POTENTIAL OF VERTICAL AXIS WIND TURBINES IN URBAN AREAS

Lappeenranta–Lahti University of Technology LUT

Master's degree in Energy Technology, Bio Energy System

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ABSTRACT

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Wind energy is one of the growing renewable energy sources. Usage is on the rise worldwide because of the cheap capital. It is used to produce electricity using the kinetic energy created by air in motion. A generator which is connected with a shaft produces electrical energy through electromagnetism. The trend of usage is also rising up in Finland. The amount of power which can be harvested increase each year. The scope of this thesis focused on determination of the potential of vertical axis wind turbine (VAWT) in urban area - turbulent flow area in which VAWT could be installed. Annual energy production of each VAWT was compared and evaluated for the effectiveness. Scope area was separated to urban area and neighbourhood area in a different hight level. QR6 turbine was found to be the most effective in VAWT. The capability of VAWT in the market would be increase further in the future due to the new technologies.

SYMBOLS AND ABBREVIATIONS

p	pressure	[bar], [Pa]
V	volume	[m^3]
A	area	[m^2]
R	radius	[m]
Ke	kinetic energy	[J]
U	velocity	[m/s]

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1 Introduction

Renewable is energy from natural resources which could be constantly replenished. It is naturally regenerated and derived directly and indirectly from the sun or from the environment. It does not include energy resources derived from fossil fuels, waste products from fossil sources or inorganic sources. Occasionally, renewable energy is called green energy due to minimize carbon footprint from the environment. [6]

Renewable energy sources can be classified into 6 types: wind energy, solar energy, hydro energy, bio energy, geothermal energy, and marine energy. The most global electricity generation comes from hydro energy and wind energy respectively. [2] Moreover, the sources quickly and effectively replenish themselves and can be used repeatedly. For this reason, renewable energies are sometimes termed as “infinity energy resources [6].

In 2017, the amount of electricity produced with renewable energy sources excluded biomass and waste in Finland is 19,611 GWh (29.043%) which the shared of each source shown in Fig.1. Hence, the trend of wind energy usage since 2014 has shown the growth of share of wind energy. [1][2]

The growth of wind energy usage demonstrates the booming wind energy industry in Finland.

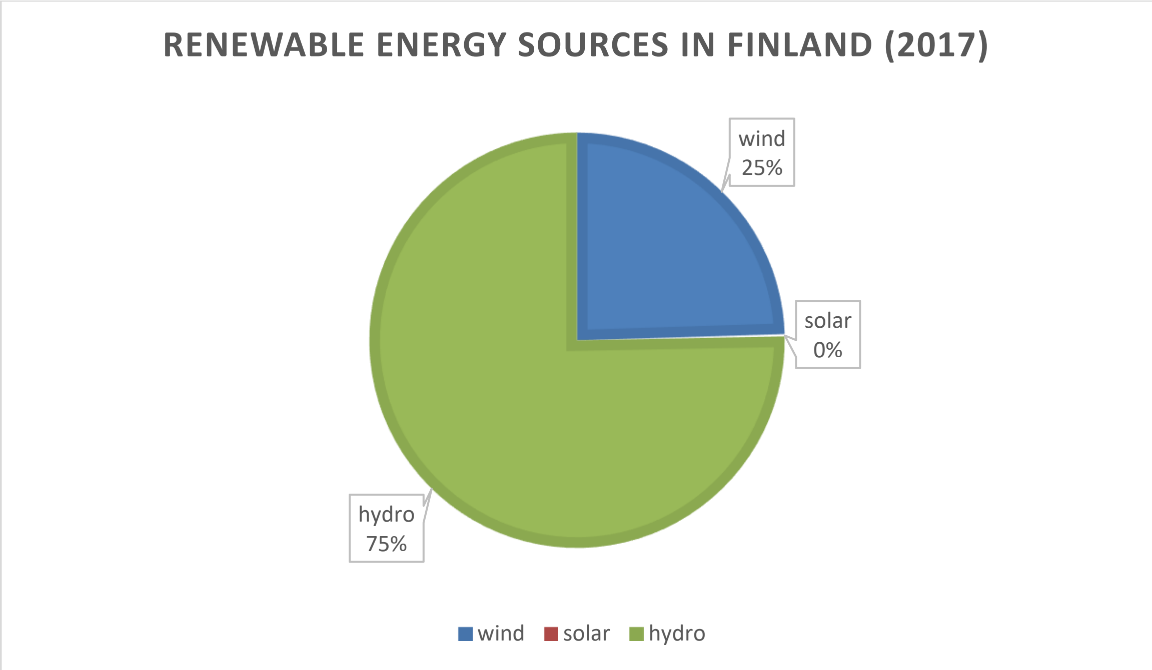

Figure 1. Electricity Production from renewable energy (excluded biomass and waste) 2017 [1]

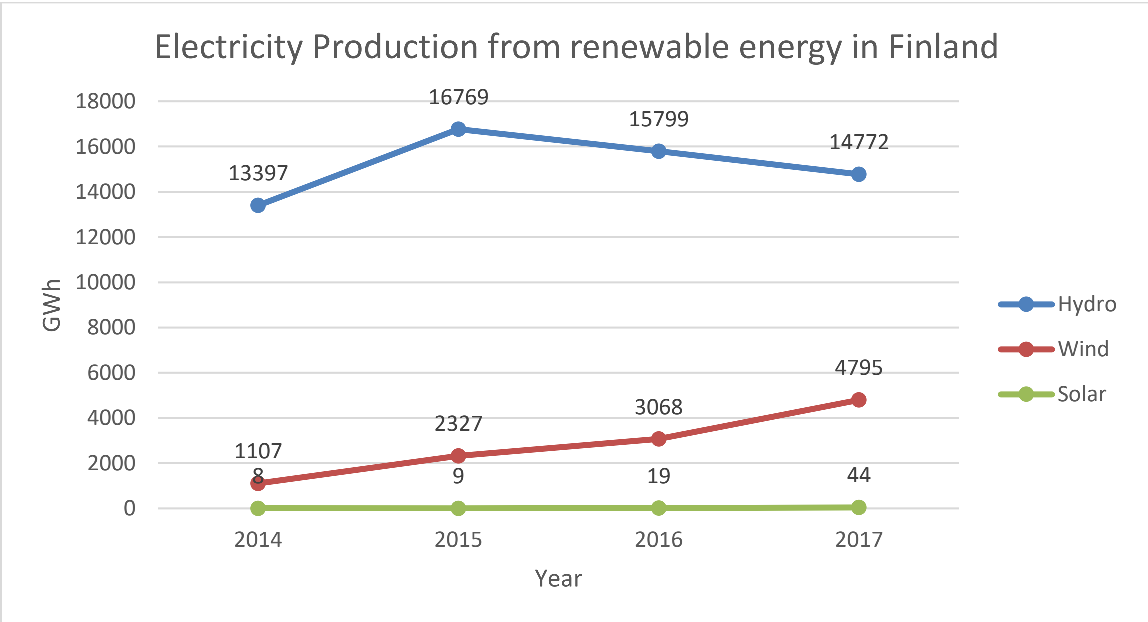

Figure 2. Electricity Production from renewable energy (excluded biomass and waste) from 2014 – 2017 [2]

A wind turbine is a machine which converts the power in the wind into electricity. There are 2 types based on the axis: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). HAWT is used in medium-large scale of power generation because of high performance. The small scale is defined as about 400 watts to 20 kilowatts which is the amount of energy used in resident area. Above 20 kilowatts become medium to large scale which for larger city or other purpose. Even though HAWT have many benefits, the performance is not suitable to be installed and used in urban area due to unstable direction and wind speed. For this reason, VAWT becomes an option to optimize the power generation in urban area instead.

Bhutta et al focus on the concepts leads towards the fact that VAWTs are suitable for electricity generation in the conditions which traditional HAWTs are unable to give efficient output.[10]

Tummala et al reviewed on small scale wind turbines. As large scale wind turbines alter the global climatic conditions and have adverse effects on the atmosphere, small scale wind turbines offer a great scope to produce valuable power which can be sufficient for domestic needs without altering the climatic conditions.[9]

As the wind is free and sustainable, the capital cost is mostly installation and maintenance. Mass production and technology make turbines cheaper. Moreover, people are more interested in Renewable Energy. VAWT are developed to be used in urban areas. The turbine which available in markets should be compared the performance in electrical generation.

1.1 Objectives

Due to the increasing in electricity consumption and demanding of reducing emission, using wind energy is the option used in this work. This work objective is focusing on finding the potential of vertical axis wind turbine in the urban area with various condition more than comparing vertical axis wind turbine with horizontal axis wind turbine.

1.2 Methodology

The idea of this research is to evaluate the power output of different Vertical axis wind turbine in a specific area. The models that chosen were QR6 from VWT power limited, WS-12 from OY Windside production Ltd. and WRE.007 from Ropatec S.p.a. The turbine will calculate in 2 different area which are City centre in Lappeenranta and Skinnarila area. The Skinnarila is an example of neighborhood area which most buildings are apartment buildings.

There are 3 different factors that calculated in the result which are annual production, capacity factor and the utilization time of maximum power. The annual power production is calculated from the power curve of each turbine and the wind speed in each location.

At the end, the comparison of each turbine will be concluded in the table to show the performance of each turbine in each location.

2 Theoretical Background

Wind energy is a renewable energy. It forms from solar energy which is available without any limits. Wind energy is a result of an air pressure difference which make the air move and create a kinetic energy. A wind turbine is a machine which converts the power in the wind into electricity.

