Implementation of Urban Wind Farms in Winnipeg, MB, Canada

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Executive Summary

The objective of this project was to determine how urban wind farms can be implemented in Winnipeg, MB, Canada. This objective was completed by first evaluating the feasibility of implementing urban wind farms in downtown Winnipeg and then selecting a suitable wind turbine for installation.

The order to complete the study, the Richardson building was chosen as the case site due to its height and location downtown Winnipeg. The feasibility of building urban wind farms in Winnipeg was studied through the initial wind resource investigation which concluded the annual mean velocity at the roof level of the Richardson building was considered satisfactory. Next, the wind turbine design was determined using the standard engineering concept selection method which was comprised of two stages. A sensitivity analysis was conducted to determine the rotor axis orientation between a horizontal axis wind turbine (HAWT) or vertical axis wind turbine (VAWT). The two options were compared on 14 total criteria and the optimal rotor axis design for the use in Winnipeg was determined to be the VAWT. Further quantitative analysis was conducted on 10 VAWT concepts that have previously been used in projects. The designs were scored based on six criteria. These criteria were inputted into a weighted decision matrix which revealed the top two turbines that were the most suitable for the urban wind farm.

The first proposed wind farm is comprised of two Ropatec T30proS turbines on the northwest and south-west facing sides of the Richardson building. The estimated annual power production of the wind farm will be 155000kWh at an estimated cost of $277000 for the turbines. The second proposed wind farm is comprised of 11 Quiet Revolution Qr6 wind turbines. The wind turbines will cost approximately $683247 and are estimated to produce 154000kWh of energy per year. Both wind farm concepts will offset 1% of the estimated energy demand for the building resulting in a cost savings of $12500 and displacing 0.77 tonnes of CO_2 from the atmosphere.

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1 Introduction

The following report presents the investigation of integrating urban wind farms into downtown Winnipeg, MB. This document contains an introduction which outlines the objectives and rationale for the research. The results of the wind resource estimation and the case site for the study are presented. The concept generation stage was completed after the initial wind resource concluded that Winnipeg's urban area is suitable for the implementation of wind turbines. To determine the wind turbines that are most suitable for an urban wind farm in Winnipeg a sensitivity analysis and quantitative comparison was completed. Finally, the resulting wind farms are proposed for potential urban wind farms in Winnipeg, MB.

Urban wind farms utilize small wind turbines (SWTs) usually located on the roof of tall buildings as a source of renewable energy in highly populated areas. These wind farms take advantage of the limited available land space and tall buildings to produce energy. Possible configurations of small wind turbines come in many forms such as built-environment wind turbines (BWTs), building-integrated or augmented wind turbines (BUWTs/BIWTs) and building-mounted wind turbines (BMWTs) [1]. The two main types of SWT are vertical-axis wind turbines (VAWTs) and horizontal-axis wind turbines (HAWTs) both requiring different cut-in speeds, height limits, and spacing. An advantage of implementing urban wind farms is that the electricity does not have to be transported far to its end-use which limits the losses in transmission lines and eliminates the need for voltage energy supply.

Winnipeg is the capital of the Canadian province of Manitoba and is located at the fork of the Red and Assiniboine rivers. The city has a population of approximately 778,489 people [2]. The climate of Winnipeg is unique as the city is considered a humid continental climate which is indicated through a large difference in seasonal temperatures [3]. The summer average temperature is 19.7°C, compared to the winter average temperature of -16.4°C [4].

1.1 Rationale for Research

The wind energy sector is becoming a key part of tomorrows energy. The energy consumption of the world is growing, in 2018 the growth of global energy consumption was 2.9%, the fastest since 2010 [5]. The increase in energy consumption comes with the increase in carbon emissions which grew by 2.0% in 2018 [5]. With increasing energy consumption, a shift to renewable and clean energy sources are necessary if the nations of the world are going to uphold the Paris Agreements terms. In 2018, wind power contributed more to renewable generation (142TWh) than any other renewable source and the sector grew by 12.6% [5]. Implementing wind energy generation in urban areas may be attractive to cities with limited open space and to help reduce the on-site energy demand for large buildings. Most of the wind energy technology research has been on large scale wind farms with multiple megawatt capacity. However, emerging innovations have recently been focused on small or microscale wind turbines for use in urban areas [6]. The combination of unexploited wind resources and improved technology provides a growing opportunity for urban wind farms.

There have been many previous urban wind projects such as the Melbourne Council House 2 which utilizes roof-mounted wind turbines to purge the air during the night and produce energy during the day [7]. The Bahrain World Trade Center has three horizontal wind turbines integrated into the design of the building. The turbines located in-between the two towers of the centre can generate up to 400MWh/year to supply the building with energy [8].

The location of Winnipeg for an urban wind farm is unique due to the demonstrated appetite of reducing energy consumption and transition to green energy production. The utility company Manitoba Hydro leads the way in lowering the demand for energy and enforcing more energy-efficient buildings. Through the incentives and rebates offered by Manitoba Hydro, the company is open to funding projects that will reduce the load on the grid. The renewable energy climate in Winnipeg seems ideal for a new green wind project in the city. A detailed discussion about the current energy state, social and political climates in Winnipeg regarding wind energy is found in Appendix A.

This research paper addresses the implementation of wind energy to reach the need for more renewable energy sources in a world of growing energy consumption. Winnipeg has demonstrated its initiative in green energy and will be a great location to build on the cities and independent buildings that have paved the way for integrating wind energy into urban areas.

1.2 Objective

The main objective of this project was to determine how urban wind farms can be implemented in Winnipeg, MB, Canada. This objective was discretized into two smaller goals:

1) Evaluate the feasibility of implementing urban wind farms in downtown Winnipeg.
2) Determine suitable urban wind turbine technology to implement.

The feasibility of building urban wind farms was studied through the initial wind resource investigation to determine if Winnipeg was a suitable location. Next, the appropriate urban wind turbine was determined using two stages of concept selection. The results of the concept selection yielded the urban wind farm concept that was recommended to be implemented in Winnipeg, MB.

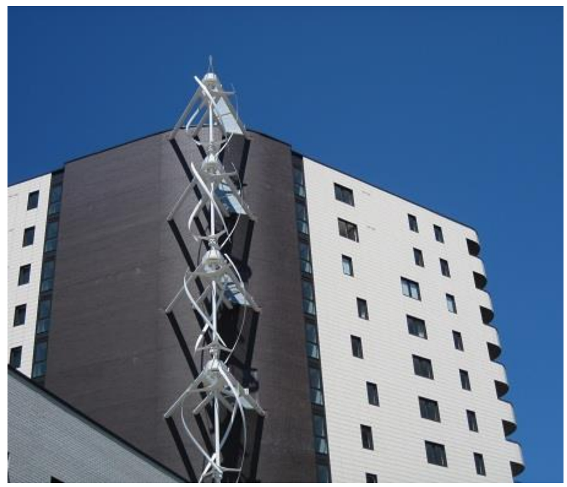
2 Initial Wind Resource Estimation and Site Study

The site used in downtown Winnipeg is presented alongside the building data used in the study. With the site selected, the feasibility of implementing wind power in Winnipeg was determined. The fundamental method of evaluating the feasibility of a wind power project is through wind resource estimation.

