these studies are explored.

7.2 RESULTS OF MATHEMATICAL STUDIES

In this study four distinct sites where selected for their wind data: Camborne, Dubai, Cairo and Hong Kong. These sites ranged from broadly distributed wind directionality in the case of Camborne to a highly concentrated prevailing wind in the case of Hong Kong.

Wind data for each which was in the form of wind roses displaying wind direction, speed and frequency was converted into Excel tables for analysis. This is represented in tables: 3, 4, 5 and 6

7.2.1 STUDY OF THE POTENTIAL POWER IN THE WIND

The basic power equation $\boldsymbol{\rho} = \boldsymbol{V}^3$ was applied to these wind data, to assess the power in the wind for each wind frequency and direction. This is represented in tables: 7, 8, 9 and 10. From those tables the following was observed:

- The highest wind power in most cases is achieved from the prevailing wind direction; this is most clear in the case of Hong Kong, Camborne and Cairo.
- In the case of Dubai however, the highest cumulative wind power is achieved from an angle 12.5^{o} from the prevailing. This is because although this orientation does not have the highest wind frequency, however wind blowing from this direction usually has higher wind speeds.
- Also in the case of Cairo, though the prevailing wind direction offers the highest wind power potential, however a secondary wind orientation is also very promising at an angle of 202^{o}. This orientation probably due to seasonal spring storms has very high wind speeds for a small period of time.
- Because of the highly concentrated wind direction in Hong Kong, the power available in the wind from the prevailing, is more than 3 times that available from all other directions.

7.2.2 STUDY OF WIND FREQUENCY

As previously explained, two accurately estimate the power generated by a turbine at a specific location, two inputs are required: the wind speed frequency for the site and the turbines power curve.

The first of these requirements was obtained from converting the data available into wind speed frequency meaning the number of hours per year that a specific wind speed from a specific orientation occurs. This was achieved for the four sites in Figures: 50 and 52.

These diagrams showed the following:

- For all sites, wind speed in the range of 5.6m/s has the highest frequency.

- Most sites have a similar wind frequency curve, with a range of higher and lower levels.
- However, Camborne experiences an increased frequency in the wind speeds above 8.3m/s. This can explain the higher wind power potential for Camborne.

As explained earlier, it was an aim for this research to compare the power potential from all wind directions versus that from the prevailing wind direction only. Hence another series of graphs was plotted for the wind frequency distributions for each site limited to the prevailing wind direction established earlier. This was shown in figures: 51, 53. The following was observed:

- Because of the highly concentrated characteristics of wind in Hong Kong, the restriction of the wind from the prevailing direction increased the frequency of the wind within the 5.6m/s range to approximately 20% of the total.
- For Camborne, the frequency after restricting the wind direction to the prevailing increased in the wind speeds above 8.3m/s range.

7.2.3 STUDY OF POWER FROM ALL ORIENTATIONS VERSUS PREVAILING

The next step was to compare the total power in the wind available from all orientations versus that from the prevailing. To do this, cumulative values for the power available in the wind for each site was plotted in Figure 54. The following was observed:

- Off course the power available from all orientations exceeds that from the prevailing in all sites however in different ratios as follows:
- For Camborne the factor is more than 3 times the power from the prevailing only. This is obviously due to the highly dispersed wind approach angles.

- A similar situation in Dubai with power available from all directions more than 3 times that from the prevailing.
- For Cairo the ratio becomes less than 2.5 times.
- However, in Hong Kong the difference becomes relatively small with the wind power from all orientations only 30% more than that available from the prevailing.

This study though gives an idea about the power available in the wind, does not tell the whole story. This is mainly because the power extracted from the wind is greatly affected by the wind turbines power curve, or its energy conversion efficiency for different wind speeds.

7.2.4 STUDY OF THE POWER CURVES FOR HAWTS AND VAWTS

Two wind turbine models were selected from each type, suitable for building integration. Namely the NORWIN 29-STALL-225 and the ROPATEC WindStar. The power curve for the HAWT is plotted in figure 55 and for the VAWT in figure 56.

However because of the big difference in size between the two models (HAWT of 29m diameter, while VAWT 8.5m Diameter) It was thought necessary to neutralize this factor by finding out the number of VAWTs that can account for the same swept area of the much larger HAWT. This was done in figure 58. It was found out that about 12 VAWTs can comprehend for that area. This also agrees with the calculated difference between the VAWT swept area and that of the H-type VAWT used.

Hence this factor was accounted for in the VAWT's power curve and the new power curve plotted against that of the HAWT on figure: 59. From this figure the following was observed:

- Both turbine models have similar starting characteristics with a cut-in wind speed of 4m/s.

- The HAWT has a higher conversion efficiency for wind speeds between 5 and 14m/s.
- However the two turbines being stall speed regulated, at 16m/s the HAWT begins to stall and its efficiency drops slightly and then stabilizes. Similarly the VAWT starts stalling at a wind speed of 14m/s, after which the power conversion efficiency is constant.
- Never the less, from 14m/s wind speed and higher, the VAWT has better efficiency.

7.2.5 APPLYING THE TURBINES' POWER CURVES

The power curves of the two types of wind turbines, was then applied to their respective wind frequencies (Total wind frequency for the VAWT and prevailing wind frequency for HAWT). This was done for each of the four sites, and results are shown in Figures: 60, 61, 62 and 63. From these the following was observed:

- For Dubai the power generated by the VAWT exceeds that from the HAWT at all wind speeds.
- The same applies to Camborne with an even bigger margin at higher wind speeds starting from 8.3m/s.
- Again in Cairo the same applies, however in the mid-range wind speeds, the performance of the HAWT is very comparable.
- However in Hong Kong, it's a different story, the highly concentrated prevailing wind with higher mid-range wind speeds, means that the HAWT is outperforming the VAWT.

The cumulative values for the power estimated by each turbine in each of the four sites is listed in figure 64. This shows the following:

- Power generated from the VAWT in Dubai is about 1.8 times that generated from the HAWT.

- Camborne shows the highest potential wind energy generated from the VAWT, more than 700MWh/year. This is more than 2.5 times that expected from a HAWT for the same location.
- In Cairo the VAWT still exceeded the power generated from the HAWT by a margin of 1.65 times the power generated.
- However, in the case of Hong Kong, the power generated from the HAWT exceeds that expected from the VAWT by around 16%.

7.2.6 STUDY OF THE EFFECT OF INSTALLATION HEIGHT ON POWER GENERATION

In the previous exercises we have estimated the power estimated by the two types of wind turbines for the different sites, however this was done using the wind data measured at the weather station which is in all cases is collected from anemometers located at a reference height of about 10m above the ground level.

However as explained earlier, the increasing popularity of high rise buildings in recent years in the Middle East and China, represents a potential of mounting the wind turbines at higher installation heights, hence benefiting from the increase in wind speed.

In this study the wind data for Dubai and Hong Kong has been corrected using the wind at height equation to predict the potential power in the wind at installation heights of: 50, 100, 200, 300, 400 and 500m above the ground. These corrected wind power data was then applied to the turbine power curves to calculate the power generated from each turbine in each case.

For Dubai the results were plotted in figures: 65 and 66. From these diagrams, the following was observed:

- At a height of 50m above the ground, the estimated power generated from the VAWT has increased by around 35% for the VAWT and around 58% for the HAWT. However the total generated from the VAWT was still higher at about 414 MWh/y.

- At 100m there was an increase of about 140% for the VAWT and around 170% for the HAWT. The VAWT still exceeded in the total of about 730 MWh/y.
- At 200m there is an increase of about 276% for the VAWT and 282% for the HAWT. However for the total power expected the VAWT still exceeded at around 1,149 MWh/y.
- At 300m the power from the VAWT increased by 325% while the VAWT was 320%. Power from the VAWT was around 1,300 MWh/y.
- At 400m the increase in power was around 376% for the VAWT and 346% for the HAWT. The total power from the VAWT was around 1,455MWh/y.
- At 500m the increase was around approx. 400% for the VAWT, and 362% for the HAWT. Total power output was 1,520MWh/y for the VAWT.

The same exercise was conducted for Hong Kong with the results plotted in figures: 67 and 68. From these diagrams, the following was observed:

- At a height of 50m above the ground, the estimated power generated from the VAWT has increased by around 42% for the VAWT and around 60% for the HAWT. However the total generated from the HAWT was still higher at about 295 MWh/y.
- At 100m there was an increase of about 170% for the VAWT and around 180% for the HAWT. The HAWT still exceeded in the total of about 510 MWh/y.
- At 200m there is an increase of about 404% for the VAWT and 320% for the HAWT. This significant increase in the potential power

harnessed by the VAWT gives it the lead total power expected at around 795 MWh/y.

- At 300m the power from the VAWT increased by 510% while the HAWT was 370%. Power from the VAWT was around 960 MWh/y.
- At 400m the increase in power was around 624% for the VAWT and 400% for the HAWT. The total power from the VAWT was around 1,140 MWh/y.
- At 500m the increase was around approx. 675% for the VAWT, and 423% for the HAWT. Total power output was 1,224MWh/y for the VAWT.

7.3 RESULTS OF THE CFD SIMULATIONS

- The results of the CFD simulations undertaken revealed that there is potential in harnessing wind through the integration of VAWT on the roof of high rise buildings.
- This potential is further enhanced by shaping the roof of the building aerodynamically to accelerate the air flow and illuminate the air flow at an angle due to the upstream along the windward façade.
- Air moving along the roof with aerodynamic enhancement was found to be accelerated up to approx. 1.4 times the ambient air speed at that height.

CHAPTER 8 CONCLUSIONS

8.1 DISSERTATION OVERVIEW & CONCLUSIONS

- The literature review undertaken showed an increased interest in wind turbines as a means for harnessing wind energy. This is also true to the integration of wind turbines in the urban environment.
- Integration of wind turbines in the urban environment is a complicated exercise compared to stand-alone wind turbines in wind farm application. However, the potential benefits of renewable energy harnessing at the consumption location is well recognized.
- Though HAWTs are the dominant type of wind turbines currently used, however VAWTs seem to be the better candidate for integration in the urban environment. This is due to many beneficial characteristics including;
    - Ability to harness highly turbulent wind, with high frequency of variation in direction, which is typical in urban environments.
    - Relatively lower cut-in speeds (for some types) as well as high power conversion efficiency at higher speeds and higher cut-off speeds.
    - Simpler integration measures and easier maintenance.
    - Lower sound pollution.
- Another important potential in urban wind energy integration is the popularity of high rise buildings. These if correctly detailed to accommodate wind turbines can offer an increase power yield due to the accelerated air movement at their height.
- Aerodynamically shaping the building roof, can aid in concentrating the air movement and reduce the turbulence.

- Special wind turbines should be designed (tailored) for urban integration. These should be able to withstand high turbulence levels and wind angles and speeds beyond the normal operation.

8.2 RECOMMENDATIONS

VAWT are recommended for urban integration for the following reasons:

- VAWTs are omni-directional with regards to wind flow, hence have a higher yearly power output.
- VAWTs are more acceptable to turbulent flow.
- Less noisy in operation.
- A wider operating range of wind speeds means that turbines will generate power for longer periods of the year.

8.3 LIMITATIONS

This study did not take into consideration the following factors with regards to Building integrated wind turbines:

- The economics of the turbine installation investment and the payback time.
- The effects of scaling up VAWTs.
- CO_2 offsetting with building integrated wind turbines.
- Safety issues related to different types of turbine integration, and insurance procedures.

8.4 SUGGESTIONS FOR FUTURE WORK

This study was an attempt to answer some of the questions related to wind turbine integration in buildings, however this topic is relatively new and there is a wide range of topics that still need to be explored. These include:

- Life testing and comparing of the performance of VAWTs versus HAWTs in an urban setting.
- The possibility for scaling up VAWTs with the intent of mounting them on high-rise towers.
- Enhancing the starting characteristics of lift-type VAWTs.
- Enhancing of VAWTs' performance through wind concentration.
- Assessment of the generated noise from VAWTs and HAWTs in the urban environment.
- Comparison between the structural implications of the integration of large scale wind turbines on high-rise buildings.
- Investigations into the safety aspects of large scale VAWTs.
- Optimizing CFD models to more correctly simulate the wind flow and urban generation in the urban environment.