2.1 Wind Power

The fundamental equation of wind power is used to define the energy in the wind. Wind power is the flux of wind energy through an area of interest. Th flow rate of the wind could be defined as:

$$\frac{dm}{dt} = \rho AU \qquad (1)$$

When ρ is air density A is an area of interest and U is a velocity.

The kinetic energy of a stream of air with mass m and moving with a velocity U could be express as:

$$KE = \frac{1}{2}mU^2 \qquad (2)$$

By substituting equation (1) into equation (2), the power of wind could be defined as:

$$P = \frac{1}{2}\rho A U^3 \quad (3)$$

This is the fundamental equation of Wind Power. This equation shows the dependency of wind speed to the wind power.[3]

The variation of the wind speed also depends on the terrain roughness. The roughness of the surface is different in each type of terrain. The approximate roughness value is shown in the Table 1.

Table 1. Values (approximate) of surface roughness length for various types of terrain [3]

Terrain description	**Z0 (mm)**
Very smooth, ice or mud 0.01	0.01
Calm open sea 0.20	0.2
Blown sea	0.5
Snow surface	3.00
Lawn grass	8.00
Rough pasture	10.00
Fallow field	30.00
Crops	50.00
Few trees	100.00
Many trees, hedges, few buildings	250.00
Forest and woodlands	500.00
Suburbs	1500.00
Centers of cities with tall buildings	3000.00

Logarithmic Profile (Log Law) is used to predict the logarithm of wind profile this analysis was given by Wortman (1982)[3]

$$U(z) = U_{Z_r} \frac{\ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_r}{Z_0}\right)} \quad (4)$$

When Zr is reference height, Uzr is average speed at reference height, Z0 is surface roughness which can be estimate from the Table 1

Wind profile also could be described in a power law. The power law represents a simple model for the vertical wind speed profile. Its basic form is

$$U(z) = U_{Z_r} \left(\frac{Z}{Z_r}\right)^{\alpha} \quad (5)$$

where U(z) is the wind speed at height z, Uzr is the reference wind speed at height zr, and α is the power law exponent.[3]

The estimate annual production at the chosen place could be calculate from the PDF (Probability Density Function) of Weibull distribution. It can be express as:

$$f = \frac{k}{A}\left(\frac{V}{A}\right)^{k-1} e^{-\left(\frac{V}{A}\right)^{k}} \quad (6)$$

When k is a Weibull shape factor, A is Weibull scale parameter and V is the wind velocity.

In the different height, the Weibull parameter A is affected by average wind speed in the area which could be define from the gamma function (Γ) as:

$$u = A\Gamma(1 + \frac{1}{k}) \quad (7)$$

When u is the average wind speed and k is Weibull constant [13]

The annual production could be estimated from using power curve of the turbine and the Weibull distributionn. The equation for annual production is

$$E_a = t_a \sum_{i=1}^{N} f(U_i) P_i \Delta U \quad (8)$$

When E_a is an annual energy production t_a is annual load hour which normally is 8760 hours f is Probability Density Function) of Weibull distribution and U is wind speed and P is power from turbine power curve.

Capacity factor

$$CF = \frac{E}{P_{nom} t} \quad (9)$$

2.2 Type of VAWT

Vertical axis wind turbine is the turbine that has axis alignment vertical to the ground. It could be divided into 2 types: Darrius wind turbine and Savonius wind turbine.

2.2.1 Darrius wind turbine

Darrieus wind turbine has been introduced in 1931 by G.J.M Darriues. This turbine is design based on lift force. It can extract more energy per swept area than Savonius turbine. The development in shape of blade could be describe from the figure 3.

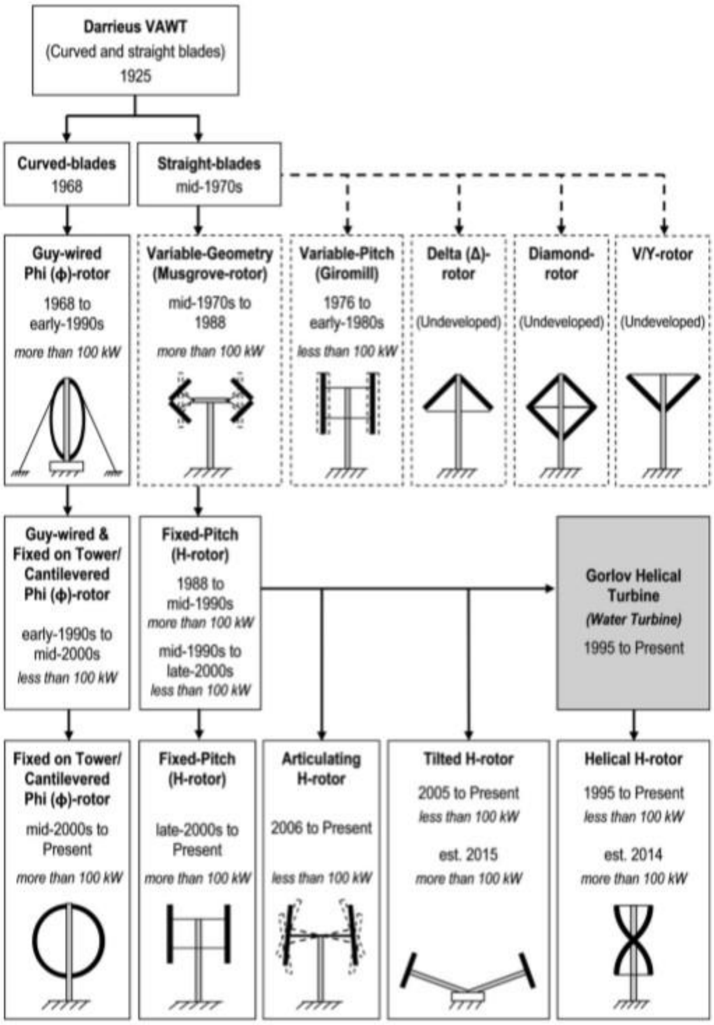

Figure 3. Timeline of darrieus VAWT development [7]

The development of Darrieus wind turbine can be separated in 2 ways. First, the development devided into curved blade and straight blade. Then, they focus is on the geometry of rotor which can be seen in figure 3. Finally, the modern turbine is based on the H-rotor type with a helical shape blade.

The design of darrieus VAWT could be in various variation depends on the number of the blades, the rotor shape or even the shape of the blade itself. The modern design of darrieus VAWT lean towards the capability of using on the rooftop or urban area.

The downside of this type of turbine are low starting torque and poor building integration. From this reason, it required an external force to start up the rotation. The development of this turbine would be modification in design of the shape of the blade and airfoils. [15]

2.2.2 Savonius wind turbine

Savonius wind turbine was invented by Finnish engineer, Savonius, in1920. Savonius rotor is a vertical axis wind that has S-shape cross section when looked from the above. The turbine design is based on drag force. The aerodynamic performance of this type of turbine is lower compared to other turbines.

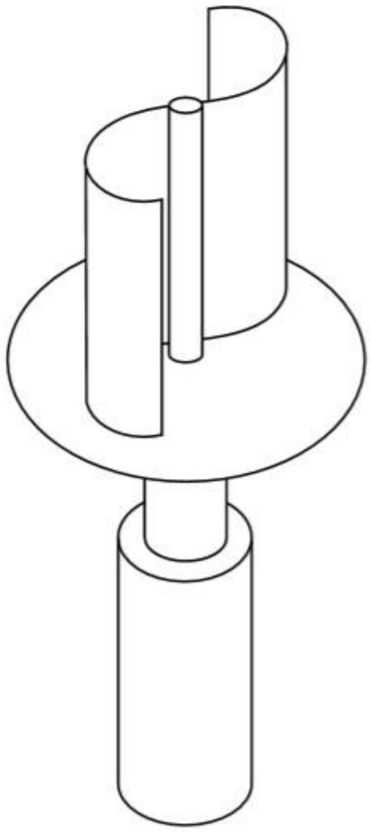

Figure 4. Savonius rotor (S. Kuntoff, reproduced under Creative Commons license) [3]

Even the performance of Savonius wind turbine cannot compete with other wind turbine, there are still advantages of it. The Savonius windturbine have a potential to be the more useful in urban area due to the operation at wind speed level associated with an urban environment. The ability to operate in multi-directional wind conditions because of its simple geometry. On top of that, it has a low cost of fabrication and production. Another benefit is that the turbine can operate noiselessly.

By the design, the generator is mounted on the ground to ease maintenance requirement both financially and technically. Last, the low required space makes it possible to install multiple turbines in the same area.