2.1 Site Study

Implementation of a wind turbine in urban areas falls into two categories, Building-Mounted (Retrofitting) Wind Turbines and Building-Integrated Wind Turbines. Building-integrated wind turbines are where the implementation of wind turbines is considered in the design and shape of the building to utilize wind energy. Building-Mounted wind turbines are projects that utilize pre-existing buildings to mount turbines onto, usually on the roof or on the sides of buildings as shown in Figure 1.

(a) [9]



(b) [10]

Figure 1. Building-Mounted wind turbines on (a) rooftop and (b) side of building.

Building-mounted wind turbines were considered since this project is with regards to implementing urban wind farms where there is currently no wind energy being utilized and there are available buildings to be retrofitted.

The site that was chosen for the study was the Richardson building located in downtown Winnipeg. The building is 124 meters tall and has approximately 1700 m^2 of rooftop area [11]. The total gross floor area of the building is 60,000 m^2 [12]. The average energy demand for office buildings (non-medical) was determined to be 1.12GJ/ m^2 as reported by the 2014 Building energy use survey [13]. The resulting estimate of the annual electricity demand for the Richardson building is 18853 MWh.

The wind rose for the building determined from the Canadian wind atlas [14] is shown for the Richardson building in Figure 2.

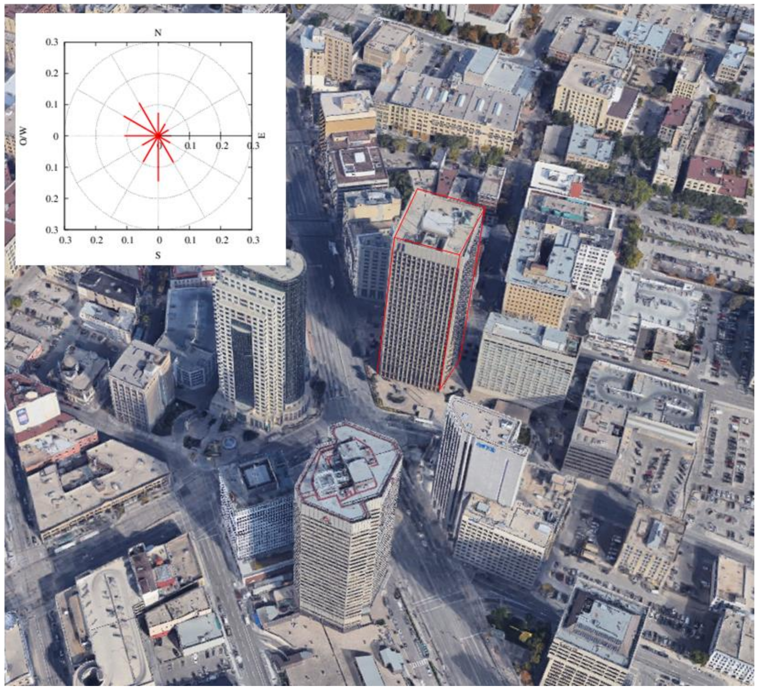


Figure 2. Richardson Building location in downtown Winnipeg and wind rose [15].

Since the building is the second tallest building in Winnipeg, wind flow at the roof of the building should be not affected significantly from surrounding structures. This is true especially for the prevailing winds from the north-west since there are no tall buildings surrounding that side as shown in Figure 2. The winds from the south and south-west will be affected more from the surrounding buildings that shield the Richardson building. The wind turbines of the urban wind farm will be installed on the south-west and north-west areas of the building's roof due to the prominent wind directions shown by the wind rose in Figure 2.

2.2 Wind Resource Estimation

The wind resource investigation provides useful information on the available wind power that will be present at the specified location. The wind resource was evaluated on both macro and micro-scales of the surrounding area. The mean annual velocity for Winnipeg was determined on a macroscale with the Weibull parameters as well as frequency and duration plots. The detailed calculations of the macro-scale wind estimation are found in Appendix A. The micro-scale wind estimation considered the effects of the Urban Boundary Layer that occurs over urban spaces. The annual mean velocity was determined to be 6.37m/s considering the effects. The detailed calculations and results are found in Appendix A. The initial wind estimate has concluded that Winnipeg will be considered as a location for an urban wind farm due to the available wind power that can be utilized.

3 Concept Analysis

To reach a final design concept, the wind turbine type was selected by performing a sensitivity analysis. After the sensitivity analysis, a quantitative analysis was performed on a variety of available wind turbine concepts. The information from the sensitivity and quantitative analyses were then used in a weighted decision matrix to select the final design concepts that were recommended to be implemented in Winnipeg.

3.1 Sensitivity Analysis

The sensitivity analysis was performed for the rotor axis orientation between a Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) concept. The turbine orientations were rated on three main categories of criteria: performance aspects, environmental impacts and economic aspects.

3.1.1 Rotor Axis Orientation

The main difference between wind turbines on the market is the orientation of the rotor axis. Most wind turbines fall into two categories: rotors that rotate about a horizontal axis, Horizontal Axis Wind Turbines (HAWT) or rotors that rotate vertically, Vertical Axis Wind Turbines (VAWT). The different types of wind turbines are shown in Figure 3.

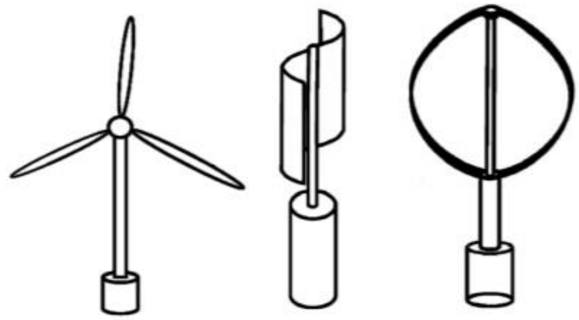


Figure 3. Main types of wind turbines [16].

Horizontal Axis Wind Turbine

A turbine is considered a horizontal axis wind turbine when the main axis of rotation which is used to turn a shaft and rotate a generator is horizontal. HAWT can either be a downwind rotor or up-wind rotor design with the latter dominating the market [17]. The traditional design of a HAWT is comprised of three blades attached to a hub which rotates a shaft that is connected through a gearbox to the generator which is housed in the nacelle. HAWT's cover a large range of rated capacity from 0.6 Watts for residential use to multiple mega-Watts for large scale wind farms.