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APPENDICES

Study of Normal Componant from Wind Rose

Wind Rose: **Dubai, UAE**

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s)	2.78	0.90	0.50	0.30	0.40	0.30	0.20	0.10	0.10	0.20	0.10	0.20	0.20	0.60	1.10	1.00	0.90
	4.17	1.80	1.30	0.80	0.90	0.80	0.70	0.50	0.50	0.50	0.40	0.80	0.60	1.50	2.40	2.90	2.30
	5.56	2.20	1.70	1.40	1.10	1.20	1.10	0.90	0.70	0.60	0.50	0.80	1.40	1.50	2.80	2.90	2.90
	6.95	2.10	1.50	1.40	1.30	1.20	1.00	0.70	0.50	0.40	0.50	0.90	1.00	1.50	2.30	2.40	2.60
	8.33	1.60	1.30	0.90	0.80	0.60	0.50	0.40	0.30	0.40	0.30	0.40	0.60	0.90	1.70	1.80	1.90
	9.72	1.00	0.70	0.50	0.40	0.40	0.40	0.10	0.20	0.20	0.10	0.30	0.30	0.50	1.00	1.10	1.20
	11.11	0.50	0.40	0.20	0.20	0.20	0.10	0.10	0.10	0.02	0.02	0.10	0.20	0.30	0.40	0.50	0.60
	12.50	0.30	0.10	0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.20	0.20	0.20
	13.89	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.10	0.02	0.10
	15.28	0.02	0.02	0.02	0.02	0.00	0.02	0.00	0.02	0.02	0.02	0.00	0.00	0.02	0.10	0.00	0.00
	16.67																
	18.06																
Total %		10.52	7.54	5.64	5.24	4.82	4.06	2.84	2.46	2.38	1.98	3.54	4.34	7.02	12.10	12.82	12.70

Total Percentages 100.00 %

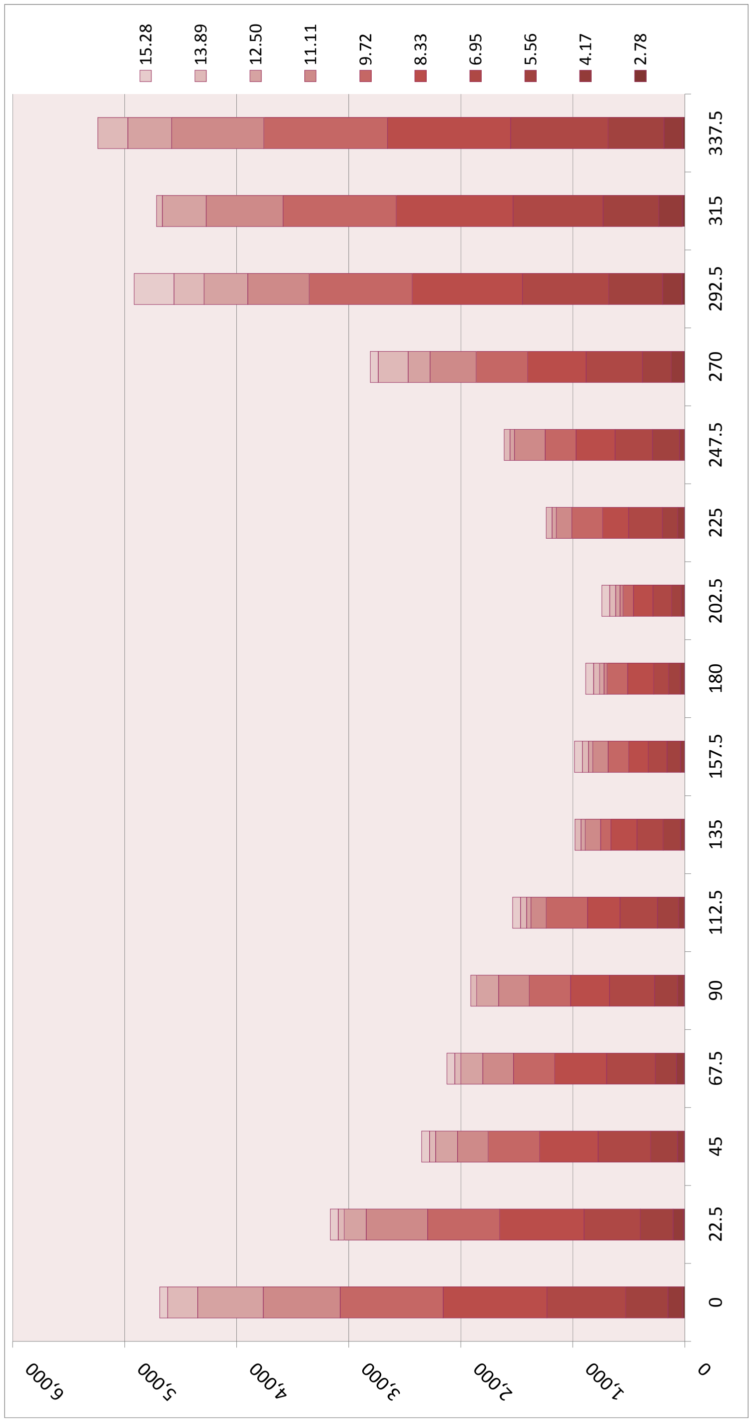
DUBAI WEATHER DATA

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Power Generated at 10m Height	2.78	19	11	6	9	6	4	2	2	4	2	4	4	13	24	21	19
	4.17	130	94	58	65	58	51	36	36	36	29	58	43	109	174	210	166
	5.56	377	292	240	189	206	189	154	120	103	86	137	240	257	480	497	497
	6.95	703	502	469	435	402	335	234	167	134	167	301	335	502	770	804	871
	8.33	926	752	521	463	347	289	232	174	232	174	232	347	521	984	1,042	1,100
	9.72	919	643	460	368	368	368	92	184	184	92	276	276	460	919	1,011	1,103
	11.11	686	549	274	274	274	137	137	137	27	27	137	274	412	549	686	823
	12.50	586	195	195	195	195	39	39	39	39	39	39	39	195	391	391	391
	13.89	268	54	54	54	54	54	54	54	54	54	54	54	268	268	54	268
	15.28	71	71	71	71	0	71	0	71	71	71	0	0	71	357	0	0
Total		4,687	3,164	2,349	2,123	1,910	1,537	980	985	884	741	1,238	1,613	2,808	4,915	4,716	5,239

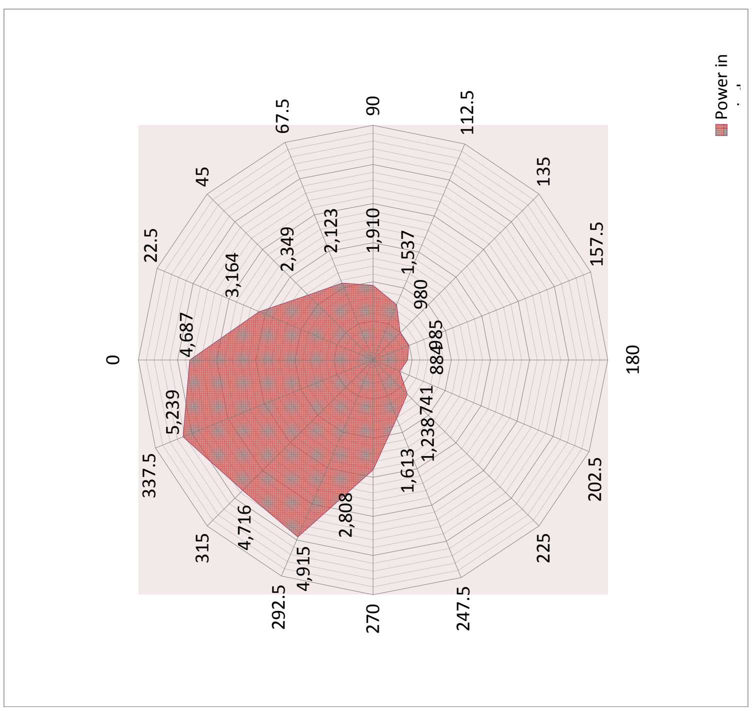
Power from HAWT (Power within 45 degrees from max.) **12,654**

Power from VAWT: **39,890** 3.15

DUBAI WEATHER DATA



DUBAI WEATHER DATA



DUBAI WEATHER DATA

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s) at 50m height	3.11	0.90	0.50	0.30	0.40	0.30	0.20	0.10	0.10	0.20	0.10	0.20	0.20	0.60	1.10	1.00	0.90
	4.67	1.80	1.30	0.80	0.90	0.80	0.70	0.50	0.50	0.50	0.40	0.80	0.60	1.50	2.40	2.90	2.30
	6.22	2.20	1.70	1.40	1.10	1.20	1.10	0.90	0.70	0.60	0.50	0.80	1.40	1.50	2.80	2.90	2.90
	7.78	2.10	1.50	1.40	1.30	1.20	1.00	0.70	0.50	0.40	0.50	0.90	1.00	1.50	2.30	2.40	2.60
	9.33	1.60	1.30	0.90	0.80	0.60	0.50	0.40	0.30	0.40	0.30	0.40	0.60	0.90	1.70	1.80	1.90
	10.89	1.00	0.70	0.50	0.40	0.40	0.40	0.10	0.20	0.20	0.10	0.30	0.30	0.50	1.00	1.10	1.20
	12.45	0.50	0.40	0.20	0.20	0.20	0.10	0.10	0.10	0.02	0.02	0.10	0.20	0.30	0.40	0.50	0.60
	14.00	0.30	0.10	0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.20	0.20	0.20
	15.56	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.10	0.02	0.10
	17.11	0.02	0.02	0.02	0.02	0.00	0.02	0.00	0.02	0.02	0.02	0.00	0.00	0.02	0.10	0.00	0.00
Total %		10.52	7.54	5.64	5.24	4.82	4.06	2.84	2.46	2.38	1.98	3.54	4.34	7.02	12.10	12.82	12.70

Power Generated at 50m Height	3.11	27	15	9	12	9	6	3	3	6	3	6	6	18	33	30	27
	4.67	183	132	81	91	81	71	51	51	51	41	81	61	152	244	295	234
	6.22	530	410	337	265	289	265	217	169	145	120	193	337	361	675	699	699
	7.78	988	706	659	612	565	471	329	235	188	235	424	471	706	1,082	1,129	1,224
	9.33	1,301	1,057	732	651	488	407	325	244	325	244	325	488	732	1,382	1,464	1,545
	10.89	1,291	904	646	517	517	517	129	258	258	129	387	387	646	1,291	1,421	1,550
	12.45	964	771	386	386	386	193	193	193	39	39	193	386	578	771	964	1,157
	14.00	823	274	274	274	274	55	55	55	55	55	55	55	274	549	549	549
	15.56	376	75	75	75	75	75	75	75	75	75	75	75	376	376	75	376
	17.11	100	100	100	100	0	100	0	100	100	100	0	0	100	501	0	0
Total		6,585	4,445	3,300	2,983	2,684	2,159	1,378	1,383	1,242	1,042	1,739	2,266	3,945	6,906	6,626	7,360

Power from HAWT (Power within 45 degrees from max.)	17,778
Power from VAWT:	56,042

DUBAI WEATHER DATA

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s) at 100m height	3.89	0.90	0.50	0.30	0.40	0.30	0.20	0.10	0.10	0.20	0.10	0.20	0.20	0.60	1.10	1.00	0.90
	5.83	1.80	1.30	0.80	0.90	0.80	0.70	0.50	0.50	0.50	0.40	0.80	0.60	1.50	2.40	2.90	2.30
	7.78	2.20	1.70	1.40	1.10	1.20	1.10	0.90	0.70	0.60	0.50	0.80	1.40	1.50	2.80	2.90	2.90
	9.72	2.10	1.50	1.40	1.30	1.20	1.00	0.70	0.50	0.40	0.50	0.90	1.00	1.50	2.30	2.40	2.60
	11.67	1.60	1.30	0.90	0.80	0.60	0.50	0.40	0.30	0.40	0.30	0.40	0.60	0.90	1.70	1.80	1.90
	13.61	1.00	0.70	0.50	0.40	0.40	0.40	0.10	0.20	0.20	0.10	0.30	0.30	0.50	1.00	1.10	1.20
	15.56	0.50	0.40	0.20	0.20	0.20	0.10	0.10	0.10	0.02	0.02	0.10	0.20	0.30	0.40	0.50	0.60
	17.50	0.30	0.10	0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.20	0.20	0.20
	19.45	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.10	0.02	0.10
	21.39	0.02	0.02	0.02	0.02	0.00	0.02	0.00	0.02	0.02	0.02	0.00	0.00	0.02	0.10	0.00	0.00
Total	%	10.52	7.54	5.64	5.24	4.82	4.06	2.84	2.46	2.38	1.98	3.54	4.34	7.02	12.10	12.82	12.70