The unpopularity of the Savonius turbine is because of the low coefficient of power associated with the drag type wind converters. [16]

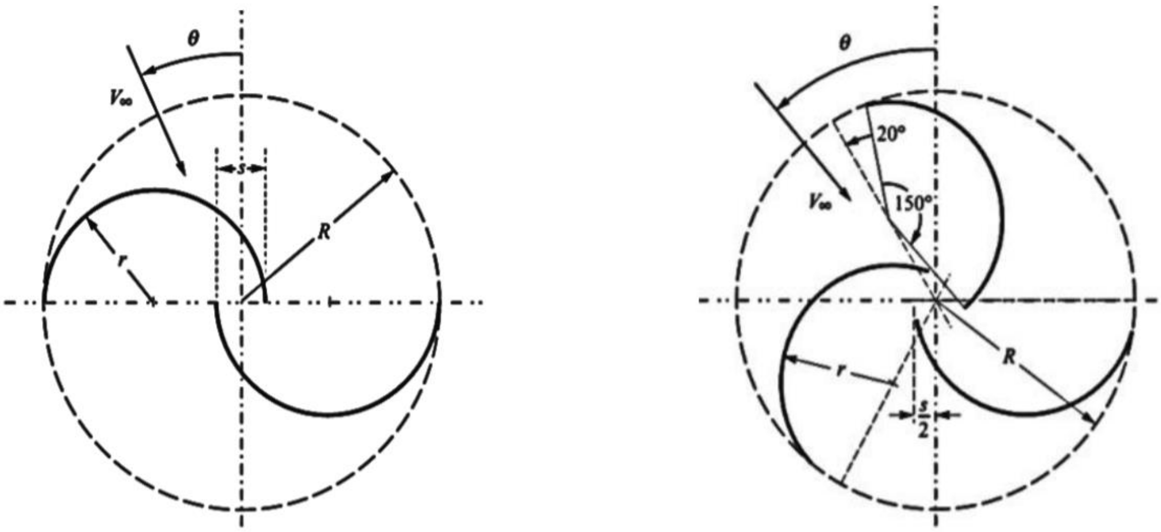

Figure 5. 2-blades (buckets) and 3-blades (buckets) Savonius turbine (Paraschivoiu, 2002)

According to research of Irunokhai[16] The improvement of the Savonius wind turbine efficiency still have more potential which is the improvement in design factor such as addition of stator vanes. Their goal is to improve the power coefficient of VAWT as much as possible. But in this thesis will focus on how the commercial Savonius wind turbine in the current market will perform in the study case environment.

2.2.3 Mixed type

In term of the design, it is possible to combine both types of VAWT to create a new one. The idea is to take advantage of both types. The advantage of savonius being high starting torque. The advantage of darrieus being more efficient. [17]

2.3 Operational limits

Wind turbine operated by wind current. Wind speed become an important parameter. To specified, the important speeds for wind turbine are cut-in speed, cut-out speed and the rated speed. All three of these can be determine from the power curve of the turbine. The cut-in speed is the speed which any turbine starts producing energy. The cut-out speed is the speed that wind turbine stops working due to the overwhelm wind speed. The rated speed is the speed which wind turbine work at the maximum to produce energy.

The specification number of the speed will determine from the power curve which acquired from the catalog of the turbine itself. Power curve is a graph represent the electrical power output of the turbine in different wind speeds.

3 Literature review

3.1 Weibull distribution

Weibull distribution is used to describe the long-term frequency distribution of the horizontal wind speed which make the calculation of the wind speed throughout the year easier. In order to observe the Weibull distribution, the main factor is the long-term data of the wind speed. The equation of Weibull distribution could be described in equation [6]. The idea is to use the statistical analysis on the wind frequency. This study told how the different between the land, coastal and marine site. The example location selected are Hamburg Høvsøre land and Høvsøre coastal.

Conclude that the Weibull distribution is accepted to describe the general frequency of wind speed in many sites, and it is a tool to estimate the potential of wind energy in the specific area. [18]

3.2 Efficiency improvement of Vertical axis wind turbine

As far as we know, the most benefit of VAWT is that they can operated in different wind direction. This also leads to the problem of having negative torque. In order to decrease the loss, installing guide vanes or stators is the simplest way to achieve. In this literature, the focus is to investigate the fluid flow around a three-bladed VAWT and the effect of an upstream deflector on the turbine efficiency.

The methodology is divided into two parts which are the simulation part and the real experiment part. First, the comparison between the starting rotor and the augmented rotor were done on CFD modelling on ANSYS then the experiment continued on testing their prototype wind turbine in the wind tunnel.

In conclusion of this experiment, the deflector has a positive impact on the turbine’s performance. [19]

3.3 Urban wind energy

There most important reason of generating energy in urban area is to utilize the area to distribute an electricity power generation. Due to the limitation of light and water resources, wind become reasonable option in urban area. Wind turbine can also make a profitability from the external surfaces of the buildings such as roof or walls. Installing wind turbine on the building can also cause issues which are noise emission, infrasound and vibration (can affect the building infrastructure), local birds’ environment and TV/radio signal reception.

The most common types of wind turbine are Vertical axis wind turbine and Horizontal axis wind turbine. Each of them has their own pros and cons. HAWT has a higher ceiling in generation but more restrict to the condition which are wind direction and speed. Mainly recommended on the open area. On the other hand, VAWT has a lower in generation comparing to VAWT. The advantages are functional in multi-wind direction, lower vibration, lower cost and more simplicity. The most important condition in urban area is multidirectional wind. This required an analysis on a wind velocity fields.[20]

3.4 Darrius wind turbine optimization

In highway area, the most important application is street lightning. Currently, solar energy is widely used to supply electricity to the lightning but a good quality of silicon to solar cell still at high price. Wind energy become a suitable alternative way because of the high wind movement from the high-speed car. In this research, Darrieus wind turbine model was chosen. Three steps in the research are observation of air velocity, create of wind turbine design, and wind turbine simulation. After getting all the parameters, the first variant of the simulation is using a twist angle of 0°and the second variant is 30°.[21]

As the results of CFD simulation, the second variant of twist angle 30° perform better than the first variant which is 0° twist angle. This conclude the apply twist angle to the turbine help the performance in power generation which could be investigated and include more variant in the future. [21]

3.5 Hybrid VAWT optimization

Most popular vertical axis wind turbine are Savonius and Darrieus turbine. However, each of them has their own advantage and disadvantage. Darrieus rotorhas a low starting torque which leads to self-starting problem. On the other hand, Savonius rotor has a low speed which make it less efficient in power generation. The idea is to make a hybrid Savonius-Darrieus turbine to overcome those disadvantages.

In this research, the process is started with T. Letcher hybrid Savonius-Darrieus wind turbines. Their result was concluded that these hybrid rotors can operate at low wind speeds and perform better than HAWT.

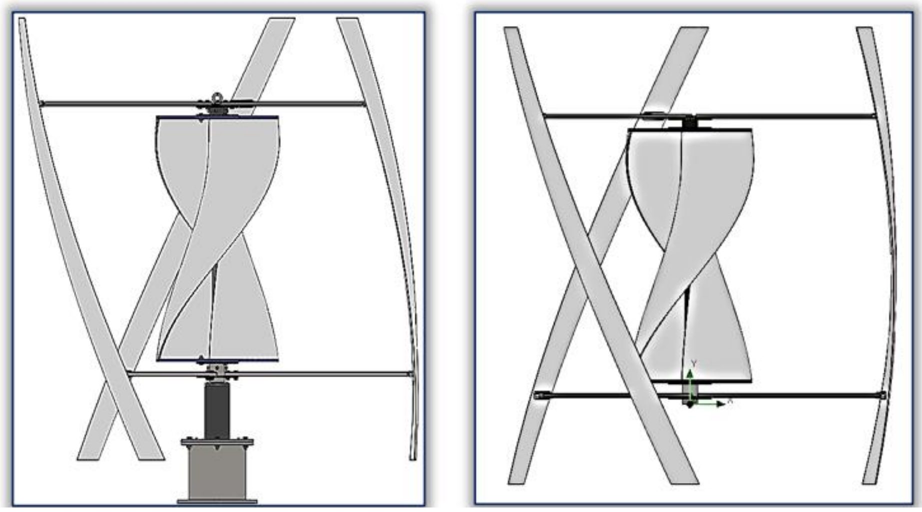

Figure 6 First design [21]

To improve the design, first removing the shaft from the inside of Savonius rotor then remove the Savonius rotor from inside of the Darrieus one and place it outside the rotor.

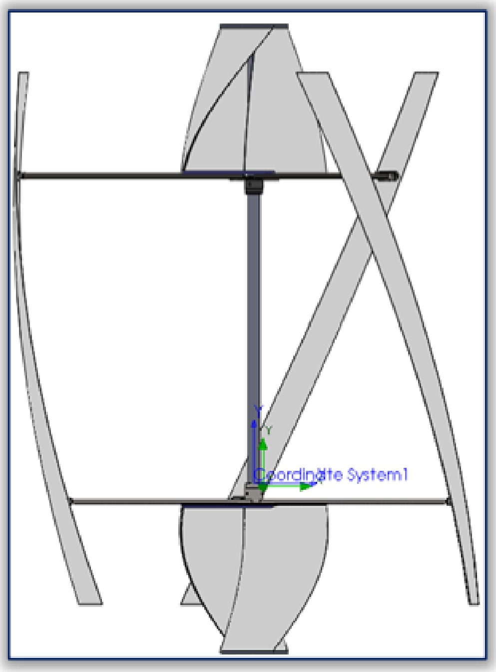

Figure 7. Modified design [21]

After doing the computaiotnal fluid analysis (CFD), the result confirm that the improved design has a better torque. The result torque from the first step has increase for 10.5% and the second step increase torque for another 11.8%. By comparing the last result to the initial model, torque has been increased for 22.3%. [21]

4 CHAPTER 2. Methodology

4.1 Data Source

In this research, 3 different wind turbines have been chosen QR6 VWT Power Ltd., WS-12 OY Windside Production Ltd. and WRE.007 Ropatec S.p.a. These 3 turbines are available in the market.

Technical information of each turbine is available in the following tables.

4.1.1 QR6 wind turbines VWT Power Ltd.

Figure 8. QR6 turbine model

Table 2. Qr6 Turbine dimensional information

Infomation		unit
Rotor height	5.1	m
Rotor diameter	3.1	m
Swept area	16	m^2
Rated power	8	kw
Rated wind speed	20	m/s
Cut-in	2	m/s
Cut-out	none	m/s

Having a helical rotor design shape, the swept area is 16 m^2 which is higher than the other turbine in our study. The dimension is roughly the same as another turbine which mentioned below.