Vertical Axis Wind Turbine

Vertical axis wind turbines are any turbine where the axis of rotation of the shaft and generator is vertically opposed to horizontal. VAWTs offer a new concept of turbine for urban environments even though HAWT's have dominated the market and thus have received the most interest, research and funding. The two main types of VAWT's are lift turbines also called Darrius turbines and drag turbines also referred to as Savonius. The Darrius turbines have led the market in VAWT due to their better performance compared to Savonius types. Examples of common Darrius turbine configurations are shown in Figure 4.

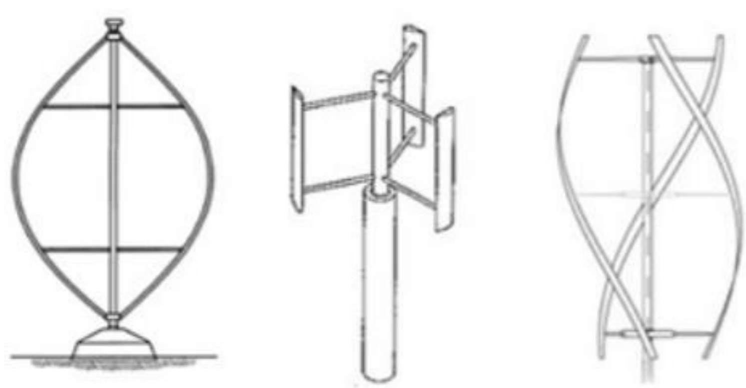


Figure 4.Darrius VAWT main types [16].

Both types of turbines have varying positive and limiting aspects to the designs and a thorough comparison will require a wide range of criteria to select the proper turbine for the specific project.

3.1.2 Sensitivity Analysis Criteria

The sensitivity analysis utilizes a total of 14 criteria to determine which rotor orientation is the most suitable for the application in Winnipeg, MB. The criteria are split into three main sections, the performance aspects, environmental impacts and economic aspects. The three categories are comprised of 14 total criteria: (1) Technology development, (2) Energy Density, (3) Efficiency, (4) Performance in Turbulent Wind, (5) Operating Temperature Range, (6) Vibration, (7) Public Safety, (8) Shadow Flicker, (9) Public Opinion, (10) Noise, (11) Biodiversity Effects, (12) Annual Energy Yield, (13) Maintenance and operation costs, (14) Cost. The detailed introduction, rationale and comparison of the rotor orientations for each criterion are found in Appendix B. For the sensitivity analysis of the rotor orientation design, the HAWT is used as a reference and the VAWT is scored either better (+) or worst (-) with respect to the reference as shown in Table I. The concept with the highest net score will be chosen to pursue further in the quantitative analysis.

TABLE I: ROTOR AXIS DESIGN SENSITIVITY ANALYSIS

Selection Criteria		Rotor Axis Orientation	
		HAWT (Reference)	VAWT
Performance			
(1)	Technology Development	0	-
(2)	Energy Density	0	+
(3)	Efficiency	0	-
(4)	Performance in Turbulent Wind	0	+
(5)	Operating Temperature Range	0	+
(6)	Vibration	0	-
Environmental Impacts			
(7)	Public Safety	0	+
(8)	Shadow Flicker	0	+
(9)	Public Opinion	0	+
(10)	Noise	0	+
(11)	Biodiversity Effects	0	+
Economical Aspects			
(12)	Annual Energy Yield	0	+
(13)	Maintenance and Operation Costs	0	+
(14)	Cost	0	-
	Sum of "+"	0	10
	Sum of "- "	0	4
	Net Score	0	6
	Rank	2	1
	Continue with Design?	No	Yes

The VAWT received the highest score and is considered the rotor orientation that is best suited for the urban wind farm in Winnipeg. The VAWT orientation will be considered in the quantitatively analyzed.

3.2 Concepts for Quantitative Analysis

The sensitivity analysis revealed the rotor orientation design that will be continued in a more detailed and quantitative analysis. A total of 10 varying VAWT designs were selected for the analysis which is presented in Table II.

TABLE II: VAWT TURBINES FOR QUANTITATIVE ANALYSIS

Code	Company	Model	Turbine Type	Rated Power [kW]
1	Ropatec	WRE.030	Savoius	3
2	Ropatec	WRE.060	Savoius	6
3	Ropatec	SA40	Darrieus	10
4	Ropatec	T30proS	Darrieus	30
5	OY Windside Production Ltd	WS-12	Savoius	8
6	HEA Energy Ball	V100	Alt HAWT	0.5
7	HEA Energy Ball	V200	Alt HAWT	2.5
8	Quiet Revolution	Qr6	Darrieus	7.5
9	Aerotecture	610V	Darrieus	1
10	Aerotecture	712V	Darrieus	2.5

Detailed descriptions and technical data for each turbine are found in Appendix C.

3.3 Quantitative Criteria

Quantitative parameters were calculated for each of the turbines selected using the corresponding technical data from each. The quantitative criteria were discretized into two main sections, the performance aspects and economic aspects. The criteria were calculated for all ten turbines and the results are presented for the two criteria sections. Each turbine is then ranked with respect to the others with a ranking of 10 indicating the best performing turbine in that case. The detailed results and equations for calculating each criterion are found in Appendix D.

3.3.1 Performance Aspects

The performance aspects selected were used in the decision matrix to rank the turbines in order of the best performing to worst. The performance criteria include the non-dimensional parameters of the tip speed ratio, power coefficient and power specific tip speed. The results and ranking of the concepts for the first three criteria are summarized in Table III.

TABLE III: PERFORMANCE CRITERIA RANKING

Code	Rated Power [kW]	Performance Coefficient (C_p)	Rank	Tip Speed Ratio	Rank	Power Specific tip speed	Rank
1	3	0.229	5	1.234	4	0.350	3
2	6	0.287	7	1.196	3	0.410	4
3	10	0.297	8	4.561	8	**6.176**	**10**
4	30	**0.309**	**10**	4.320	7	5.770	7
5	8	0.178	2	0.748	1	0.100	2
6	0.5	0.179	3	2.891	6	1.499	6
7	2.5	0.196	4	**5.582**	**10**	6.094	9
8	7.5	0.275	6	4.689	9	6.049	8
9	1	0.169	1	0.753	2	0.096	1
10	2.5	0.302	9	1.318	5	0.524	5

Furthermore, the capacity factor and wind potential dependent efficiency coefficient was determined for each turbine and the results are summarized in Table IV.