Power Generated at 100m Height	3.89	53	29	18	24	18	12	6	6	12	6	12	12	35	65	59	53
	5.83	357	258	159	179	159	139	99	99	99	79	159	119	298	477	576	457
	7.78	1,035	800	659	518	565	518	424	329	282	235	376	659	706	1,318	1,365	1,365
	9.72	1,930	1,379	1,287	1,195	1,103	919	643	460	368	460	827	919	1,379	2,114	2,206	2,390
	11.67	2,541	2,065	1,430	1,271	953	794	635	477	635	477	635	953	1,430	2,700	2,859	3,018
	13.61	2,522	1,766	1,261	1,009	1,009	1,009	252	504	504	252	757	757	1,261	2,522	2,774	3,027
	15.56	1,882	1,506	753	753	753	376	376	376	75	75	376	753	1,129	1,506	1,882	2,259
	17.50	1,608	536	536	536	536	107	107	107	107	107	107	107	536	1,072	1,072	1,072
	19.45	735	147	147	147	147	147	147	147	147	147	147	147	735	735	147	735
	21.39	196	196	196	196	0	196	0	196	196	196	0	0	196	979	0	0
Total		12,861	8,682	6,445	5,826	5,242	4,217	2,690	2,702	2,426	2,034	3,397	4,426	7,705	13,488	12,941	14,375

Power from HAWT (Power within 45 degrees from max.)	34,722
Power from VAWT:	######

DUBAI WEATHER DATA

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s) at 200m height	4.92	0.90	0.50	0.30	0.40	0.30	0.20	0.10	0.10	0.20	0.10	0.20	0.20	0.60	1.10	1.00	0.90
	7.38	1.80	1.30	0.80	0.90	0.80	0.70	0.50	0.50	0.50	0.40	0.80	0.60	1.50	2.40	2.90	2.30
	9.83	2.20	1.70	1.40	1.10	1.20	1.10	0.90	0.70	0.60	0.50	0.80	1.40	1.50	2.80	2.90	2.90
	12.29	2.10	1.50	1.40	1.30	1.20	1.00	0.70	0.50	0.40	0.50	0.90	1.00	1.50	2.30	2.40	2.60
	14.75	1.60	1.30	0.90	0.80	0.60	0.50	0.40	0.30	0.40	0.30	0.40	0.60	0.90	1.70	1.80	1.90
	17.21	1.00	0.70	0.50	0.40	0.40	0.40	0.10	0.20	0.20	0.10	0.30	0.30	0.50	1.00	1.10	1.20
	19.67	0.50	0.40	0.20	0.20	0.20	0.10	0.10	0.10	0.02	0.02	0.10	0.20	0.30	0.40	0.50	0.60
	22.13	0.30	0.10	0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.20	0.20	0.20
	24.59	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.10	0.02	0.10
	27.04	0.02	0.02	0.02	0.02	0.00	0.02	0.00	0.02	0.02	0.02	0.00	0.00	0.02	0.10	0.00	0.00
Total %		10.52	7.54	5.64	5.24	4.82	4.06	2.84	2.46	2.38	1.98	3.54	4.34	7.02	12.10	12.82	12.70
Power Generated at 200m Height	4.92	107	59	36	48	36	24	12	12	24	12	24	24	71	131	119	107
	7.38	722	522	321	361	321	281	201	201	201	160	321	241	602	963	1,164	923
	9.83	2,092	1,617	1,331	1,046	1,141	1,046	856	666	571	476	761	1,331	1,427	2,663	2,758	2,758
	12.29	3,901	2,786	2,601	2,415	2,229	1,858	1,300	929	743	929	1,672	1,858	2,786	4,272	4,458	4,830
	14.75	5,136	4,173	2,889	2,568	1,926	1,605	1,284	963	1,284	963	1,284	1,926	2,889	5,457	5,778	6,099
	17.21	5,097	3,568	2,549	2,039	2,039	2,039	510	1,019	1,019	510	1,529	1,529	2,549	5,097	5,607	6,116
	19.67	3,804	3,043	1,522	1,522	1,522	761	761	761	152	152	761	1,522	2,283	3,043	3,804	4,565
	22.13	3,250	1,083	1,083	1,083	1,083	217	217	217	217	217	217	217	1,083	2,167	2,167	2,167
	24.59	1,486	297	297	297	297	297	297	297	297	297	297	297	1,486	1,486	297	1,486
	27.04	396	396	396	396	0	396	0	396	396	396	0	0	396	1,978	0	0
Total		25,991	17,544	13,024	11,774	10,594	8,522	5,437	5,460	4,903	4,111	6,865	8,944	15,571	27,257	26,151	29,050

Power from HAWT (Power within 45 degrees from max.) **70,168**

Power from VAWT: **######**

DUBAI WEATHER DATA

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s) at 460m height	6.48	0.90	0.50	0.30	0.40	0.30	0.20	0.10	0.10	0.20	0.10	0.20	0.20	0.60	1.10	1.00	0.90
	9.71	1.80	1.30	0.80	0.90	0.80	0.70	0.50	0.50	0.50	0.40	0.80	0.60	1.50	2.40	2.90	2.30
	12.95	2.20	1.70	1.40	1.10	1.20	1.10	0.90	0.70	0.60	0.50	0.80	1.40	1.50	2.80	2.90	2.90
	16.18	2.10	1.50	1.40	1.30	1.20	1.00	0.70	0.50	0.40	0.50	0.90	1.00	1.50	2.30	2.40	2.60
	19.42	1.60	1.30	0.90	0.80	0.60	0.50	0.40	0.30	0.40	0.30	0.40	0.60	0.90	1.70	1.80	1.90
	22.65	1.00	0.70	0.50	0.40	0.40	0.40	0.10	0.20	0.20	0.10	0.30	0.30	0.50	1.00	1.10	1.20
	25.89	0.50	0.40	0.20	0.20	0.20	0.10	0.10	0.10	0.02	0.02	0.10	0.20	0.30	0.40	0.50	0.60
	29.13	0.30	0.10	0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.20	0.20	0.20
	32.36	0.10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.10	0.02	0.10
	35.60	0.02	0.02	0.02	0.02	0.00	0.02	0.00	0.02	0.02	0.02	0.00	0.00	0.02	0.10	0.00	0.00
Total	%	10.52	7.54	5.64	5.24	4.82	4.06	2.84	2.46	2.38	1.98	3.54	4.34	7.02	12.10	12.82	12.70

Power Generated at 460m Height	2.78	245	136	82	109	82	54	27	27	54	27	54	54	163	299	272	245
	4.17	1,647	1,190	732	824	732	641	458	458	458	366	732	549	1,373	2,197	2,654	2,105
	5.56	4,773	3,688	3,037	2,386	2,603	2,386	1,953	1,519	1,302	1,085	1,736	3,037	3,254	6,075	6,291	6,291
	6.95	8,898	6,356	5,932	5,508	5,085	4,237	2,966	2,119	1,695	2,119	3,814	4,237	6,356	9,746	10,169	11,017
	8.33	11,715	9,519	6,590	5,858	4,393	3,661	2,929	2,197	2,929	2,197	2,929	4,393	6,590	12,447	13,180	13,912
	9.72	11,627	8,139	5,814	4,651	4,651	4,651	1,163	2,325	2,325	1,163	3,488	3,488	5,814	11,627	12,790	13,952
	11.11	8,678	6,942	3,471	3,471	3,471	1,736	1,736	1,736	347	347	1,736	3,471	5,207	6,942	8,678	10,413
	12.50	7,413	2,471	2,471	2,471	2,471	494	494	494	494	494	494	494	2,471	4,942	4,942	4,942
	13.89	3,390	678	678	678	678	678	678	678	678	678	678	678	3,390	3,390	678	3,390
	15.28	902	902	902	902	0	902	0	902	902	902	0	0	902	4,512	0	0
Total		59,289	40,021	29,709	26,858	24,166	19,441	12,403	12,454	11,184	9,378	15,660	20,403	35,519	62,176	59,654	66,268

Power from HAWT (Power within 45 degrees from max.) 160,064

Power from VAWT: 504,584

Study of Normal Componant from Wind Rose

Wind Rose: **Camborne, UK**

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s)	2.78	0.30	0.20	0.20	0.20	0.20	0.10	0.10	0.40	0.30	0.20	0.20	0.10	0.10	0.10	0.20	0.20
	4.17	0.40	0.50	0.50	0.60	0.90	0.30	0.70	0.70	1.30	0.60	0.40	0.40	0.60	0.50	0.60	0.50
	5.56	1.20	0.80	0.80	1.10	2.40	1.20	1.10	1.20	2.20	1.10	1.00	0.50	1.50	1.20	1.40	1.00
	6.95	0.90	0.50	0.40	0.60	0.90	0.70	0.80	1.10	1.30	0.70	0.60	0.60	1.20	0.70	0.80	0.90
	8.33	0.70	0.30	0.20	0.30	0.80	0.90	0.90	0.90	1.20	0.90	0.70	1.10	1.50	1.10	1.00	0.90
	9.72	0.70	0.30	0.10	0.10	0.40	1.10	0.70	0.90	1.30	0.70	1.10	1.70	1.80	0.90	1.00	0.80
	11.11	0.10	0.20	0.10	0.10	0.20	0.90	0.60	0.60	1.00	0.70	0.60	1.00	1.40	0.90	0.60	0.40
	12.50	0.10	0.02	0.10	0.00	0.20	0.40	0.50	0.40	0.70	0.50	0.50	0.80	0.90	0.80	0.60	0.20
	13.89	0.02	0.00	0.02	0.00	0.10	0.10	0.50	0.40	0.60	0.40	0.60	0.50	0.70	0.60	0.50	0.20
	15.28	0.02	0.00	0.00	0.00	0.02	0.30	0.50	0.30	0.70	0.50	0.40	0.70	1.30	1.10	0.30	0.20
	16.67																
	18.06																
Total %		4.44	2.82	2.42	3.00	6.12	6.00	6.40	6.90	10.60	6.30	6.10	7.40	11.00	7.90	7.00	5.30