4.1.2 WS-12 OY Windside Production Ltd.

Figure 8. WS-12 turbine model

Table 3. WS-12 Turbine Dimensional information

Information		unit
Rotor height	6	m
Rotor diameter	2	m
Swept area	12	m^2
Rated power	7	kw
Rated wind speed	20	m/s
cutin	1.5	m/s
Cut out	20	m/s

This turbine has the most comparable size to the QR6 which has 12 m^2 swept area with 6m in height and 2m diameter

4.1.3 WRE.007 Ropatec S.p.a.

Figure 9 WRE.007 turbine model

Table 4. WRE.007 Turbine dimensional information

Dimemsion		unit
Rotor height	1.5	m
Rotor diameter	1.5	m
Swept area	2.25	m^2
Rated power	0.75	kw
Rated wind speed	14	m/s
cutin	2	m/s
Cut out	none	m/s

This turbine has a smallest in size but with the lower rated wind speed. There is a potential of this turbine to do better in a certain condition.

4.2 Power curve

Power curve is the graph that show the amount of electricity output at different wind speed. The power curve of QR6 VWT Power Ltd., WS-12 OY Windside Production Ltd. and WRE.007 Ropatec S.p.a. are shown in the figure 11 12 13 respectively.

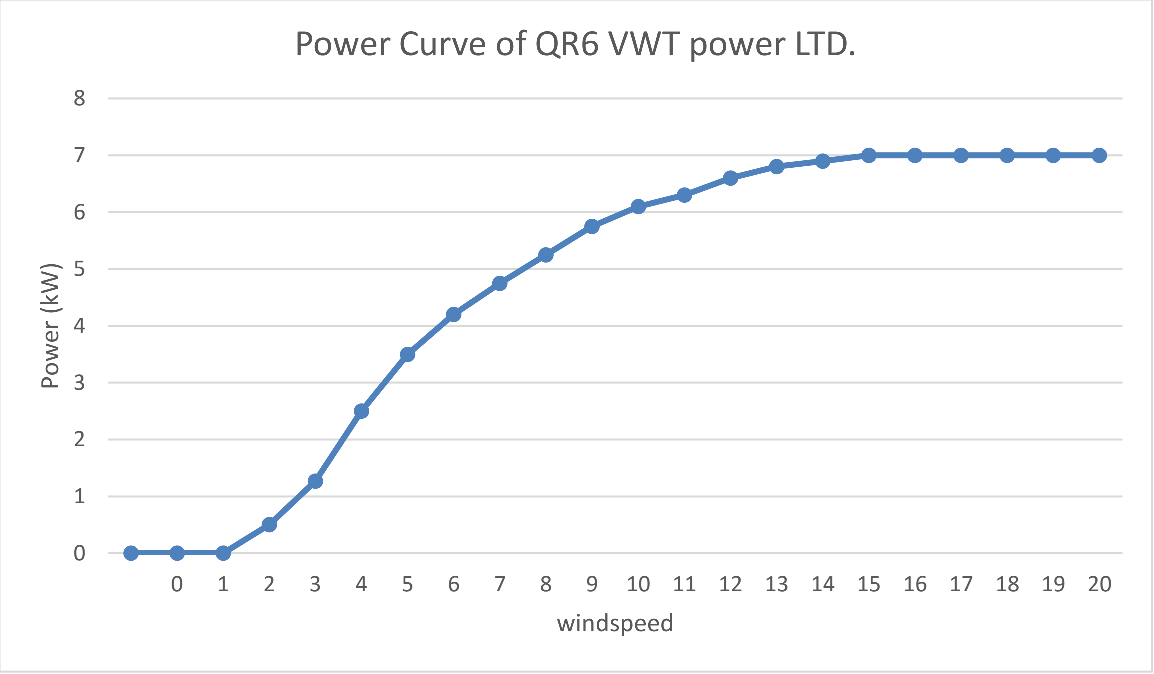

Figure 10. Power curve of QR6 [14]

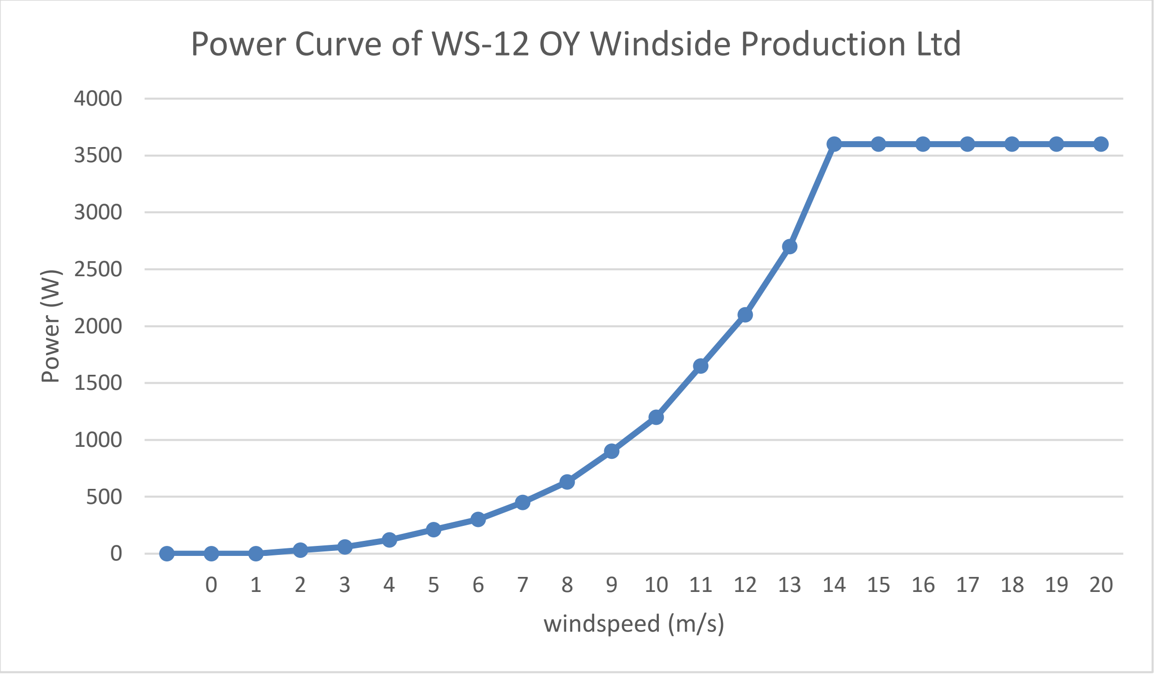

Figure 11. WS-12 Windside power curve [11]

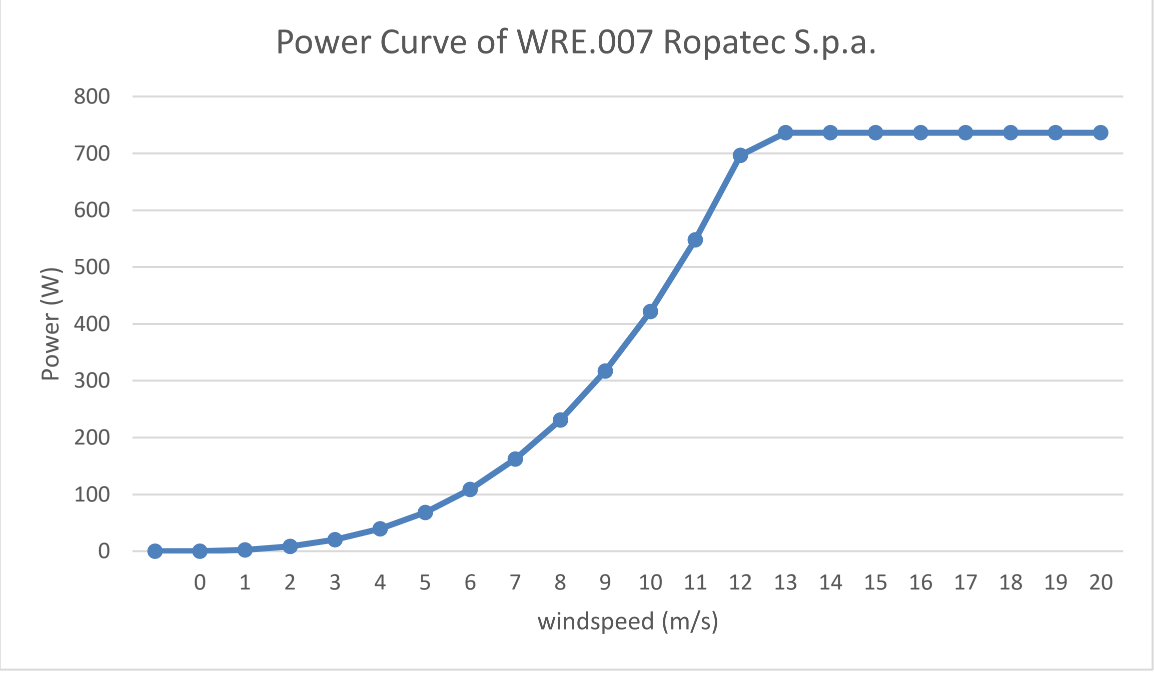

Figure 12. WRE.007 Ropatec S.p.a power curve [11]

From the reference turbine, they all have a different in nominal power which could be hard to compare in term of energy production. In order to compare them, we multiply the power curve to get nominal power of 7kW. However, this approximation will slightly underestimate the performance of the turbine.