TABLE IV: CAPACITY AND EFFICIENCY COEFFICIENT RANKING

Code	Rated Power [kW]	Power [kWh]	Power Density [kWh/m^2]	Power in Wind [kWh]	Capacity Factor [%]	Rank	Efficiency Coefficient (C_E) [%]	Rank
1	3	4140	570.30	19305	16%	6	21%	6
2	6	10965	755.21	38611	21%	7	28%	9
3	10	22431	562.18	106101	26%	9	21%	5
4	30	77384	586.25	351014	**29%**	**10**	22%	7
5	8	5512	459.38	31910	8%	1	17%	3
6	0.5	453	453.95	2659	10%	3	17%	2
7	2.5	1919	505.04	10104	9%	2	19%	4
8	7.5	14025	876.59	42547	21%	8	**33%**	**10**
9	1	1332	332.36	10660	15%	5	12%	1
10	2.5	3330	593.78	14917	15%	4	22%	8

3.3.2 Economic Aspects

The economic criterion was used to rank the turbines in order of the most economically viable. The criterion selected for the economic analysis was the Levelized cost of energy which was determined for each turbine. A summary of the economic criteria calculations and results are shown in Table V.

TABLE V: ECONOMIC CRITERIA SUMMARY AND RANKING

Code	Lifespan [yrs.]	Annual Energy Yield [kWh]	Cost ($CAD)	ENC [$/year]	NPV [$CAD]	Levelized Cost of Energy	Rank
1	15	4140	$ 12,909.12	$ 336.58	-$ 8,584.29	2.07	6
2	15	10965	$ 16,063.03	$ 891.45	-$ 4,608.50	0.42	8
3	25	22431	$ 43,000.00	$ 1,823.64	-$ 7,396.24	0.33	9
4	25	77384	$ 138,360.38	$ 6,291.32	-$ 15,532.08	**0.20**	**10**
5	50	5512	$ 422,963.71	$ 448.13	-$408,881.99	74.18	1
6	25	453	$ 2,389.59	$ 36.83	-$ 1,670.56	3.69	4
7	15	1919	$ 4,915.03	$ 156.01	-$ 2,910.36	1.52	7
8	30	14025	$ 62,113.39	$ 1,140.23	-$ 36,576.22	2.61	5
9	30	1332	$ 15,000.00	$ 108.29	-$ 12,574.65	9.44	2
10	30	3330	$ 25,000.00	$ 270.73	-$ 18,936.63	5.69	3

3.4 Final Concept Selection

A weighted decision matrix was used to determine the top two designs that were recommended for the urban wind farm. To determine the weight of each criterion for the decision matrix, each criterion was first compared to each other to decide which was most important. The more important criteria between each selection are shown in Table VI. The total hits for each letter were used to determine a percentage which will weigh the rankings in the decision matrix.

TABLE VI: CRITERIA DECISION MATRIX

		Coefficient of Performance	Tip Speed Ratio	Power Specific Tip Speed	Capacity	Efficiency Coefficient (CE)	Levelized Cost of Energy
		A	**B**	**C**	**D**	**E**	**F**
		A	B	C	D	E	F
Coefficient of Performance	**A**		A	C	A	E	A
Tip Speed Ratio	**B**			C	B	E	B
Power Specific Tip Speed	**C**				C	E	C
Capacity	**D**					E	F
Efficiency Coefficient (CE)	**E**						E
Levelized Cost of Energy	**F**						
Weightings		**22%**	**17%**	**22%**	**4%**	**26%**	**9%**

A weight decision matrix was produced combining the ranking of each wind turbine and the weights of each criteria resulting in a score. The results of the decision matrix are shown in Table VII where a higher score implies a more desirable solution.

TABLE VII: WIND TURBINE WEIGHTED DECISION MATRIX

Code	Criteria	Performance					Economic
		Performance Coefficient	**Tip Speed Ratio**	**Power Specific Tip Speed**	**Capacity**	**Efficiency Coefficient (CE)**	**Localized Cost of Energy**
	Weight	22%	17%	22%	4%	26%	9%
1	Score	5	4	3	10	6	6
	Total	1.09	0.70	0.65	0.43	1.57	0.52
2	Score	7	3	4	9	9	8
	Total	1.52	0.52	0.87	0.39	2.35	0.70
3	Score	8	8	10	3	5	9
	Total	1.74	1.39	2.17	0.13	1.30	0.78
4	Score	10	7	7	3	7	10
	Total	2.17	1.22	1.52	0.13	1.83	0.87
5	Score	2	1	2	7	3	1
	Total	0.43	0.17	0.43	0.30	0.78	0.09
6	Score	3	6	6	9	2	4
	Total	0.65	1.04	1.30	0.39	0.52	0.35
7	Score	4	10	9	6	4	7
	Total	0.87	1.74	1.96	0.26	1.04	0.61
8	Score	6	9	8	3	10	5
	Total	1.30	1.57	1.74	0.13	2.61	0.43
9	Score	1	2	1	6	1	2
	Total	0.22	0.35	0.22	0.26	0.26	0.17
10	Score	9	5	5	6	8	3
	Total	1.96	0.87	1.09	0.26	2.09	0.26

The final scores of each concept are presented in Table VIII alongside the ranking and whether the design will be recommended.

TABLE VIII: WEIGHTED DECISION MATRIX RESULTS AND RANKING

Code	Total	Rank	Continue
1	4.96	7	No
2	6.35	6	No
3	7.52	3	No
4	7.74	2	Yes
5	2.22	9	No
6	4.26	8	No
7	6.48	5	No
8	7.78	1	Yes
9	1.48	10	No
10	6.52	4	No

From the weighted decision matrix, the concept of using the (4) Ropatec T30proS and the (8) Quiet Revolution Qr6 is proposed for the urban wind farm in Winnipeg, MB.

4 Proposed Urban Wind Farms

As a result of the final concept selection phase, two designs are proposed for the implementation of the wind turbine in the urban area of Winnipeg, MB. The two concepts offer different strategies of installing wind turbines onto the existing buildings.

Ropatec T30proS Final Concept

The first proposed urban wind farm for Winnipeg is using the Ropatec T30proS wind turbine. The turbines rotor is 11 meters in diameter with a mast height of 24 meters [18]. The roof space on the Richardson building is approximately 31.5 meters square. The installation of two turbines located on the northwest and south-west facing sides of the building are recommended. The potential locations of the turbines on the case site are shown in Figure 5.