Total Percentages ###### %

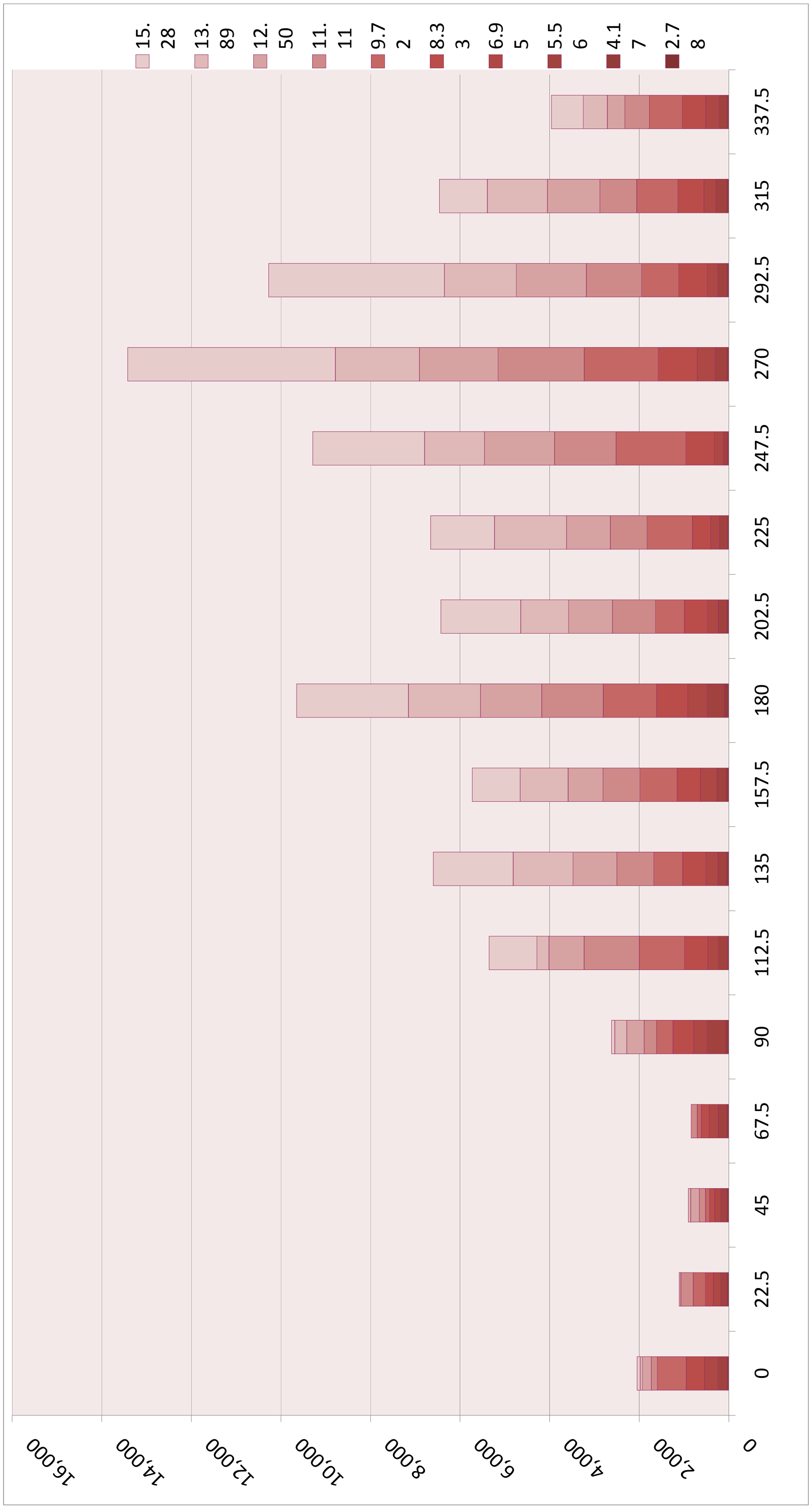
CAMBORNE WEATHER DATA

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Power Generated	2.78	6	4	4	4	4	2	2	9	6	4	4	2	2	2	4	4
	4.17	29	36	36	43	65	22	51	51	94	43	29	29	43	36	43	36
	5.56	206	137	137	189	412	206	189	206	377	189	172	86	257	206	240	172
	6.95	301	167	134	201	301	234	268	368	435	234	201	201	402	234	268	301
	8.33	405	174	116	174	463	521	521	521	695	521	405	637	868	637	579	521
	9.72	643	276	92	92	368	1,011	643	827	1,195	643	1,011	1,563	1,655	827	919	735
	11.11	137	274	137	137	274	1,235	823	823	1,372	960	823	1,372	1,921	1,235	823	549
	12.50	195	39	195	0	391	781	977	781	1,368	977	977	1,563	1,758	1,563	1,172	391
	13.89	54	0	54	0	268	268	1,340	1,072	1,608	1,072	1,608	1,340	1,876	1,608	1,340	536
	15.28	71	0	0	0	71	1,070	1,783	1,070	2,497	1,783	1,427	2,497	4,637	3,924	1,070	713
Total		2,049	1,108	906	840	2,618	5,351	6,597	5,728	9,647	6,428	6,657	9,289	13,420	10,272	6,459	3,959

Power from HAWT: (Power within 45 degrees from max.) **28,845**

Power from VAWT: **91,326** 3.17

CAMBORNE WEATHER DATA



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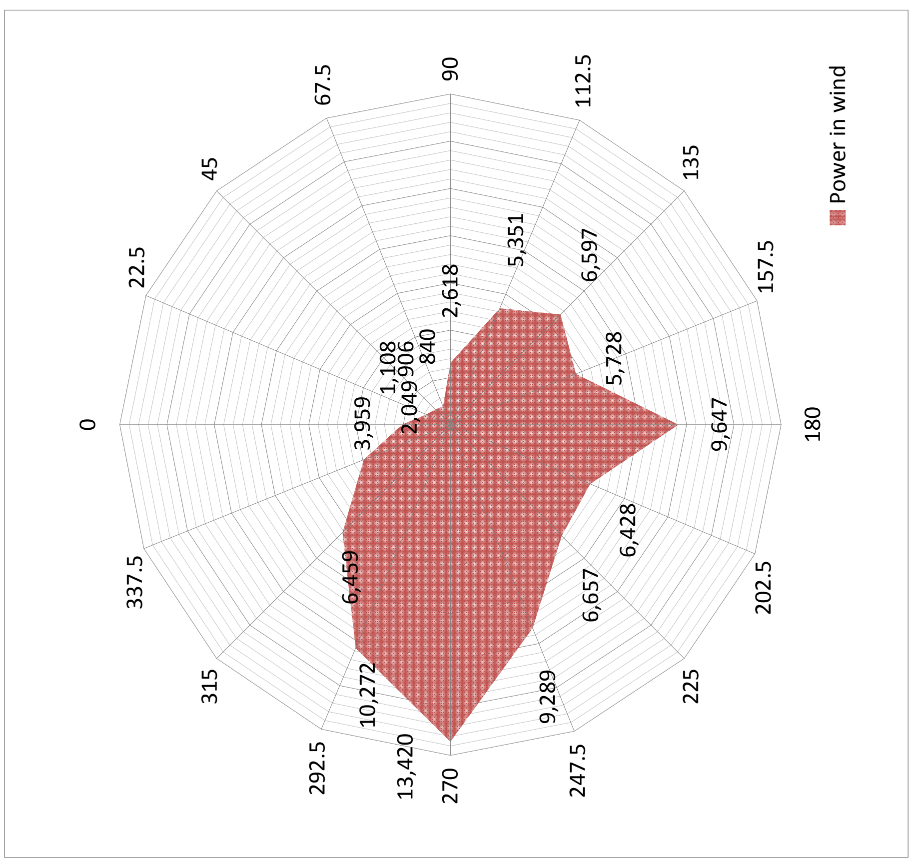


Study of Normal Componant from Wind Rose

Wind Rose: **Cairo, Egypt**

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s)	2.78	2.50	1.20	1.00	1.20	1.20	0.60	0.60	0.60	0.60	0.20	0.20	0.20	0.60	0.70	1.10	1.30
	4.17	5.60	3.00	2.60	1.80	1.40	0.50	0.40	0.50	1.00	0.70	0.40	0.60	1.00	1.80	2.40	3.30
	5.56	5.30	3.50	2.80	1.30	1.00	0.40	0.20	0.10	1.00	1.10	0.60	0.70	1.70	1.60	2.20	3.50
	6.95	4.10	2.40	1.60	0.60	0.40	0.10	0.10	0.10	0.30	0.50	0.50	0.50	1.00	0.60	1.30	1.90
	8.33	2.40	2.10	1.30	0.40	0.20	0.04	0.10	0.02	0.20	0.50	0.50	0.40	0.90	0.60	0.60	0.90
	9.72	0.50	0.50	0.30	0.04	0.04	0.02	0.00	0.02	0.10	0.40	0.40	0.30	0.40	0.02	0.10	0.10
	11.11	0.02	0.04	0.04	0.02	0.02	0.00	0.00	0.00	0.02	0.20	0.10	0.10	0.10	0.02	0.02	0.02
	12.50	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.02	0.30	0.10	0.10	0.10	0.02	0.02	0.02
	13.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.02	0.00	0.10	0.00	0.00	0.02
	15.28	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.02
	16.67																
	18.06																
Total	%	20.44	12.76	9.68	5.36	4.26	1.66	1.40	1.36	3.24	4.02	2.84	2.90	5.90	5.36	7.74	11.08

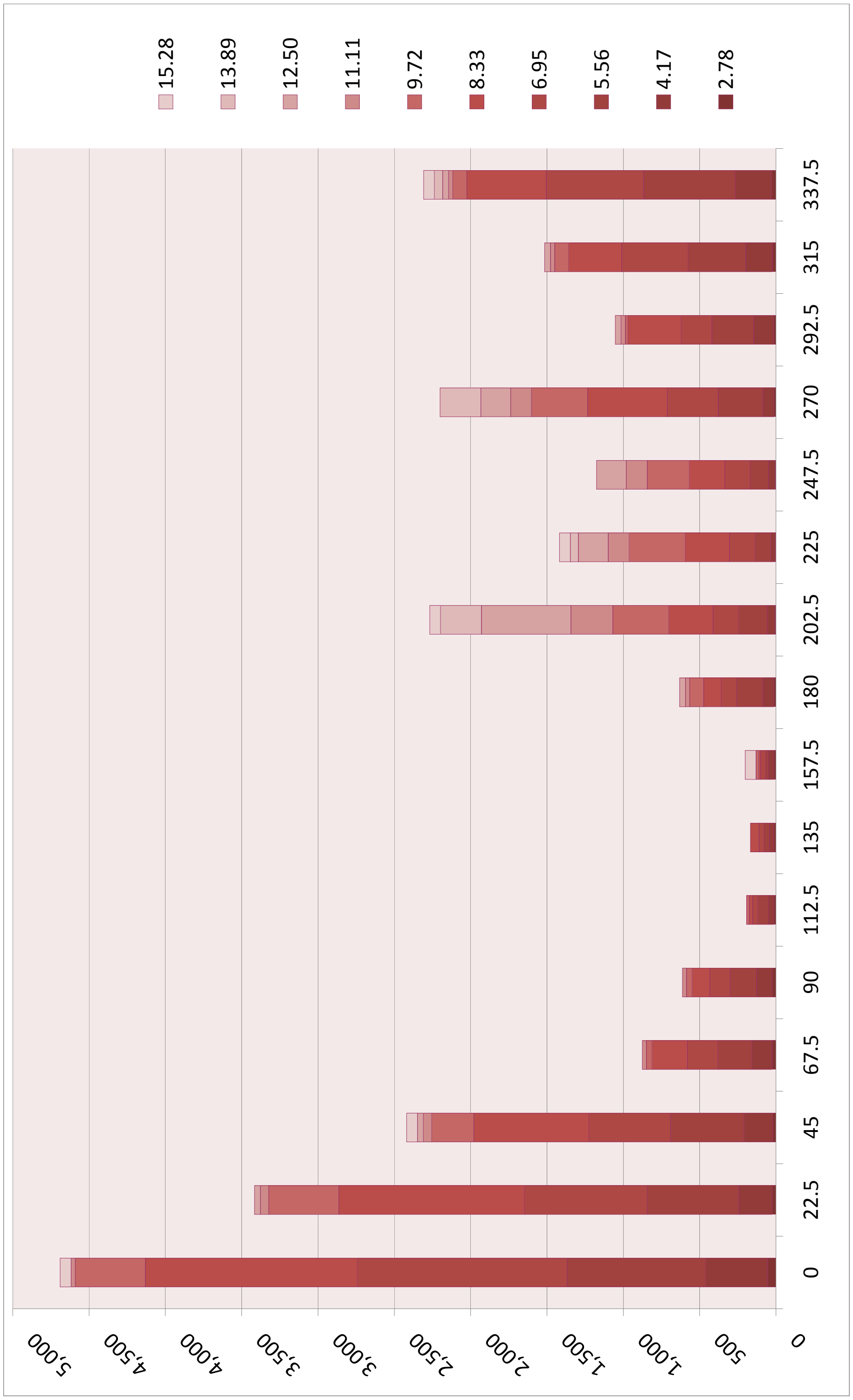
Total Percentages ###### %

CAIRO WEATHER DATA

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Power Generated	2.78	54	26	21	26	26	13	13	13	13	4	4	4	13	15	24	28
	4.17	405	217	188	130	101	36	29	36	72	51	29	43	72	130	174	239
	5.56	909	600	480	223	172	69	34	17	172	189	103	120	292	274	377	600
	6.95	1,373	804	536	201	134	33	33	33	100	167	167	167	335	201	435	636
	8.33	1,389	1,216	752	232	116	23	58	12	116	289	289	232	521	347	347	521
	9.72	460	460	276	37	37	18	0	18	92	368	368	276	368	18	92	92
	11.11	27	55	55	27	27	0	0	0	27	274	137	137	137	27	27	27
	12.50	0	39	39	0	0	0	0	0	39	586	195	195	195	39	39	39
	13.89	0	0	0	0	0	0	0	0	0	268	54	0	268	0	0	54
	15.28	71	0	71	0	0	0	0	71	0	71	71	0	0	0	0	71
Total		4,689	3,416	2,419	876	613	193	167	201	631	2,268	1,418	1,175	2,201	1,053	1,516	2,308

Power from HAWT (Power within 45 degrees from max.)	**9,202**	
Power from VAWT:	**25,144**	2.73