4.3 Finnish wind atlas

Finnish wind atlas is a tool that used in the estimation of potential of wind energy in Finland. The Wind atlas provide average win speed (m/s) in each month and year. It also provides a potential of power production of turbine from 50mter to 400 meter above the sea level. The information is given in 2.5 km by 2.5 km and could be downscaling to 250 m by 250 m. The average wind speed could be roughly described from the color on the shown in the figure 8

Figure 13.Wind atlas in 250 meter scale

4.4 Calculation

From wind atlas, we can obtain the Weibull distribution value k and A but only at 50 meters height. In this research, we assume the installation height to be lower than 50 meters so in the city center area we choose40 and 30 meter and in the Skinnarila area (neighborhood area), 20 meter and 30 meters was chosen. We can calculate the average wind speed from equation (4) which describe in the chapter 2. After that we can calculate the Weibull parameter A from the average windspeed by equation (7). We assume the at below 50 meter height the Weibull k is not much difference so we will used k at 50 meters height. The Weibull power density function gives an estimate of the annual electricity production at the selected altitude. The annual electricity production, the utilization time of maximum power and the capacity factor calculated from equation 6 by using excel spreadsheet program. The fact that each turbine has a different power curve, in order to compared each of them it need some adjustment. The power curve of each turbine will be converted to maximum of 7 kw which make them equally compared. The building in Skinnarila area have around 3-6 floors, which can converted into average of 20 meters height.

5 CHAPTER 4 – STUDY CASE

5.1 Analysis of the Data

Two different location have been selected. First is in the city center and the second is Skinnarila area.

Skinarila is an area that is a neighborhood area which close to the university. Most building is this area is a living apartment which have an average height around 20 meters. The height is calculated from the resident building height from Emporis. Most of the student from Lappeenranta University of Technology is living here.

City center of Lappeenranta does not have various in term of building height. In this research, the chosen height are 30 meters and 40 meters. This also come from the range of building height in Emporis.

The result of the energy production of each turbine will be shown in graph below.

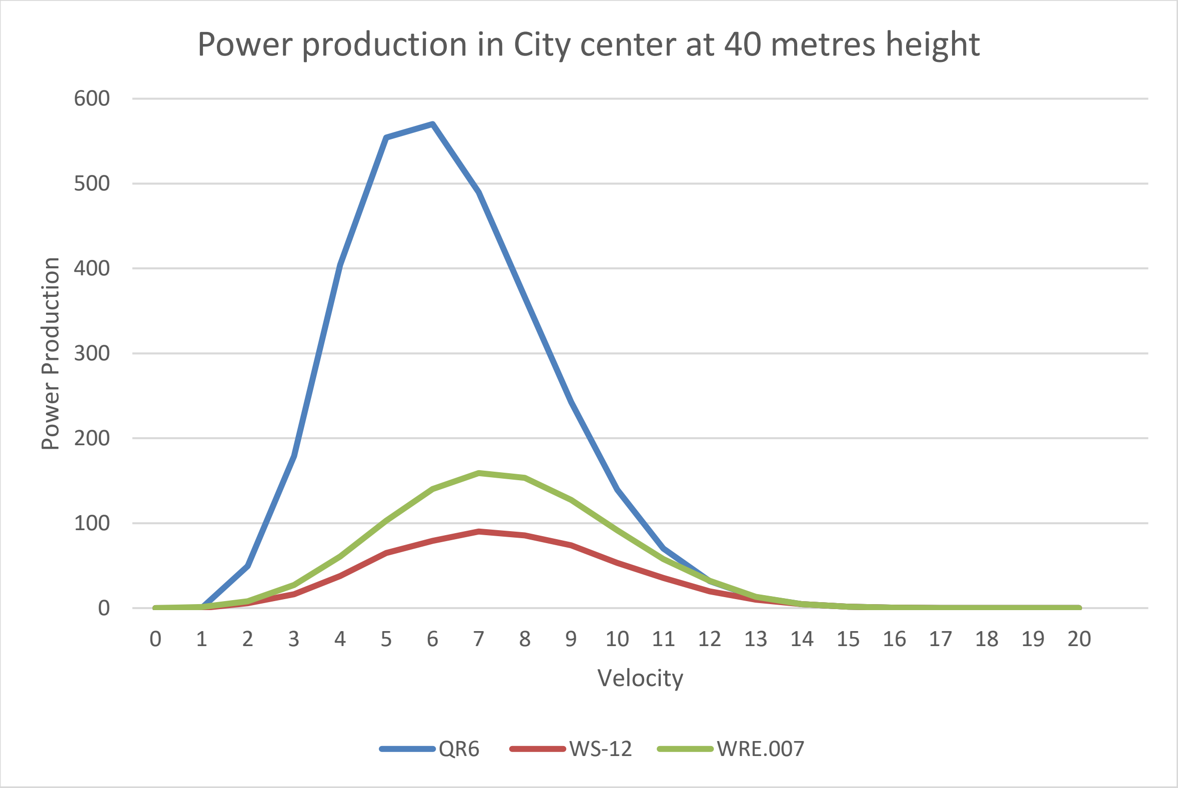

Figure 14. Power production in City centre at 40 metres height

The maximum energy produced from the QR6 turbine is around 5-6 m/s. On the other hand, both WS-12 and WRE.007 have a rated speed around 6-7 m/s. not only that the cut in speed of qr6 6 is lower which mean the range of the wind speed that it can produce is much larger.

The result of the energy production of QR6 turbine in the city center at 30 metre height is shown in the table 2 but for ws12 and wre007 will be shown in appendix B3 and B4

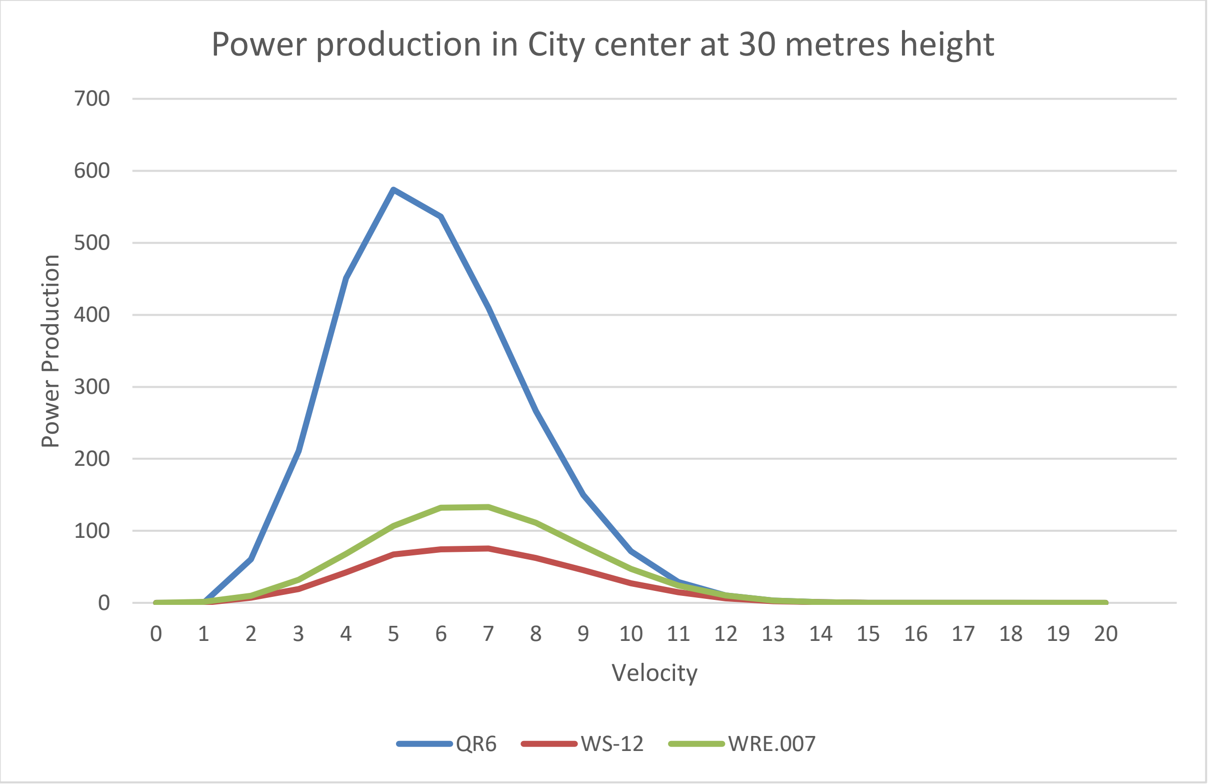

Figure 15. Power production in City centre at 30 metres height

The maximum energy production of each turbine similar to 40 meter height but the wind speed is lower which make it more benefit the QR6 which has a lower rated speed around 5-6 meters

The result of the energy production of QR6 turbine in the Skinnarila at 20 metre height is shown in the table 2 but for ws12 and wre007 will be shown in appendix B5 and B6