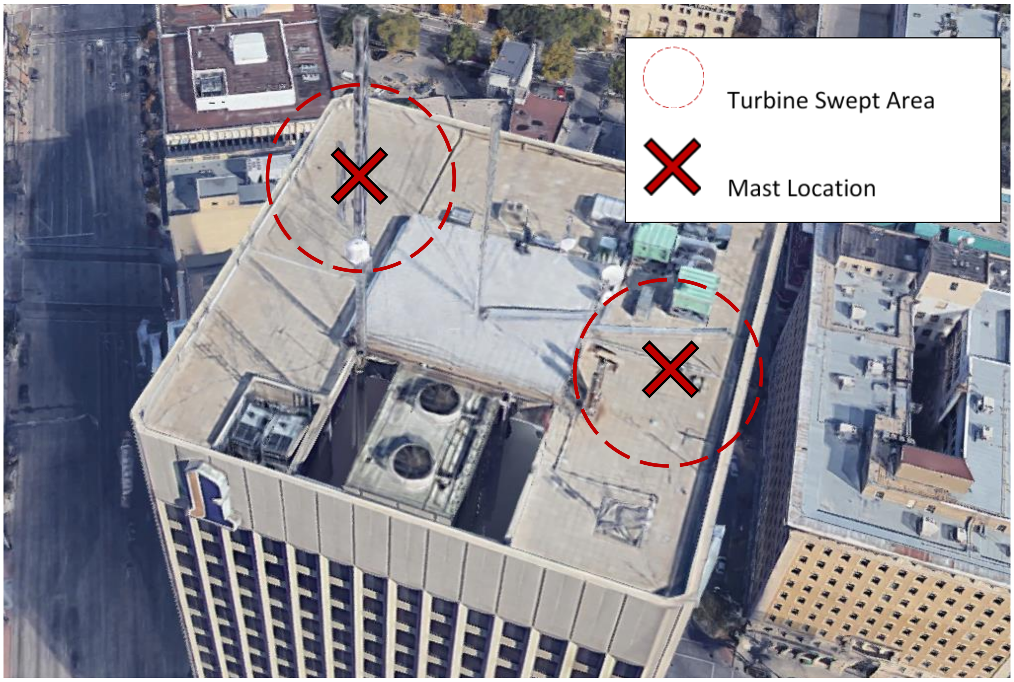


Figure 5. Potential locations of Ropatec T30proS wind turbines on Richardson Building [15].

The Ropatec wind turbines have a large diameter of 11 meters which is approximately a third of the length of the buildings side dimension which makes positioning the wind turbines important. The building has existing towers which must be taken into consideration. The proposed locations are in an open spot on the roof and positioned such that the wakes of the turbines will not affect each other under the prevailing wind directions. The estimated cost and estimated wind power for the urban wind farm located on the Richardson Building are presented in Table IX.

TABLE IX: ROPATEC T30PROS WIND FARM INFORMATION

	Turbine	**Farm (2 Turbines)**
Cost	$138360	$276720
Estimated Annual Power Production	77384 [kWh]	154768 [kWh]

The energy offset by the wind farm was calculated as a percentage from the estimated annual electricity demand for the Richardson building of 18853 MWh. The cost savings of the wind farm was determined using the calculated rate for purchasing wind power in Manitoba. The rate was calculated using the C$130 million Manitoba Hydro spent in 2017-18 on Fuel and Power which includes purchasing wind power and on electricity imports [19]. Manitoba Hydro reported that 911GWh of wind power and 688GWh in contracted imports was purchased in 2017-18 [20]. This produces an estimated rate of purchasing power at 0.0813$/kWh from Manitoba Hydro for wind energy. The greenhouse gas offset was determined using the production method of electricity in Manitoba in which the wind farm would be offsetting. Manitoba's electricity primarily is generated from Hydropower comprising 97% of the share and the remaining sources include Wind (2%) and Natural gas (1%) [21]. The only source of greenhouse gas associated with producing energy comes from Natural gas. The amount of greenhouse gas offset by clean energy was determined from the rate of 0.005 tCO_2/MWh [22]. The results of this analysis are summarized in Table X.

TABLE X: ROPATEC T30PROS WIND FARM BENEFITS

Annual Estimated Power Production [kWh]	77384
Wind Farm Estimated Power Production [kWh]	154768
Total Energy Offset	1%
Cost Savings	$ 12,582.64
Green House Gas Offset [tCO2]	0.77384

Quiet Revolution Qr6 Final Concept

The wind turbines rotor design is 5.5 meters tall and 3.1 meters in diameter with the mast for roof mounting 6 meters tall [23]. The recommended implementation of a total of 11 turbines located on the northwest and south-west facing sides of the building to utilize the prevailing wind directions. The potential locations of the turbines on the case site are shown in Figure 6.

Figure 6. Potential locations of Quiet Revolution Qr6 wind turbines on Richardson Building [15].

The Quiet Revolution wind turbines have a smaller diameter of 3.1 meters which is approximately a tenth of the length of the buildings side dimension. The proposed locations are comprised of two groups of wind turbines with the south-west group having 5 turbines. The south-west group is positioned in a staggered orientation in order to minimize wake interacting when the prevailing winds are from the southwest direction. The north-west turbines are a group of six which are in a single file line across the edge of the building façade which will capture the wind from the north-west direction.

The estimated cost and estimated wind power for the urban wind farm located on the Richardson Building are presented in Table XI.

TABLE XI: QUIET REVOLUTION QR6 WIND FARM INFORMATION

	Turbine	**Farm (11 Turbines)**
Cost	$62113	$683247
Estimated Annual Power Production	14025 [kWh]	154275 [kWh]

Following the same calculations for the Ropatec T30proS, the results of the benefit analysis are summarized in Table XII.

TABLE XII: QUIET REVOLUTION QR6 WIND FARM BENEFITS

Annual Estimated Power Production [kWh]	14025
Wind Farm Estimated Power Production [kWh]	154275
Total Energy Offset	1%
Cost Savings	$ 12,542.56
Green House Gas Offset [tCO2]	0.771375

5 Summary

The objective of this project was to determine how urban wind farms can be implemented in Winnipeg, MB, Canada. This objective was completed by first evaluating the feasibility of implementing urban wind farms in downtown Winnipeg and then selecting a suitable wind turbine to be implemented.

The feasibility of building urban wind farms was studied through the initial wind resource investigation which concluded the estimated annual mean velocity of 6.27m/s located on the roof of the Richardson building which was considered satisfactory. Next, the wind turbine design was determined using the standard engineering concept selection method which was comprised of two stages. A sensitivity analysis was conducted to determine the rotor axis orientation between a horizontal axis wind turbine (HAWT) or vertical axis wind turbine (VAWT). The two options were compared on 14 total criteria: (1) Technology development, (2) Energy Density, (3) Efficiency, (4) Performance in Turbulent Wind, (5) Operating Temperature Range, (6) Vibration, (7) Public Safety, (8) Shadow Flicker, (9) Public Opinion, (10) Noise, (11) Biodiversity Effects, (12) Annual Energy Yield, (13) Maintenance and operation costs, (14) Cost. The optimal rotor axis design for the use in Winnipeg was determined to be the VAWT from the sensitivity analysis to be further analyzed.