CAIRO WEATHER DATA



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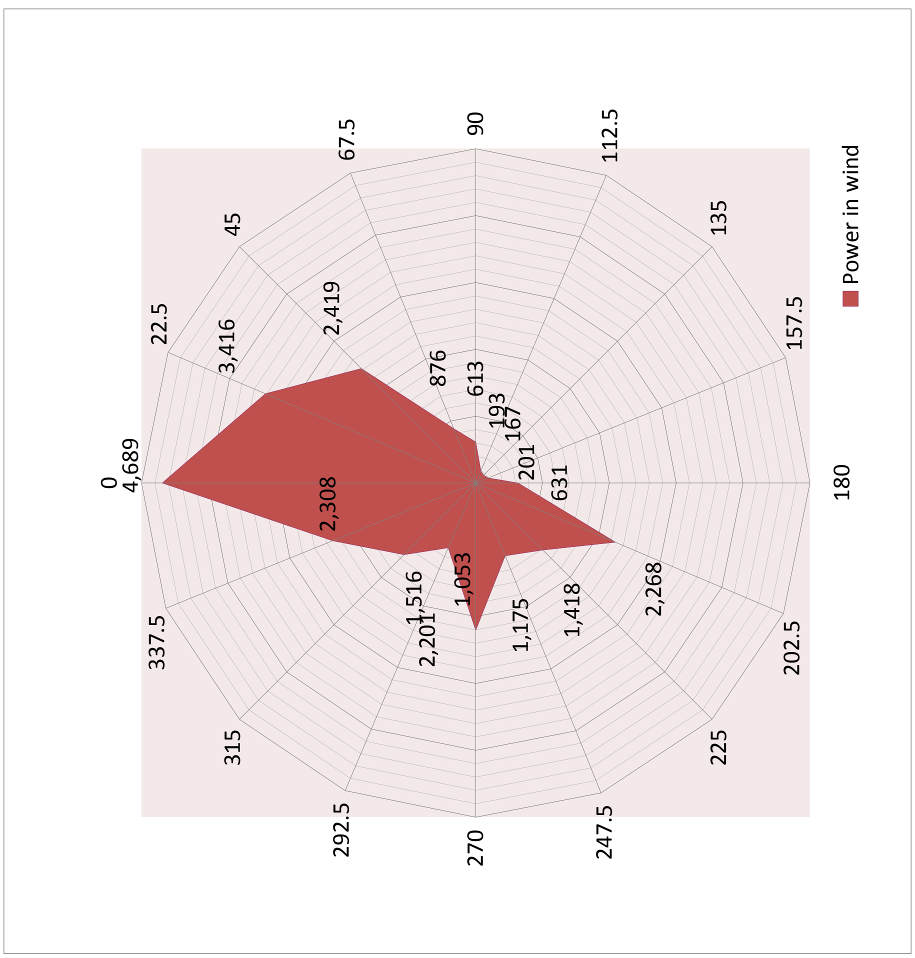


Study of Normal Componant from Wind Rose

Wind Rose: **Hong Kong, China**

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Wind Speed (m/s)	2.78	1.20	1.70	1.90	1.30	2.90	0.80	0.30	0.30	0.60	0.40	0.30	0.70	3.50	1.00	0.20	0.30
	4.17	0.50	1.50	1.40	1.40	7.30	1.40	0.30	0.40	1.00	0.80	0.60	0.80	4.30	0.70	0.02	0.10
	5.56	0.30	1.10	0.80	1.60	15.30	2.70	0.20	0.20	0.90	0.70	0.50	0.70	4.40	0.20	0.02	0.02
	6.95	0.10	0.40	0.20	0.50	14.90	1.70	0.02	0.02	0.10	0.30	0.40	0.30	1.80	0.20	0.01	0.01
	8.33	0.00	0.10	0.10	0.10	4.90	0.30	0.02	0.00	0.02	0.10	0.10	0.10	0.30	0.02	0.00	0.00
	9.72	0.00	0.02	0.02	0.02	2.10	0.10	0.01	0.00	0.00	0.02	0.10	0.00	0.01	0.00	0.00	0.00
	11.11	0.00	0.01	0.00	0.01	0.40	0.10	0.00	0.00	0.00	0.00	0.02	0.00	0.10	0.01	0.00	0.00
	12.50	0.00	0.00	0.00	0.01	0.20	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
	13.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	15.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
	16.67																
	18.06																
Total %		2.10	4.83	4.42	4.94	48.00	7.12	0.85	0.92	2.62	2.32	2.06	2.60	14.41	2.13	0.25	0.43

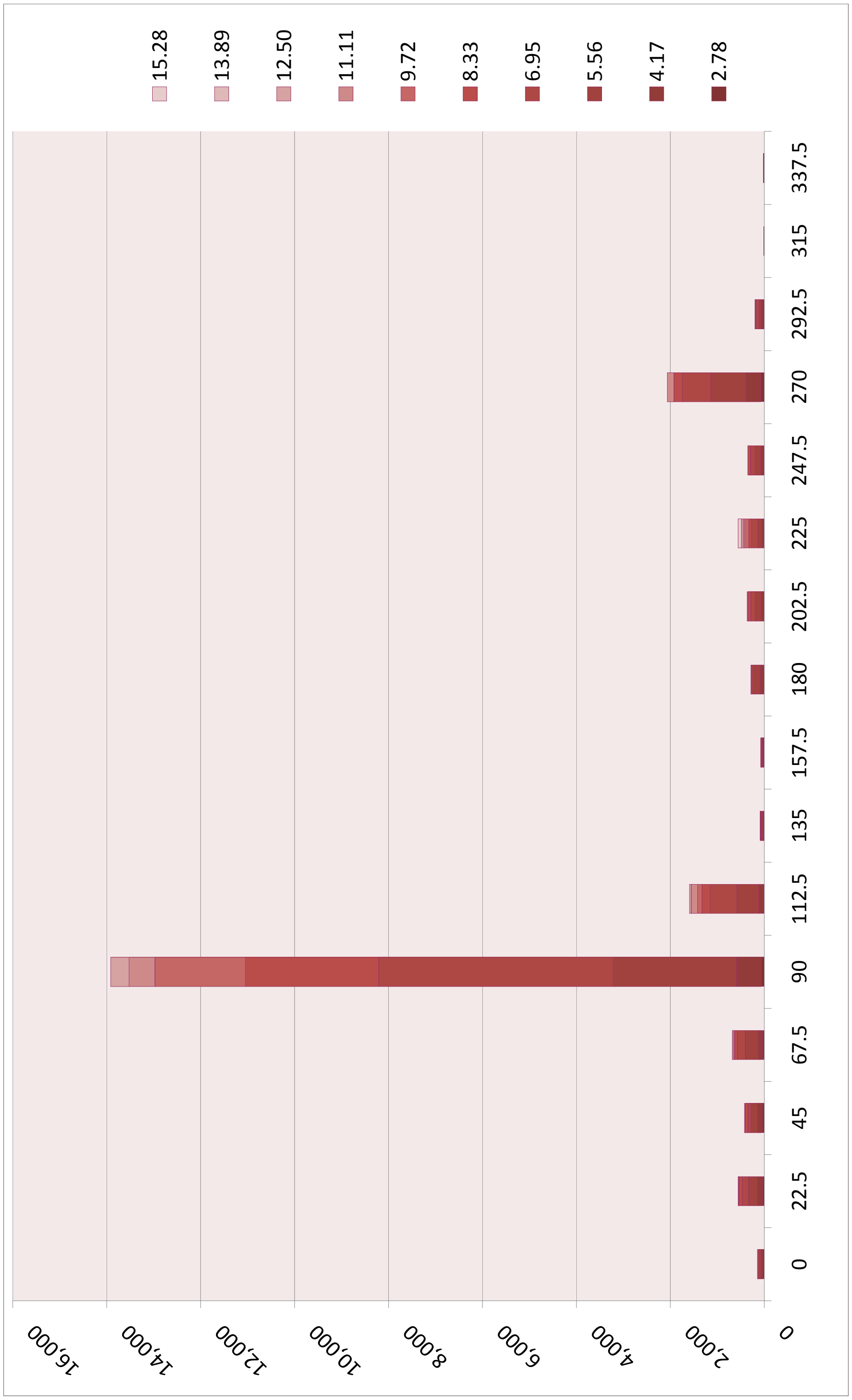
Total Percentages ###### %

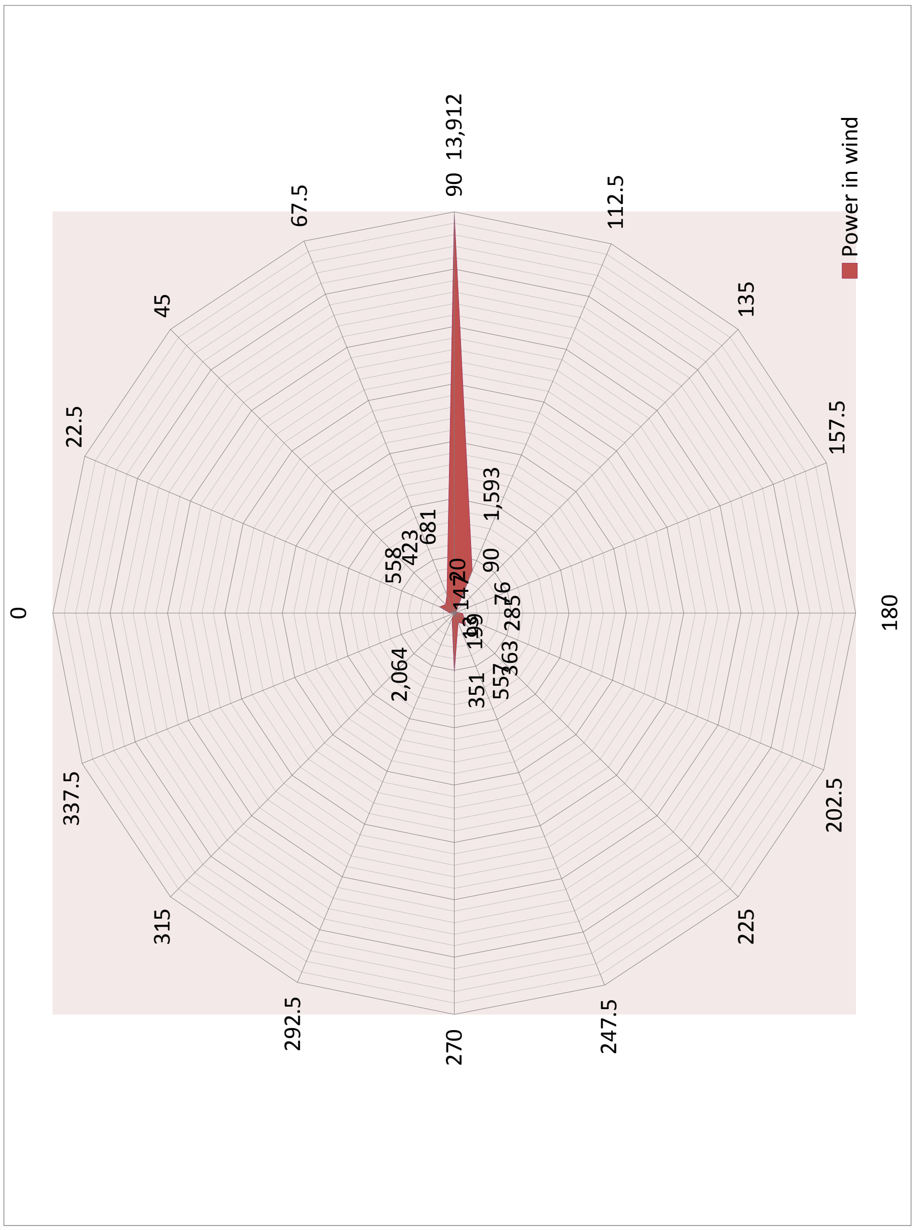
HONG KONG WEATHER DATA

Wind Direction		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Power Generated	2.78	26	36	41	28	62	17	6	6	13	9	6	15	75	21	4	6
	4.17	36	109	101	101	528	101	22	29	72	58	43	58	311	51	1	7
	5.56	51	189	137	274	2,624	463	34	34	154	120	86	120	755	34	3	3
	6.95	33	134	67	167	4,991	569	7	7	33	100	134	100	603	67	3	3
	8.33	0	58	58	58	2,836	174	12	0	12	58	58	58	174	12	0	0
	9.72	0	18	18	18	1,930	92	9	0	0	18	92	0	9	0	0	0
	11.11	0	14	0	14	549	137	0	0	0	0	27	0	137	14	0	0
	12.50	0	0	0	20	391	39	0	0	0	0	39	0	0	0	0	0
	13.89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	15.28	0	0	0	0	0	0	0	0	0	0	71	0	0	0	0	0
Total		147	558	423	681	13,912	1,593	90	76	285	363	557	351	2,064	199	13	20

Power from HAWT (Power within 45 degrees from max.)	**15,705**	
Power from VAWT:	**21,330**	1.36