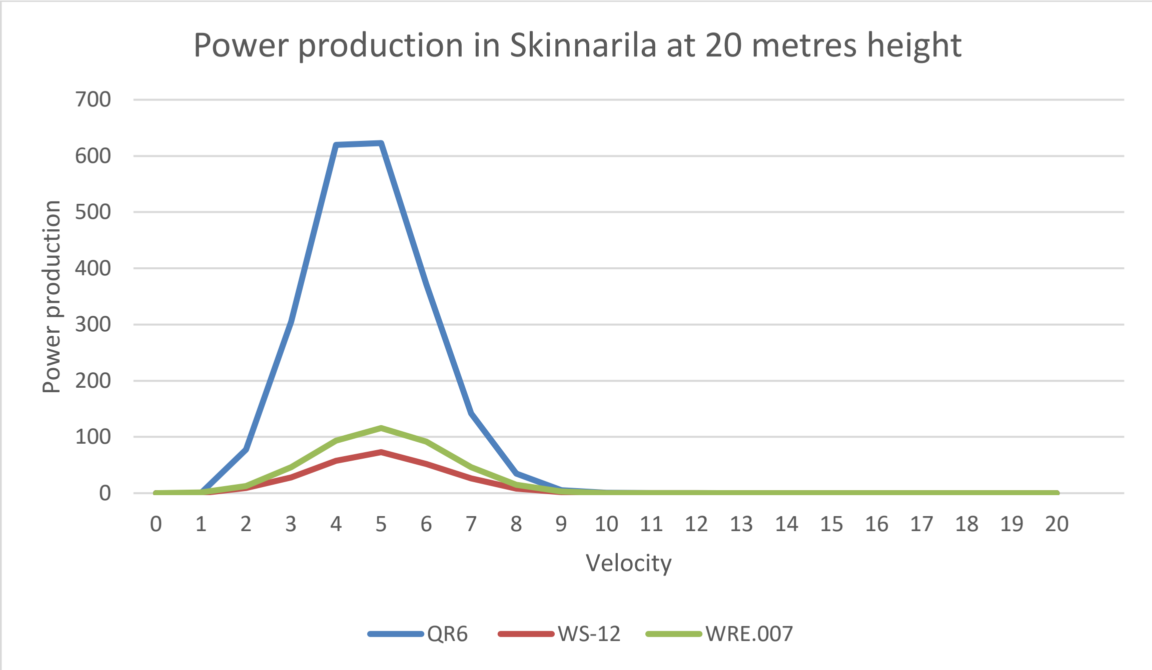

Figure 16. Power production in Skinnarila at 20 metres height

In the Skinnarila area, the wind speed is lower and the build is not as tall as in the city center. The maximum power production wind speed of all 3 turbines is around 4-5 meters but QR6 model have a higher maximum power output

The result of the energy production of QR6 turbine in the Skinnarila at 30 metre height is shown in the table 2 but for ws12 and wre007 will be shown in appendix B7 and B8

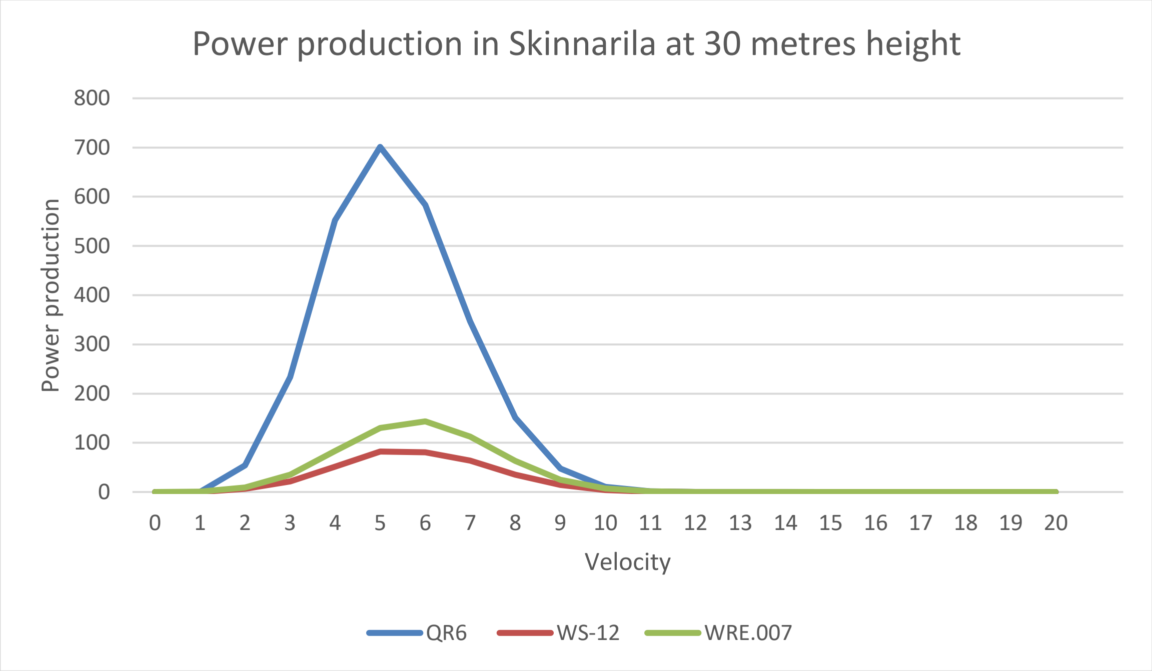

Figure 17. Power production in Skinnarila at 30 metres height

Similar to previous graph, the maximum power production wind speed of all 3 turbines is around 5-6 meters/s

5.2 Results of Study Case

The result of calculation for each turbine is shown in the following table which are the annual electricity production the capacity factor and the utilization time of maximum power.

Table 5. Annual electricity production of each turbine in different area.

Location	**Annual electricity production (kWh)**		
	QR6	WS-12	WRE.007
City center at 40 m. height	27302.5	5071.7	8599.2
City center at 30 m. height	24297.6	3903.9	6646.8
Skinnarila at 20m. height	19099.6	2240.8	3722.6
Skinnarila at 30m. height	23489.6	3162.6	5355.6

This table show the annual electricity production from the calculation in formula 8. The annual electricity product of QR6 is higher in every scenario with a maximum of 27302 kWh at city center 40 m. height. And the lowest generation is from WS-12 with 2240.8 kWh at Skinarila area 20m. height. QR6 has a wider range in power curve which leads to more power generation.

Table 6. Capacity factor of each turbine in different area.

Location	Capacity factor		
	QR6	WS-12	WRE.007
City center at 40 m. height	0.445	0.0827	0.140
City center at 30 m. height	0.396	0.0636	0.108
Skinnarila at 20m. height	0.311	0.0365	0.0607
Skinnarila at 30m. height	0.383	0.0515	0.0873

This table show the capacity factor of each turbine from the calculation in formula 9.The capacity factorof QR6 is higher in every scenario. The highest capacity is 0.445 at city center 40 m. height and the lowest is 0.311 at Skinnatila 20m. height. By looking at the formula, the capacity factor will be varied on the amount of power generation since the assumption is comparing them at the same power rating of 7 kW.

Table 7. The utilization time of maximum power of each turbine at each height

Location	The utilization time of maximum power (Hours)		
	QR6	WS-12	WRE.007
City center at 40 m. height	3900.36	724.53	1228.46
City center at 30 m. height	3471.09	557.70	949.54
Skinnarila at 20m. height	2728.52	320.12	531.81
Skinnarila at 30m. height	3355.67	451.81	765.09

This table show the utilization time of maximum power of each turbine from the calculation in formula 9. The utilization time of QR6 is higher in every scenario. The highest times is 3900 hours which equal to 162 days.

5.3 Summarized Results

According to the result, annual production of each wind turbine was different in each area, height level and average wind speed. The wind density in Lappeenranta mostly around 3-5 m/s. This mean that the turbine which has the highest power output during those range will perform the best. The most effective capacity is QR6. It could produce almost more than 20,000 kWh annually. On the other hand, WS-12 Windside and WRE.007 Ropatec S.p.a could produce much lower electricity which shown in the table 14. At 40 meters height in the city center, every turbine could produce electricity the most.

The Capacity Factor of QR6 is around 0.4 at every height and location. For the WS-12 the result is vary depending on the location and height which is highest at 0.082 in the city center at 40 m. height. Similar to WRE.007 which has highest at 0.14 in city center at 40m. height. The main reason being the shape of the QR6 turbine being three bladed helical design. QR6 shows that modern turbine model has improve in energy extraction.

The utilization time of the maximum power of each turbine could be calculated and shown as the following number. QR6 in the city center at 40 m. height has utilization time of 3900 hours which is the highest number and equal to almost half of the year. Unfortunately, WS-12 has only 724 hours and WRE.007 also only has 1228 hours.

In general, QR6 model perform better in all ways than the others. The reason for that is the design of the turbine is Darrieus type which based on the lift forced. This makes the power extraction and the overall efficiency higher. On top of that, the model of QR6 has a bigger swept area which is 16 square-metre. It has about 33% higher than WS-12 which have almost the same rated power. The comparison between QR6 and WRE.007 in term of size is more complicated due to the big different in original rated power.

6 CONCLUSIONS

6.1 Conclusions and discussion

The potential of the VAWT in urban area could be determine from different perspective. In this research, point that considering are the annual production, the capacity factor and the utilization time of the chosen VAWT. The product that chosen in the research was 1 Darrius Turbine and 2 Savonius Turbine. Darius wind turbine like QR6 has more potential in term of energy production. It performs well in different height and location. Even with the commercial Savonius wind turbine still perform worse than the Darius wind turbine. But this conclusion still not considering the cost and complication of production. This mean that if the Savonius wind turbine have a better efficiency it might be able to compete more in the market. It also has a steady power output which easier to used with electricity grid. In my perspective, VAWT have a lot of potential in the future when the new development lowers the disadvantage in power coefficient and power generation.

In the other hand, if considering the size of the turbine the dimension of rotor of WRE is 1.5 m in height and 1.5 m. in diameter. WS-12 has 2m. diameter with 6m. height. Last, QR6 is 5.1m. height and 3.1 diameter. This mean that the practical use of WS-12 and WRE/007 might be more suitable for the city depend on the location of installation. In term of physical size, all of these vertical axis wind turbines have a smaller size compared to the horizontal axis wind turbine in the market which open an opportunity to install multiple wind turbines in the same location or close to it.