Further quantitative analysis was conducted on 10 VAWT concepts that are on the market and have been used in previous projects. The designs were scored based on six criteria: (1) Coefficient of Performance, (2) Tip speed ratio, (3) Power specific tip speed, (4) Capacity, (5) Efficiency coefficient, and

(6) Levelized cost of energy. These criteria were inputted into a weighted decision matrix which revealed the top two turbines that are the most suitable for the urban wind farm.

The first proposed wind farm is comprised of two Ropatec T30proS turbines on the northwest and south-west facing sides of the Richardson building. The estimated annual power production of the wind farm will be 155000kWh at an estimated cost of $277000 for the turbines. The wind turbines will offset 1% of the estimated energy demand for the building resulting in a cost savings of $12500 and displacing 0.77 tonnes of CO_2 from the atmosphere. The second proposed wind farm is comprised of 11 Quiet Revolution Qr6 wind turbines. The proposed locations are comprised of two groups of wind turbines with the south-west group having 5 turbines. The north-west turbines are a group of six which are in a single file line across the edge of the building façade. The wind turbines will cost approximately $683247 and are estimated to produce 154000kWh of energy per year. The wind turbines will offset 1% of the estimated energy demand for the building resulting in a cost savings of $12500 and displacing 0.77 tonnes of CO_2 from the atmosphere.

6 Recommendations

The wind resource analysis in this study was only an initial study due to the wind data being taken from the local station located at the Winnipeg International Airport. The wind data collected from this location was then extrapolated using analytical equations to represent the wind conditions at the roof of the Richardson Building. To improve the results, a more thorough wind resource analysis should be conducted by measuring wind speeds on the roof and better understand the wake development over the roof.

The economic analysis can be improved by using a more complete calculation of the net present volume. In this study, the initial turbine cost and annual savings were the only parameters used to determine the present value. For a more accurate result, factors such as the maintenance and operating costs should be included. The result will also be affected by the change in property value due to the installation of wind turbines on the roof. The costs of decommissioning the turbines at the end of the lifecycle should also be included.

The conclusions of this study may be extended to other locations in Winnipeg. A review of the wind resource should be completed to ensure the building has enough wind to produce. The layouts of the turbine should be reviewed depending on the roof space available on other buildings.

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Appendix A

Wind Energy Social Climate and Initial Wind Resource Estimation

Contents

List of Figures

List of Tables

A.1 Introduction

The current energy state alongside the social and political climate of wind energy in Winnipeg is fully described. After, a detailed outline of the initial wind resource analysis completed in the project is presented.

A.2 Winnipeg Current Energy State

The first subject that was studied was the current state of energy production in Manitoba and the energy needs of the city. Manitoba's electricity primarily is generated from Hydropower comprising 97% of the share [1]. The remaining sources include Wind (2%) and Natural gas (1%) [1]. The annual electricity consumption per capita was reported in 2016 as 17.2 MWh which ranked 6th in Canada [2]. The largest portion of Manitoba's energy consumption is due to heating and cooling, accounting for 27% of all energy uses [3]. It follows that the highest load on energy consumption is during Winnipeg's cold winters when the energy used on heating is the highest. Having a technology that could subsidize the energy consumption of the city would aid in lowering the dependence on grid power and reduce energy costs.

A.3 Wind Energy Social and Political State

The buildings in Winnipeg generate over one-third of the greenhouse gas emissions and consume the largest amount of energy in Winnipeg [3]. The city is aware of this and has led the way in improving the energy efficiency of the buildings and upgrading with renewable energy.

The government of Winnipeg and Manitoba have supported this green push through policies and initiatives such as the Green Building Policy. The Green Building Policy which, was adopted in 2010, outlines how the City of Winnipeg will improve the performance of Government-funded buildings with respect to environmental and energy concerns. The policy requires buildings, renovations, and major additions to have a minimum Leadership in Energy and Environmental Design (LEED) Silver Certification, Energy Efficiency MNECB +33% Power Smart, Life Cycle Costing and Low or Zero Carbon Energy [4]. There are 47 government-funded buildings to date in Winnipeg that are above the Silver LEED Level and 4 that have achieved the highest Platinum LEED Level [5].

The power utility company Manitoba Hydro has led the way in green building through the construction of their headquarters, Manitoba Hydro Place. The building uses 70% less energy compared to conventional office building designs [6]. The building is one of the 4 government-funded buildings that achieved the Platinum LEED level by the Canada Green Building Council. The building utilizes passive systems such as south-facing winter gardens, natural daylighting and a solar chimney to reduce energy in a natural way. The energy requirements are also reduced through active systems such as programmable lighting. The Manitoba Hydro headquarters in Winnipeg is shown in Figure 1.

Figure 1. Manitoba Hydro Place [7].

Manitoba implements demand-side management through the Power Smart Plan which aims to manage the provinces energy needs and assist customers to be more energy efficient. The program plans to reduce electricity demand by 355 GWh in 2018-2019 [8]. The reduction of energy consumption is achieved by the $76 million invested in incentives for residential, commercial, and industrial consumers [8]. Manitoba Hydro offers many incentives and rebates for commercial and industrial buildings ranging from bioenergy optimization, HVAC upgrades and implementation of solar energy [9]. The New Building Program offers a financial incentive to buildings that utilize integrated design, energy modelling, and energy management [10]. The Energy Modelling assistance incentive from Manitoba Hydro offers C$10000 for customers that submit design energy modelling reports during building design phases [11]. The Performance path incentive offers a varying financial amount depending on the building projects final energy model performance [11].

The current state of wind power in Manitoba includes 258MW of installed capacity from the wind farms located onshore at St. Joseph and St. Leon [12]. Manitoba Hydro reported that 911GWh of wind power was purchased in 2017-18 which makes up 2.58% of the total power resources used in the province [13]. Overall, it seems that the public opinion on wind power is good and they are willing to expand the wind capacity of the province.

A.4 Initial Wind Resource Estimation

The initial wind resource estimation was completed to determine if Winnipeg, MB had a suitable wind resource for the implementation of a wind farm. Both macro and microscale effects on the wind resources were investigated.

A.4.1 Macro-Scale Wind Estimation

The potential wind energy that can be produced in Winnipeg, MB depends on the wind speeds that are characteristic of the area. The approximate wind speeds of southern Manitoba are shown in Figure 2.