HONG KONG WEATHER DATA

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45
67.5
90
112.5
135
157.5
180
202.5
225
247.5
270
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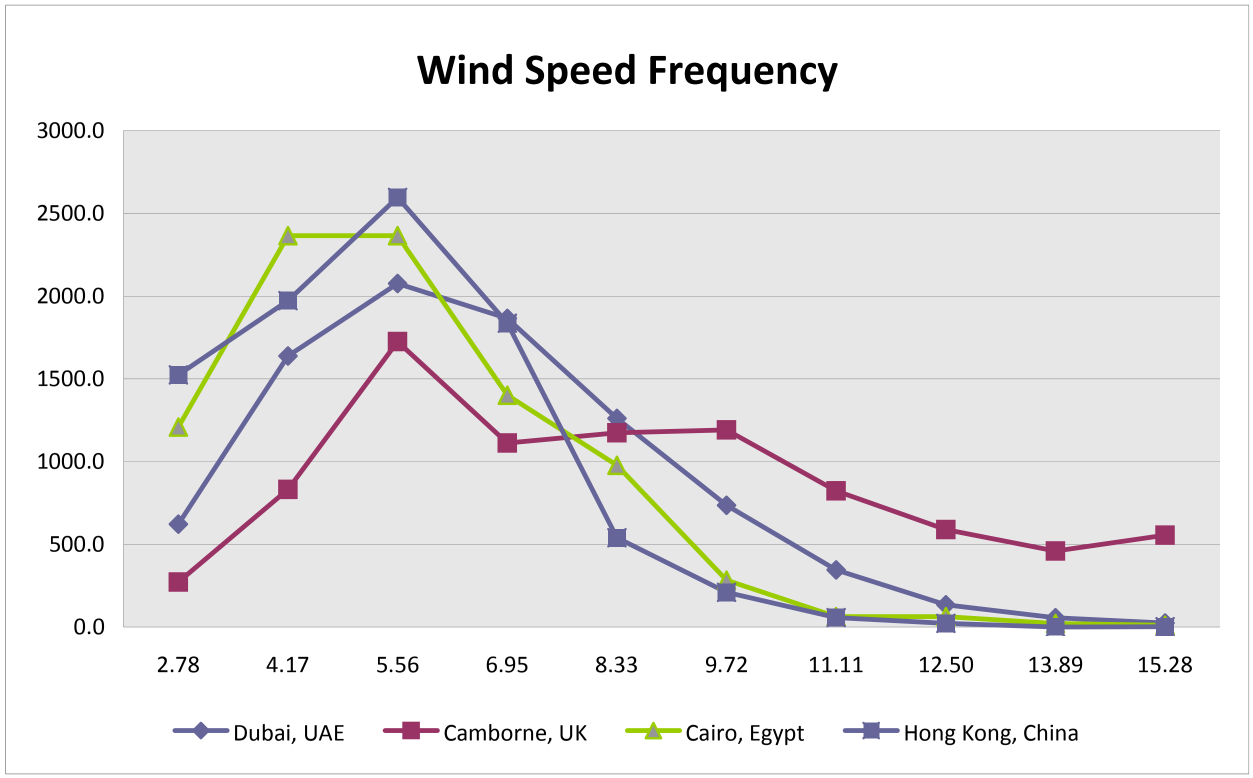
315
337.5
13,912
1,593
2,064
681
558
423
90
76
285
363
557
351
199



Wind Speed Frequency
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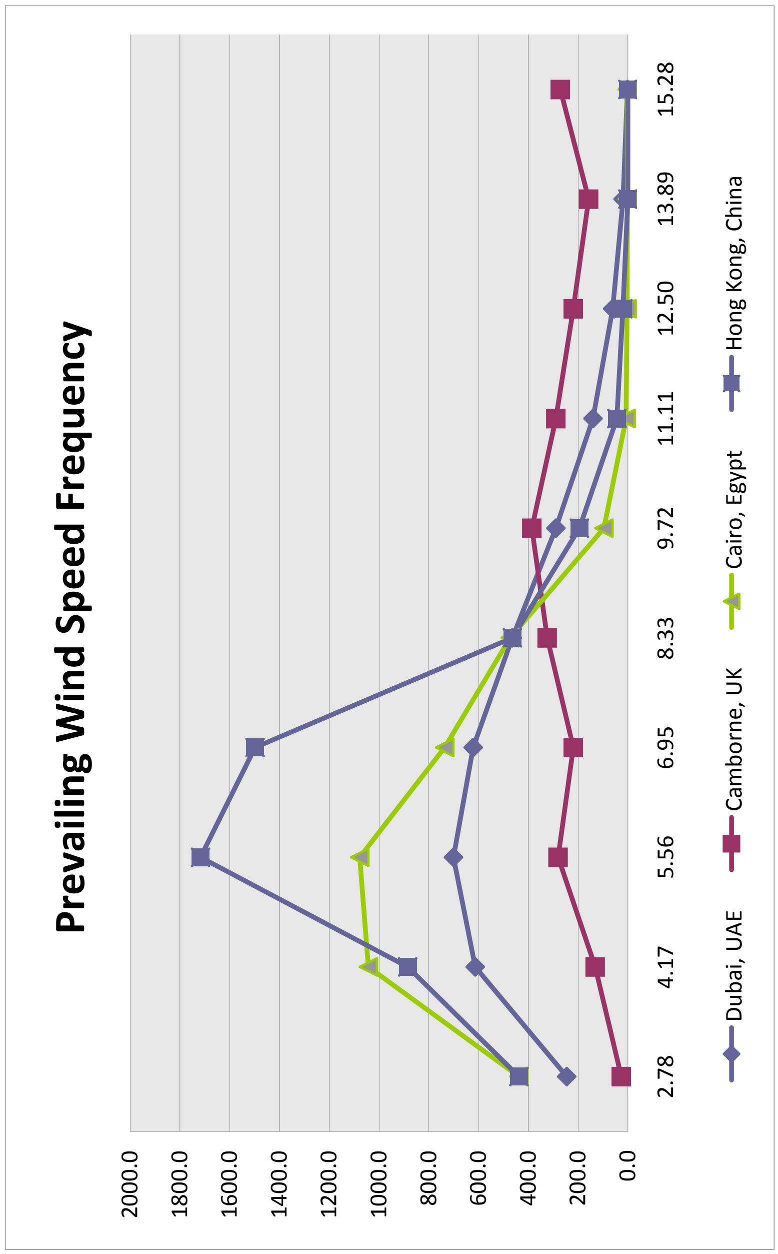
2500.0
2000.0
1500.0
1000.0
500.0
0.0
2.78
4.17
5.56
6.95
8.33
9.72
11.11
12.50
13.89
15.28
Dubai, UAE
Camborne, UK
Cairo, Egypt
Hong Kong, China


Prevailing Wind Speed Frequency
2000.0
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1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
2.78
4.17
5.56
6.95
8.33
9.72
11.11
12.50
13.89
15.28
Dubai, UAE
Camborne, UK
Cairo, Egypt
Hong Kong, China

Dubai

	Total	Prevailing
2.78	622.0	245.3
4.17	1638.1	613.2
5.56	2076.1	700.8
6.95	1865.9	622.0
8.33	1261.4	464.3
9.72	735.8	289.1
11.11	345.1	140.2
12.50	134.9	61.3
13.89	56.1	19.3
15.28	24.5	1.8

VAWT

	Total	Prevailing
0	0.0	0.0
6.24	10,221.9	3,826.4
14.5	30,103.7	10,161.6
28.2	52,617.8	17,539.3
50.1	63,198.1	23,260.4
80.52	59,249.8	23,276.7
120.4	41,555.3	16,875.3
212.7	28,694.1	13,042.8
228.3	12,799.4	4,399.8
297.2	7,289.7	520.7
	305,730	**112,903**

HAWT

	Total	Prevailing
0	0.0	0.0
1	1,638.1	613.2
11	22,837.3	7,708.8
53	98,891.6	32,963.9
100	126,144.0	46,428.0
135	99,338.4	39,025.8
176	60,745.3	24,668.2
200	26,980.8	12,264.0
215	12,053.8	4,143.5
226	5,543.3	396.0
	454,173	**168,211**

Camborne

	Total	Prevailing
2.78	271.6	26.3
4.17	832.2	131.4
5.56	1725.7	280.3
6.95	1112.5	219.0
8.33	1173.8	324.1
9.72	1191.4	385.4
11.11	823.4	289.1
12.50	588.7	219.0
13.89	459.0	157.7
15.28	555.4	271.6

VAWT

	Total	Prevailing
0	0.0	0.0
6.24	5,192.9	819.9
14.5	25,022.9	4,064.6
28.2	31,373.1	6,175.8
50.1	58,809.4	16,238.4
80.52	95,928.3	31,035.6
120.4	99,142.2	34,805.2
212.7	125,210.5	46,581.3
228.3	104,795.2	35,998.3
297.2	165,060.1	80,707.6
	710,535	**256,427**

HAWT

	Total	Prevailing
0	0.0	0.0
1	832.2	131.4
11	18,982.9	3,083.5
53	58,963.6	11,607.0
100	117,384.0	32,412.0
135	160,833.6	52,034.4
176	144,925.4	50,878.1
200	117,734.4	43,800.0
215	98,690.2	33,901.2
226	125,516.8	61,372.6
	843,863	**289,220**

Cairo

	Total	Prevailing
2.78	1208.9	438.0
4.17	2365.2	1042.4
5.56	2365.2	1077.5
6.95	1401.6	735.8
8.33	977.6	473.0
9.72	283.8	96.4
11.11	63.1	7.0
12.50	63.1	3.5
13.89	21.0	1.8
15.28	10.5	3.5

VAWT

	Total	Prevailing
0	0.0	0.0
6.24	14,758.8	6,504.8
14.5	34,295.4	15,623.5
28.2	39,525.1	20,750.7
50.1	48,978.6	23,699.3
80.52	22,853.5	7,758.9
120.4	7,593.9	843.8
212.7	13,415.4	745.3
228.3	4,799.8	400.0
297.2	3,124.2	1,041.4
	189,345	**77,368**

HAWT

	Total	Prevailing
0	0.0	0.0
1	2,365.2	1,042.4
11	26,017.2	11,852.3
53	74,284.8	38,999.5
100	97,761.6	47,304.0
135	38,316.2	13,008.6
176	11,100.7	1,233.4
200	12,614.4	700.8
215	4,520.2	376.7
226	2,375.7	791.9
	269,356	**115,310**

Hong Kong

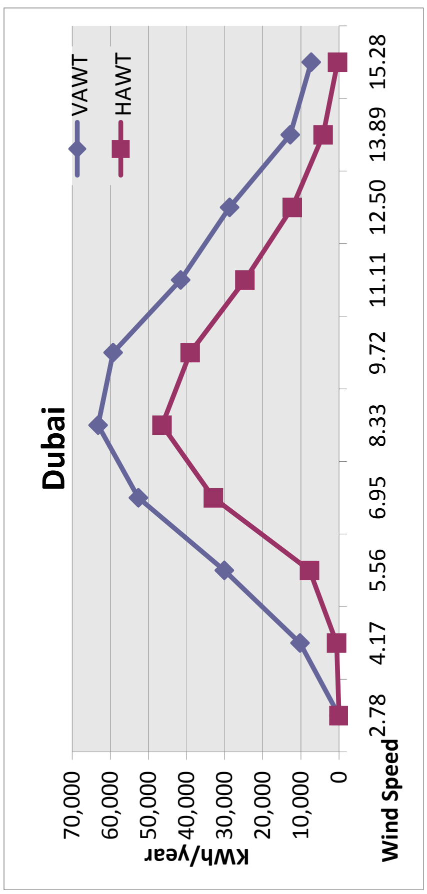
	Total	Prevailing
2.78	1524.2	438.0
4.17	1972.8	884.8
5.56	2596.5	1717.0
6.95	1836.1	1498.0
8.33	539.6	464.3
9.72	210.2	194.5
11.11	56.9	44.7
12.50	21.9	20.1
13.89	0.0	0.0
15.28	1.8	0.0