6.2 Recommendations for Future Work

The suggestions for future work:

- The location of the installation should be more specific in order to estimate the installation height precisely.
- To evaluate the potential of VAWT, not only the energy production should be considered. The cost and others parameter should be considered also.
- Experiment with different turbine models.

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APPENDIX A. Power curve

A.1 QR6 VWT Power Ltd.

Velocity	Power (kW)
0	0
1	0
2	0.5
3	1.27
4	2.5
5	3.5
6	4.2
7	4.75
8	5.25
9	5.75
10	6.1
11	6.3
12	6.6
13	6.8
14	6.9
15	7
16	7
17	7
18	7

19	7
20	7

A.2 WS-12 OY Windside Production Ltd.

Velocity	Power(W)
0	0
1	0
2	30
3	60
4	120
5	211
6	300
7	450
8	630
9	900
10	1200
11	1650
12	2100
13	2700
14	3600
15	3600
16	3600
17	3600
18	3600
19	3600
20	3600

A.3 WRE.007 Ropatec S.p.a

Velocity	Power (W)
0	0.32
1	2.54
`2	8.56
3	20.28
4	39.62
5	68.46
6	108.71
7	162.28
8	231.05
9	316.94
10	421.85
11	547.68
12	696.33
13	736.27
14	736.27
15	736.27
16	736.27
17	736.27
18	736.27
19	736.27

20	736.27

APPENDIX B. Result of Savonius wind turbine

B.1 WS-12 OY Windside Production Ltd. in city center at 40 meters height

Velocity	Weibull function (f)	Power (P)	Multiplied power curved	fPV	Percentage of wind distribution
0	0	0	0	0	0
1	0.045388	0	0	0	5.221993
2	0.098734	30	58.3333333	5.759491	15.49591
3	0.140949	60	116.666666	16.44406	24.04019
4	0.161696	120	233.333333	37.72903	24.81231
5	0.158356	211	410.277777	64.97013	17.80863
6	0.135748	300	583.333333	79.1866	8.857252
7	0.103087	450	875	90.20095	2.99147
8	0.069776	630	1225	85.47617	0.667719
9	0.042231	900	1750	73.9042	0.095564
10	0.022889	1200	2333.33333	53.40859	0.008497

11	0.011116	1650	3208.33333	35.66521	0.000454
12	0.004837	2100	4083.33333	19.75282	1.42E-05
13	0.001885	2700	5250	9.898509	2.49E-07
14	0.000658	3600	7000	4.604445	2.39E-09
15	0.000205	3600	7000	1.436736	1.22E-11
16	5.72E-05	3600	7000	0.400611	3.17E-14
17	1.42E-05	3600	7000	0.099725	4.13E-17
18	3.16E-06	3600	7000	0.022141	2.59E-20
19	6.26E-07	3600	7000	0.00438	7.61E-24
20	1.1E-07	3600	7000	0.000771	1.02E-27
	0.997633			578.9646	100

B.2 WRE.007 Ropatec S.p.a in city center at 40 meters height

Velocity	Weibull function (f)	Power (P)	Multiplied power curved	fPV	Percentage of wind distribution
0	0	0.32	3.042362	0	0
1	0.045388	2.54	24.14875	1.096063	5.221993
2	0.098734	8.56	81.38319	8.035299	15.49591
3	0.140949	20.28	192.8097	27.17635	24.04019
4	0.161696	39.62	376.6825	60.90799	24.81231
5	0.158356	68.46	650.8754	103.0703	17.80863
6	0.135748	108.71	1033.547	140.3025	8.857252
7	0.103087	162.28	1542.858	159.0483	2.99147
8	0.069776	231.05	2196.681	153.2766	0.667719
9	0.042231	316.94	3013.27	127.2533	0.095564
10	0.022889	421.85	4010.689	91.80225	0.008497

11	0.011116	547.68	5207.003	57.88328	0.000454
12	0.004837	696.33	6620.275	32.02509	1.42E-05
13	0.001885	736.27	7000	13.19801	2.49E-07
14	0.000658	736.27	7000	4.604445	2.39E-09
15	0.000205	736.27	7000	1.436736	1.22E-11
16	5.72E-05	736.27	7000	0.400611	3.17E-14
17	1.42E-05	736.27	7000	0.099725	4.13E-17
18	3.16E-06	736.27	7000	0.022141	2.59E-20
19	6.26E-07	736.27	7000	0.00438	7.61E-24
20	1.1E-07	736.27	7000	0.000771	1.02E-27
	0.997633			981.6441	100

B.3 QR6 in city center at 40 meters height

Velocity	**Weibull function (f)**	**Power (P)**	**fPV**	**Percentage of wind distribution**
0	0	0	0	0
1	0.045388	0	0	5.221993
2	0.098734	500	49.36707	15.49591
3	0.140949	1270	179.0053	24.04019
4	0.161696	2500	404.2396	24.81231
5	0.158356	3500	554.2476	17.80863
6	0.135748	4200	570.1435	8.857252
7	0.103087	4750	489.6623	2.99147
8	0.069776	5250	366.3264	0.667719
9	0.042231	5750	242.8281	0.095564
10	0.022889	6100	139.6253	0.008497

11	0.011116	6300	70.0335	0.000454
12	0.004837	6600	31.92701	1.42E-05
13	0.001885	6800	12.82093	2.49E-07
14	0.000658	6900	4.538667	2.39E-09
15	0.000205	7000	1.436736	1.22E-11
16	5.72E-05	7000	0.400611	3.17E-14
17	1.42E-05	7000	0.099725	4.13E-17
18	3.16E-06	7000	0.022141	2.59E-20
19	6.26E-07	7000	0.00438	7.61E-24
20	1.1E-07	7000	0.000771	1.02E-27
	0.997633		3116.73	100

B.4 WS-12 OY Windside Production Ltd. in city center at 30 meters height

Velocity	Weibull function (f)	Power (P)	Multiplied power curved	fPV	Percentage of wind distribution
0	0	0	0	0	0
1	0.056562	0	0	0	5.673054
2	0.120677	30	58.3333333	7.039514	12.10364
3	0.166135	60	116.666666	19.38245	16.66296
4	0.180413	120	233.333333	42.0963	18.09495
5	0.163959	211	410.277777	67.26893	16.44473
6	0.127723	300	583.333333	74.50526	12.81033
7	0.086234	450	875	75.45499	8.649084
8	0.050733	630	1225	62.14754	5.088362
9	0.026071	900	1750	45.62471	2.614883

10	0.011713	1200	2333.33333	27.33145	1.174833
11	0.004601	1650	3208.33333	14.76137	0.461464
12	0.001579	2100	4083.33333	6.447809	0.158375
13	0.000473	2700	5250	2.483713	0.04745
14	0.000124	3600	7000	0.865159	0.012396
15	2.81E-05	3600	7000	0.196845	0.00282
16	5.56E-06	3600	7000	0.038954	0.000558
17	9.57E-07	3600	7000	0.006696	9.59E-05
18	1.43E-07	7000	7000	0.000998	1.43E-05
19	1.84E-08	7000	7000	0.000129	1.85E-06
20	2.06E-09	7000	7000	1.44E-05	2.06E-07
	0.997034			445.6528	100

B.5 WRE.007 Ropatec S.p.a in city center at 30 meters height

Velocity	Weibull function (f)	Power (P)	Multiplied power curved	fPV	Percentage of wind distribution
0	0	0.32	3.042362	0	0
1	0.056562	2.54	24.14875	1.365908	5.673054
2	0.120677	8.56	81.38319	9.821111	12.10364
3	0.166135	20.28	192.8097	32.0325	16.66296
4	0.180413	39.62	376.6825	67.9583	18.09495
5	0.163959	68.46	650.8754	106.7172	16.44473
6	0.127723	108.71	1033.547	132.0081	12.81033
7	0.086234	162.28	1542.858	133.0472	8.649084
8	0.050733	231.05	2196.681	111.4435	5.088362
9	0.026071	316.94	3013.27	78.55974	2.614883
10	0.011713	421.85	4010.689	46.97912	1.174833

11	0.004601	547.68	5207.003	23.95714	0.461464
12	0.001579	696.33	6620.275	10.45378	0.158375
13	0.000473	736.27	7000	3.311617	0.04745
14	0.000124	736.27	7000	0.865159	0.012396
15	2.81E-05	736.27	7000	0.196845	0.00282
16	5.56E-06	736.27	7000	0.038954	0.000558
17	9.57E-07	736.27	7000	0.006696	9.59E-05
18	1.43E-07	736.27	7000	0.000998	1.43E-05
19	1.84E-08	736.27	7000	0.000129	1.85E-06
20	2.06E-09	736.27	7000	1.44E-05	2.06E-07
	0.997034			758.764	100

B.6 B.3 QR6 in city center at 30 meters height

Velocity	Weibull function (f)	Power (P)	fPV	Percentage of wind distribution
0	0	0	0	0
1	0.056562	0	0	5.673054
2	0.120677	500	60.3387	12.10364
3	0.166135	1270	210.9918	16.66296
4	0.180413	2500	451.0317	18.09495
5	0.163959	3500	573.8582	16.44473
6	0.127723	4200	536.4378	12.81033
7	0.086234	4750	409.6128	8.649084
8	0.050733	5250	266.3466	5.088362
9	0.026071	5750	149.9098	2.614883
10	0.011713	6100	71.45221	1.174833
11	0.004601	6300	28.98597	0.461464