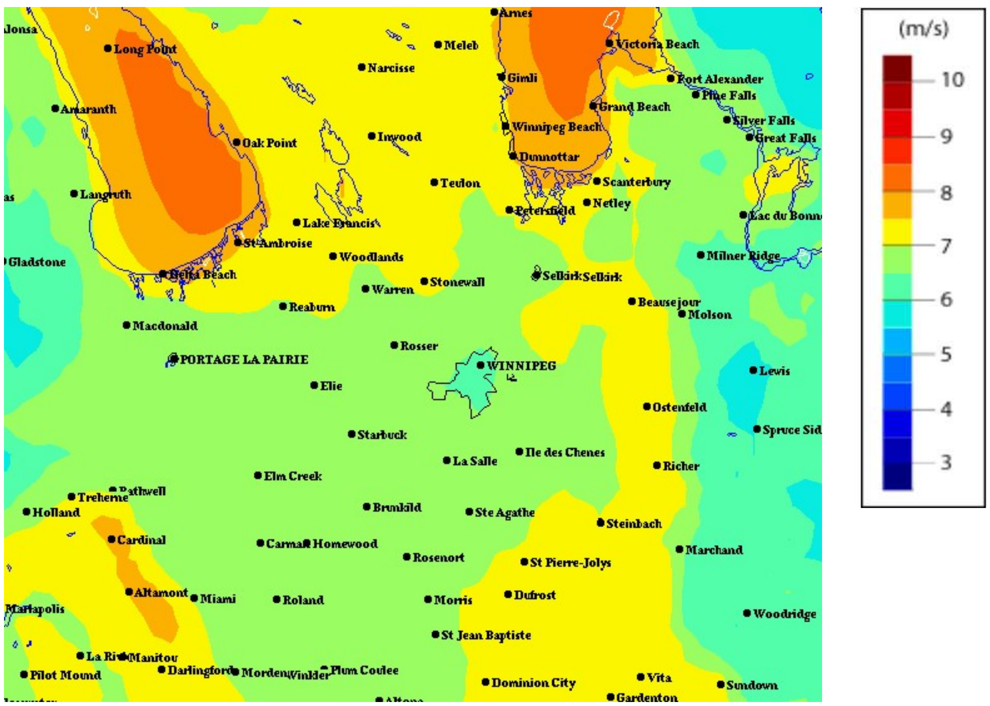


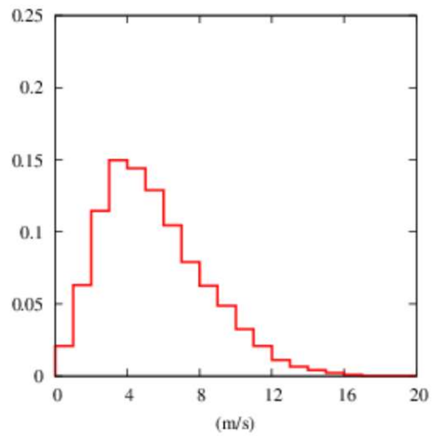
Figure 2. Southern Manitoba wind resource map [14].

For a more detailed analysis, the wind resource of Winnipeg was evaluated from two sources, the Canadian wind atlas [15] and data from the governments Historical Climate Data [16]. First, the wind data was collected from the Canadian wind atlas which provides maps of numerically derived wind speeds and wind energy. The numerical wind data at 50 meters from the wind atlas at Latitude = 49.870, longitude = -97.129 are presented in Table I.

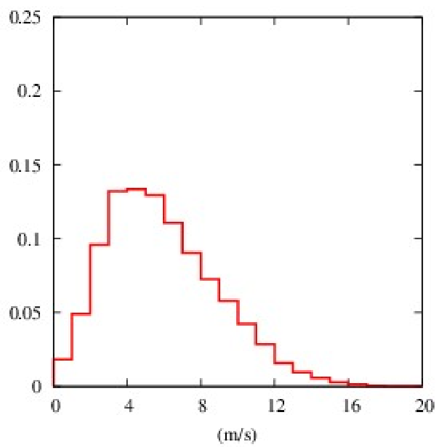
TABLE I: NUMERICAL WIND DATA AT 50M FOR WINNIPEG [15]

Period	Mean Wind Speed	Mean Wind Energy	Weibull shape parameter (k)	Weibull scale parameter (A)
Annual	5.08 m/s	125.88 W/m2	1.98	5.73 m/s
Winter (DJF)	5.48 m/s	151.00 W/m2	2.08	6.19 m/s
Spring (MAM)	4.91 m/s	112.62 W/m2	2.00	5.54 m/s
Summer (JJA)	4.31 m/s	75.44 W/m2	2.03	4.87 m/s
Fall (SON)	5.38 m/s	145.12 W/m2	2.05	6.07 m/s

The annual average wind speed of downtown Winnipeg is 5.08m/s as shown in Table I. These wind speeds are all for the height of 50 meters so it should be expected that buildings taller will experience higher wind speeds. The expected trend of higher wind speeds in the winter is shown in the data as well as slower wind speeds in the summer. This trend of varying wind speeds depending on the season is further demonstrated in the wind speed histograms shown in Figure 3.



(a)



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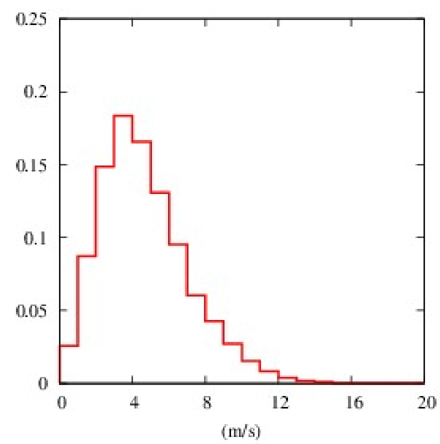

(c)

Figure 3.Wind Speed Histograms for (a) Annual, (b) Winter and (c) Summer seasons [15].

Comparing the wind speeds in winter and summer shown in Figure 3, the summer has much more frequent lower wind speeds as seen in the higher spike around 4m/s. Conversely, the winter season has higher wind speed as seen in the shifted right histogram. This trend aligns with the demand for energy determined for Winnipeg. Since the city consumes much more energy for heating and cooling during the winter months, wind power could help subsidize the larger demand.

Next, hourly data for the year of 2018 was collected from the governments Historical Climate Data [16]. The data was recorded from the station at the Winnipeg International Airport located at

Latitude = 49.54, longitude = -97.14. The wind data collected from both the Canadian wind atlas and from the governments Historical Climate Data for the year of 2018 are presented in Table II.

TABLE II: MEAN WIND SPEEDS FROM DATA SOURCES

Source	Wind Atlas [15]	Historical Wind Data 2018 [16]
Period	**Mean Wind Speed @50m**	**Mean Wind Speed**
Annual	5.08 m/s	4.84 m/s
Winter (DJF)	5.48 m/s	5.07 m/s
Spring (MAM)	4.91 m/s	4.77 m/s
Summer (JJA)	4.31 m/s	4.83 m/s
Fall (SON)	5.38 m/s	4.83 m/s

The historical wind data was unclear on the height the data was recorded but from the results, assuming similar wind profiles, the height may have been around 50m. The data once again shows the trend of higher wind speeds in the winter and having an average wind speed of approximately 5m/s. The data collected from Winnipegs Airport was further analyzed by producing a histogram of the annual wind speeds recorded as shown in Figure 4.