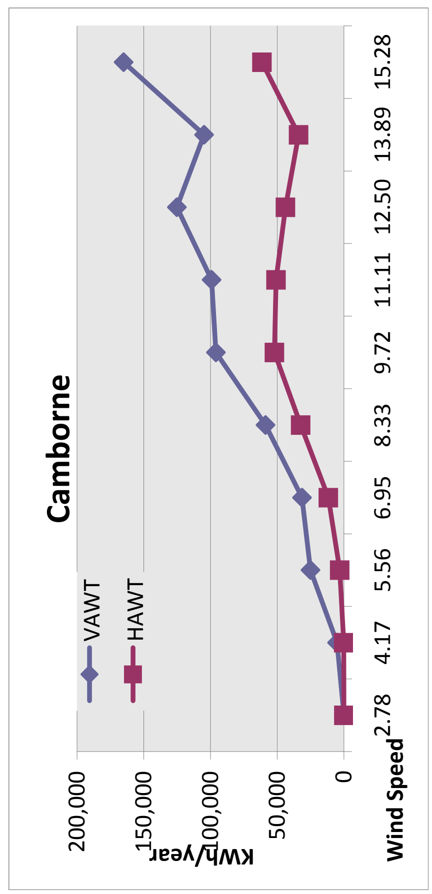
VAWT

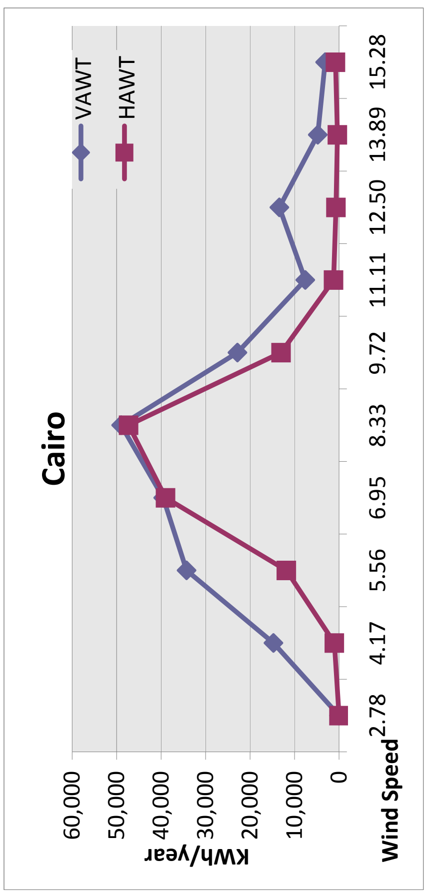
	Total	Prevailing
0	0.0	0.0
6.24	12,310.0	5,520.9
14.5	37,648.7	24,895.9
28.2	51,777.9	42,242.5
50.1	27,034.8	23,260.4
80.52	16,928.5	15,658.9
120.4	6,855.6	5,379.0
212.7	4,658.1	4,285.5
228.3	0.0	0.0
297.2	520.7	0.0
	157,734	**121,243**

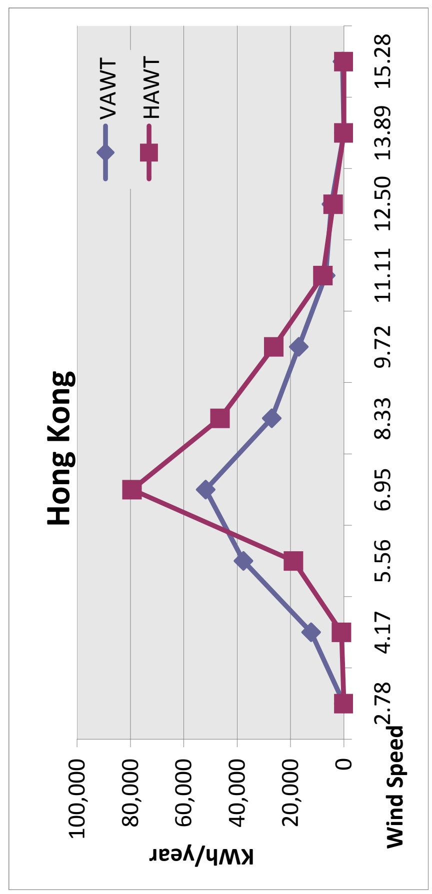
HAWT

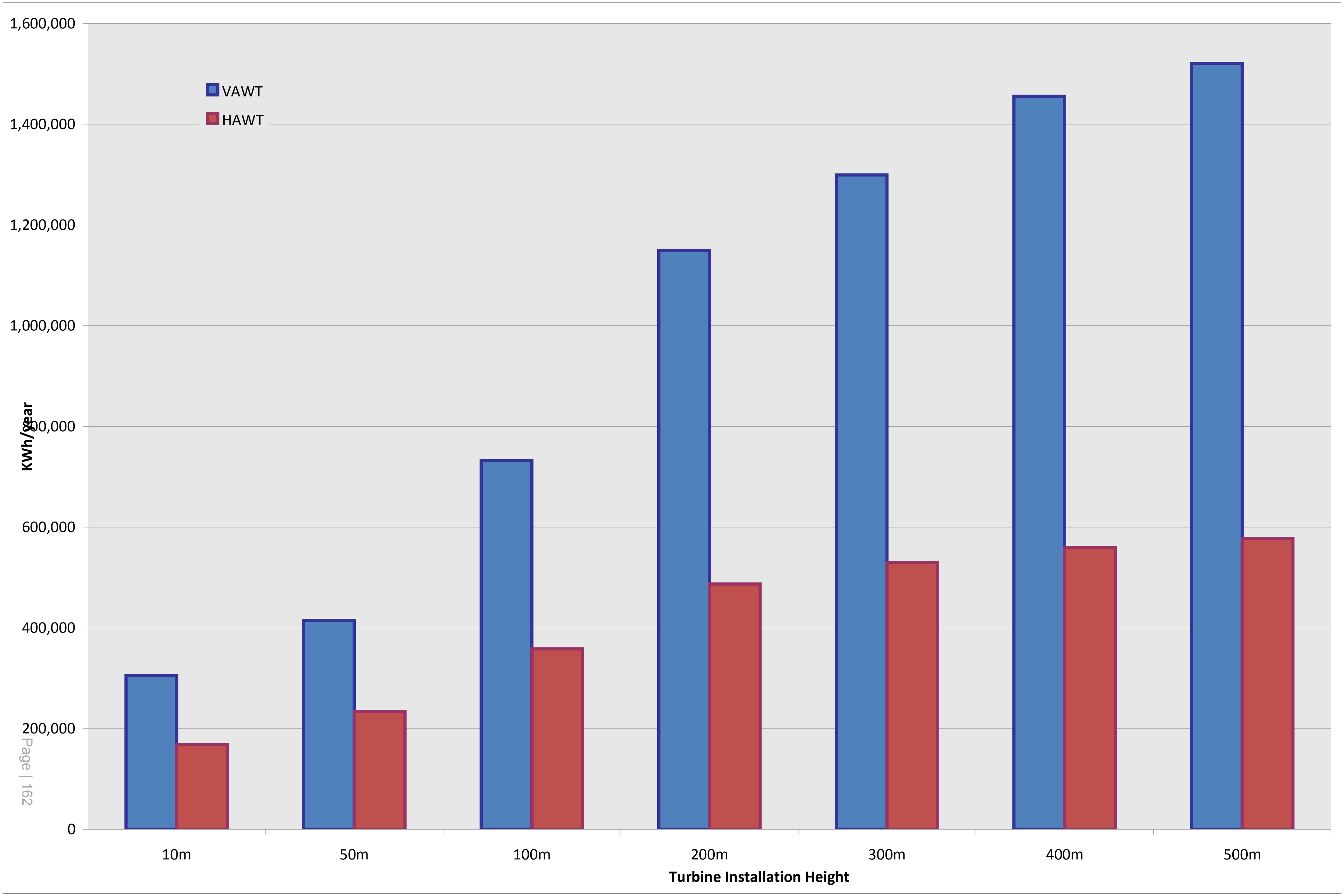
	Total	Prevailing
0	0.0	0.0
1	1,972.8	884.8
11	28,561.1	18,886.6
53	97,313.1	79,391.9
100	53,961.6	46,428.0
135	28,382.4	26,253.7
176	10,021.4	7,863.0
200	4,380.0	4,029.6
215	0.0	0.0
226	396.0	0.0
	224,988	**183,737**

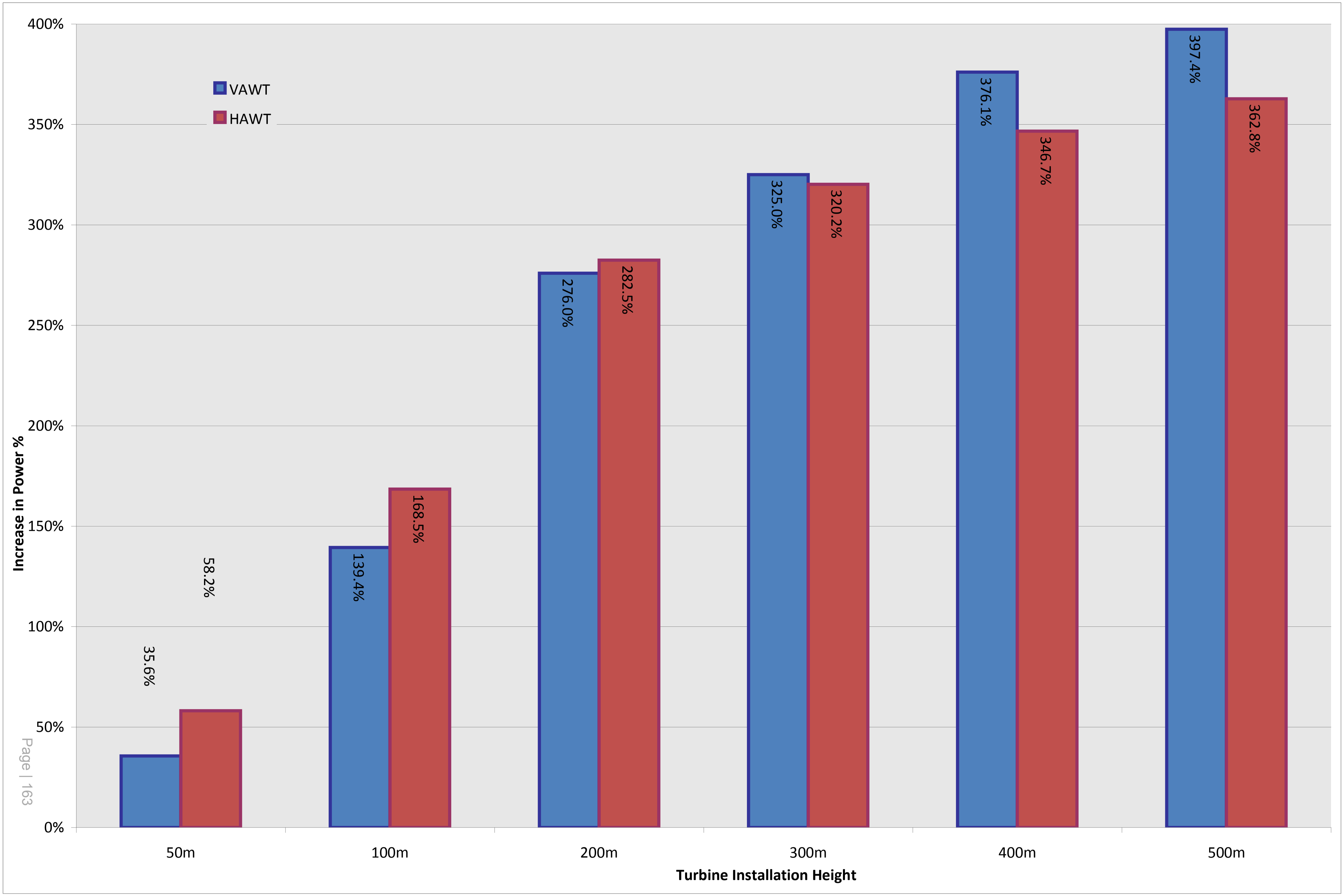

Dubai
KWh/year
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Wind Speed
2.78
4.17
5.56
6.95
8.33
9.72
11.11
12.50
13.89
15.28
VAWT
HAWT