12	0.001579	6600	10.42176	0.158375
13	0.000473	6800	3.216999	0.04745
14	0.000124	6900	0.852799	0.012396
15	2.81E-05	7000	0.196845	0.00282
16	5.56E-06	7000	0.038954	0.000558
17	9.57E-07	7000	0.006696	9.59E-05
18	1.43E-07	7000	0.000998	1.43E-05
19	1.84E-08	7000	0.000129	1.85E-06
20	2.06E-09	7000	1.44E-05	2.06E-07
	0.997034		2773.701	100

B.7 WS-12 OY Windside Production Ltd. in Skinnarila at 20 meters height

Velocity	Weibull function (f)	Power (P)	Multiplied power curved	fPV	Percentage of wind distribution
0	0	0	0	0	0
1	0.052189	0	0	0	5.221993
2	0.154869	30	58.3333333	9.033997	15.49591
3	0.240261	60	116.666666	28.03048	24.04019
4	0.247978	120	233.333333	57.86155	24.81231
5	0.177982	211	410.277777	73.02211	17.80863
6	0.088521	300	583.333333	51.63709	8.857252
7	0.029897	450	875	26.16005	2.99147
8	0.006673	630	1225	8.174773	0.667719
9	0.000955	900	1750	1.671389	0.095564
10	8.49E-05	1200	2333.33333	0.198144	0.008497

11	4.54E-06	1650	3208.33333	0.014573	0.000454
12	1.42E-07	2100	4083.33333	0.000578	1.42E-05
13	2.49E-09	2700	5250	1.31E-05	2.49E-07
14	2.39E-11	3600	7000	1.67E-07	2.39E-09
15	1.22E-13	3600	7000	8.51E-10	1.22E-11
16	3.17E-16	3600	7000	2.22E-12	3.17E-14
17	4.12E-19	3600	7000	2.89E-15	4.13E-17
18	2.59E-22	3600	7000	1.81E-18	2.59E-20
19	7.6E-26	3600	7000	5.32E-22	7.61E-24
20	1.02E-29	3600	7000	7.12E-26	1.02E-27
	0.999415			255.8048	100

B.8 WRE.007 Ropatec S.p.a in Skinnarila at 20 meters height

Velocity	Weibull function (f)	Power (P)	Multiplied power curved	fPV	Percentage of wind distribution
0	0	0.32	3.04236217	0	0
1	0.052189	2.54	24.1487497	1.260309	5.221993
2	0.154869	8.56	81.3831882	12.60369	15.49591
3	0.240261	20.28	192.809703	46.32471	24.04019
4	0.247978	39.62	376.682467	93.40899	24.81231
5	0.177982	68.46	650.875358	115.8442	17.80863
6	0.088521	108.71	1033.54747	91.49038	8.857252
7	0.029897	162.28	1542.85791	46.12714	2.99147
8	0.006673	231.05	2196.68056	14.65907	0.667719
9	0.000955	316.94	3013.26958	2.877911	0.095564
10	8.49E-05	421.85	4010.68901	0.340583	0.008497

11	4.54E-06	547.68	5207.00286	0.023652	0.000454
12	1.42E-07	696.33	6620.27517	0.000937	1.42E-05
13	2.49E-09	736.27	7000	1.74E-05	2.49E-07
14	2.39E-11	736.27	7000	1.67E-07	2.39E-09
15	1.22E-13	736.27	7000	8.51E-10	1.22E-11
16	3.17E-16	736.27	7000	2.22E-12	3.17E-14
17	4.12E-19	736.27	7000	2.89E-15	4.13E-17
18	2.59E-22	736.27	7000	1.81E-18	2.59E-20
19	7.6E-26	736.27	7000	5.32E-22	7.61E-24
20	1.02E-29	736.27	7000	7.12E-26	1.02E-27
	0.999415			424.9616	100

B.9 QR6 electricity production in Skinnarila at 20 metres height

Velocity	Weibull function (f)	Power (P)	fPV	Percentage of wind distribution
0	0	0	0	0
1	0.052189	0	0	5.221993
2	0.154869	500	77.43426	15.49591
3	0.240261	1270	305.1318	24.04019
4	0.247978	2500	619.9451	24.81231
5	0.177982	3500	622.9374	17.80863
6	0.088521	4200	371.7871	8.857252
7	0.029897	4750	142.0117	2.99147
8	0.006673	5250	35.03474	0.667719
9	0.000955	5750	5.491706	0.095564
10	8.49E-05	6100	0.518005	0.008497
11	4.54E-06	6300	0.028617	0.000454
12	1.42E-07	6600	0.000934	1.42E-05

13	2.49E-09	6800	1.69E-05	2.49E-07
14	2.39E-11	6900	1.65E-07	2.39E-09
15	1.22E-13	7000	8.51E-10	1.22E-11
16	3.17E-16	7000	2.22E-12	3.17E-14
17	4.12E-19	7000	2.89E-15	4.13E-17
18	2.59E-22	7000	1.81E-18	2.59E-20
19	7.6E-26	7000	5.32E-22	7.61E-24
20	1.02E-29	7000	7.12E-26	1.02E-27
	0.999415		2180.321	100

B.10 WS-12 OY Windside Production Ltd. in Skinnarila at 30 meters height

Velocity	Weibull function (f)	Power (P)	Multiplied power curved	fPV	Percentage of wind distribution
0	0	0	0	0	0
1	0.035326	0	0	0	5.221993
2	0.108661	30	58.3333333	6.338574	15.49591
3	0.183633	60	116.666666	21.42389	24.04019
4	0.220727	120	233.333333	51.50304	24.81231
5	0.200354	211	410.277777	82.20078	17.80863
6	0.138859	300	583.333333	81.00135	8.857252
7	0.073011	450	875	63.88424	2.99147
8	0.028718	630	1225	35.17935	0.667719
9	0.008303	900	1750	14.53033	0.095564
10	0.001731	1200	2333.33333	4.03836	0.008497

11	0.000255	1650	3208.33333	0.817712	0.000454
12	2.6E-05	2100	4083.33333	0.106059	1.42E-05
13	1.79E-06	2700	5250	0.009418	2.49E-07
14	8.22E-08	3600	7000	0.000576	2.39E-09
15	2.45E-09	3600	7000	1.72E-05	1.22E-11
16	4.65E-11	3600	7000	3.26E-07	3.17E-14
17	5.52E-13	3600	7000	3.86E-09	4.13E-17
18	4E-15	3600	7000	2.8E-11	2.59E-20
19	1.74E-17	3600	7000	1.22E-13	7.61E-24
20	4.44E-20	3600	7000	3.1E-16	1.02E-27
	0.999606			361.0337	100

B.11 WRE.007 Ropatec S.p.a in Skinnarila at 30 meters height

Velocity	Weibull function (f)	Power (P)	Multiplied power curved	fPV	Percentage of wind distribution
0	0	0.32	3.04236217	0	0
1	0.035326	2.54	24.1487497	0.853074	5.221993
2	0.108661	8.56	81.3831882	8.843201	15.49591
3	0.183633	20.28	192.809703	35.40629	24.04019
4	0.220727	39.62	376.682467	83.1441	24.81231
5	0.200354	68.46	650.875358	130.4055	17.80863
6	0.138859	108.71	1033.54747	143.5178	8.857252
7	0.073011	162.28	1542.85791	112.6449	2.99147
8	0.028718	231.05	2196.68056	63.08391	0.667719
9	0.008303	316.94	3013.26958	25.01932	0.095564
10	0.001731	421.85	4010.68901	6.941403	0.008497

11	0.000255	547.68	5207.00286	1.327115	0.000454
12	2.6E-05	696.33	6620.27517	0.171952	1.42E-05
13	1.79E-06	736.27	7000	0.012558	2.49E-07
14	8.22E-08	736.27	7000	0.000576	2.39E-09
15	2.45E-09	736.27	7000	1.72E-05	1.22E-11
16	4.65E-11	736.27	7000	3.26E-07	3.17E-14
17	5.52E-13	736.27	7000	3.86E-09	4.13E-17
18	4E-15	736.27	7000	2.8E-11	2.59E-20
19	1.74E-17	736.27	7000	1.22E-13	7.61E-24
20	4.44E-20	736.27	7000	3.1E-16	1.02E-27
	0.999606			611.3718	100

B.12 QR6 electricity production in Skinnarila at 30 metres height

Velocity	Weibull function (f)	Power (P)	fPV	Percentage of wind distribution
0	0	0	0	0
1	0.035326	0	0	3.533974
2	0.108661	500	54.33064	10.87041
3	0.183633	1270	233.2144	18.37057
4	0.220727	2500	551.8182	22.08143
5	0.200354	3500	701.2388	20.04329
6	0.138859	4200	583.2097	13.89142
7	0.073011	4750	346.8002	7.303934
8	0.028718	5250	150.7686	2.872915
9	0.008303	5750	47.74252	0.830632
10	0.001731	6100	10.55743	0.173141

11	0.000255	6300	1.605689	0.025497
12	2.6E-05	6600	0.171426	0.002598
13	1.79E-06	6800	0.012199	0.000179
14	8.22E-08	6900	0.000568	8.23E-06
15	2.45E-09	7000	1.72E-05	2.45E-07
16	4.65E-11	7000	3.26E-07	4.66E-09
17	5.52E-13	7000	3.86E-09	5.52E-11
18	4E-15	7000	2.8E-11	4E-13
19	1.74E-17	7000	1.22E-13	1.74E-15
20	4.44E-20	7000	3.1E-16	4.44E-18
	0.999606		2681.471	100