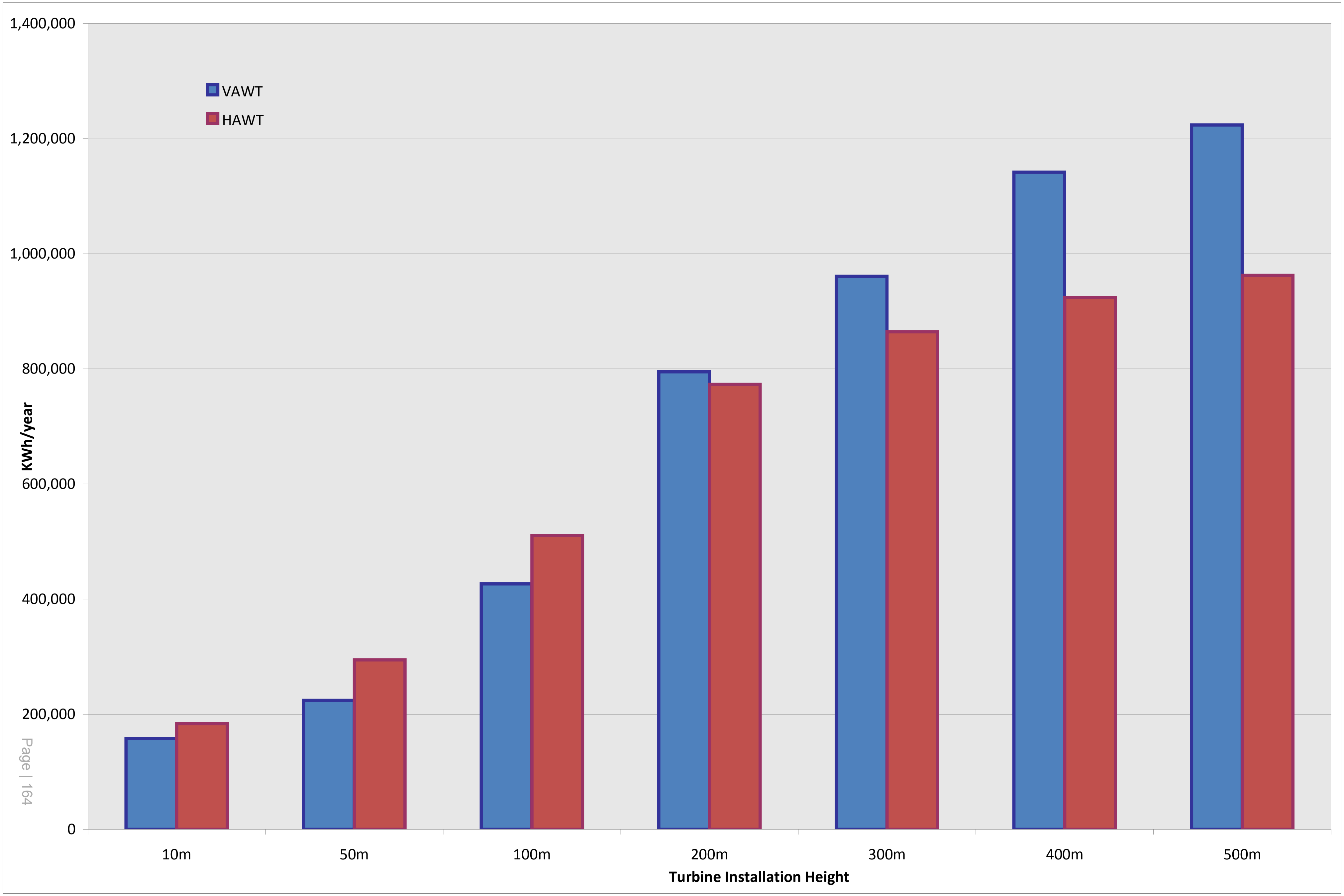

Camborne
KWh/year
200,000
150,000
100,000
50,000
0
Wind Speed
2.78
4.17
5.56
6.95
8.33
9.72
11.11
12.50
13.89
15.28
VAWT
HAWT

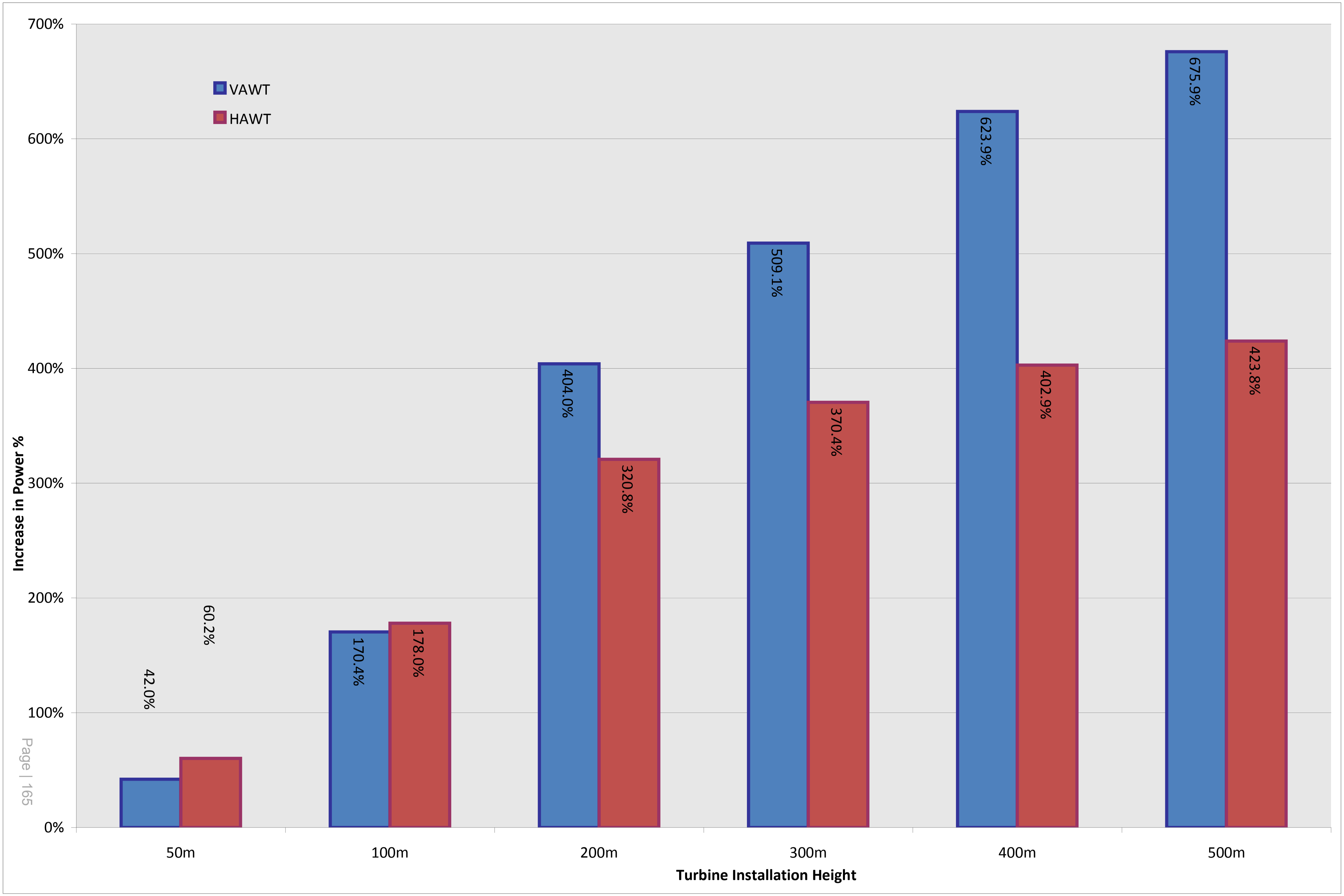

Cairo
KWh/year
60,000
50,000
40,000
30,000
20,000
10,000
0
Wind Speed
2.78
4.17
5.56
6.95
8.33
9.72
11.11
12.50
13.89
15.28
VAWT
HAWT


Hong Kong
KWh/year
100,000
80,000
60,000
40,000
20,000
0
Wind Speed
2.78
4.17
5.56
6.95
8.33
9.72
11.11
12.50
13.89
15.28
VAWT
HAWT

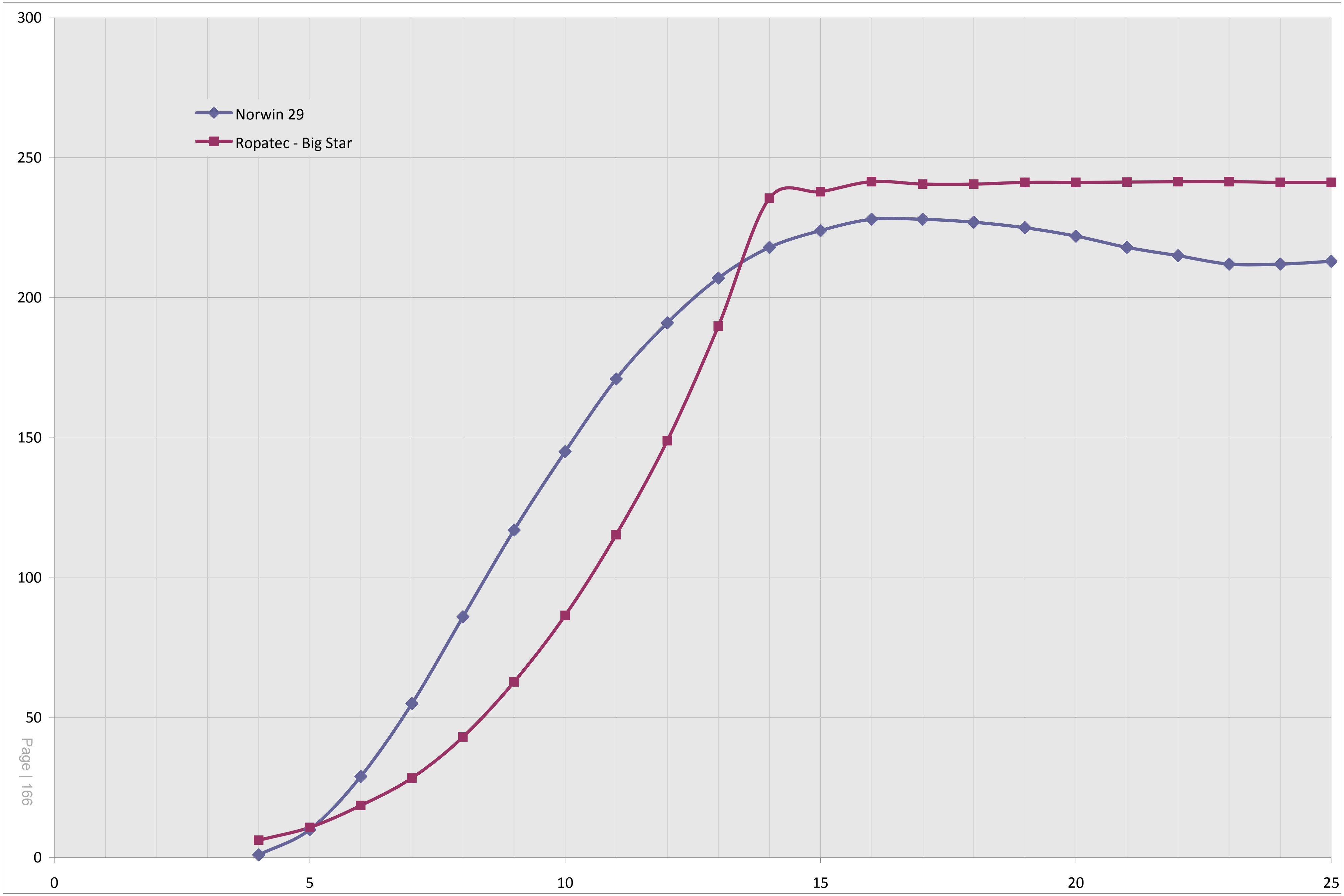

VAWT
HAWT
1,600,000
1,400,000
1,200,000
1,000,000
600,000
400,000
200,000
0
KWh/year
10m
50m
100m
200m
300m
400m
500m
Turbine Installation Height


VAWT
HAWT
Increase in Power %
400%
350%
300%
250%
200%
150%
100%
50%
0%
35.6%
58.2%
139.4%
168.5%
276.0%
282.5%
325.0%
320.2%
376.1%
346.7%
397.4%
362.8%
50m
100m
200m
300m
400m
500m
Turbine Installation Height


1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
KWh/year
VAWT
HAWT
10m
50m
100m
200m
300m
400m
500m
Turbine Installation Height



VAWT
HAWT
700%
600%
500%
400%
300%
200%
100%
0%
Increase in Power %
42.0%
60.2%
170.4%
178.0%
404.0%
320.8%
509.1%
370.4%
623.9%
402.9%
675.9%
423.8%
50m
100m
200m
300m
400m
500m
Turbine Installation Height


300
250
200
150
100
50
0
0
5
10
15
20
25
Norwin 29
Ropatec - Big Star

V(h)	22.13	Required wind velocity at height	m/s
V(met)	10	Wind velocity at station	m/s
H(met)	10	Measuring height	m
A(met)	0.22	Terrain factor for station	constant
D(met)	370	Boundary layer thickness at station	m
A	0.33	Terrain factor for required velocity	constant
D	460	Boundary layer thickness at required velocity	m
H	500	Height of required wind speed	m

(Dmet/Hmet)^Amet	Umet
2.32	10.00

H >= D	22.13
H < D	22.75

END OF DOCUMENT