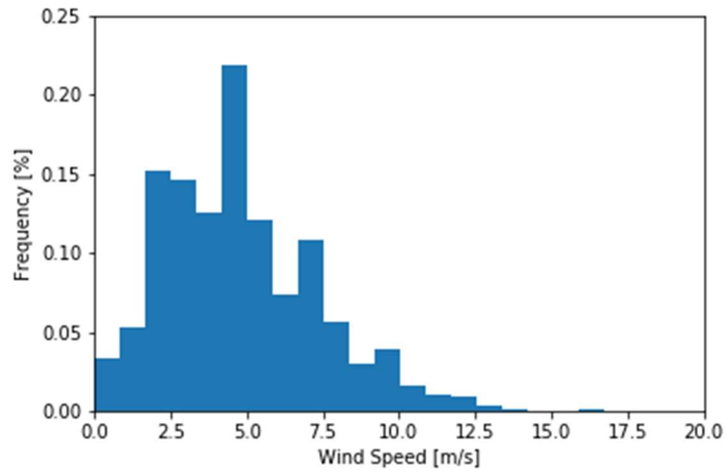

Figure 4. Wind Speed Histogram for 2018 at Winnipeg Intl A.

The annual wind speed histogram shows a similar result as the wind atlas with a large spike of wind speeds around 5m/s. The wind speed histogram results were expanded by including a wind speed duration curve as shown in Figure 5.

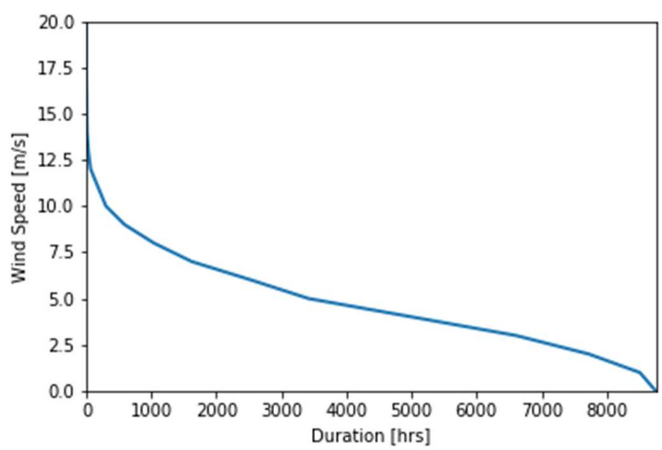

Figure 5. Wind Speed Duration Curve for 2018 at Winnipeg Intl A.

The available wind power over the length of the year is relatively high and will depend on the wind turbine concepts cut-in speed. The ideal solution will have a low enough cut-in wind speed so that the turbine will capture more energy over a longer time thus increasing its capacity.

A.4.2 Micro- Scale Wind Estimation

Urban wind farms performance is also determined by the micro-scale wind characteristics of the environment. The prevailing wind is disturbed due to the buildings in the city, often starting with flat land, then more populated rural areas until the wind reaches the highly populated urban areas. The micro-scale behaviour of the wind is investigated to ensure that the wind turbines are located in suitable areas.

A.4.2.1Urban Boundary Layer

The urban boundary layer is formed due to a change in surface roughness from the relatively lower roughness of fields and bodies of water and the higher roughness of populated areas with buildings, houses and trees. The development of the boundary layer over a city is shown in Figure 6.

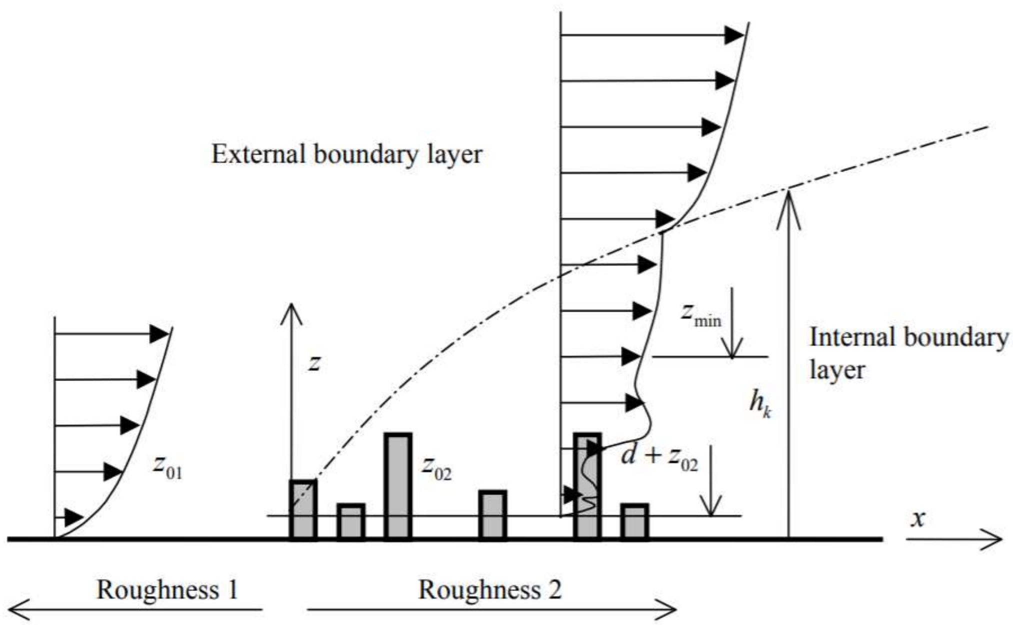

Figure 6. Urban boundary layer profile due to change in surface roughness [17].

The growth of the internal boundary layer for a step-change in roughness is given by equation (1) [17].

$$h_k(x) = 0.28 z_{0,max} \left(\frac{x}{z_{0,max}} \right)^{0.8} \tag{1}$$

Where x is the distance between the step and the location of interest in roughness 2 and $z_{0,max}$ is the larger roughness between the surface roughness heights z_{01} and z_{02}.

The velocity profile in the internal boundary layer is given by equation (2) [17].

$$u(z) = 1.31 \, \frac{ln\left(\frac{h_k}{z_{01}}\right)}{ln\left(\frac{z_1}{z_{01}}\right)} \, \frac{ln\left(\frac{z_2 - d}{z_{02}}\right)}{ln\left(\frac{h_k - d}{z_{02}}\right)} \, u_p \tag{2}$$

Where d is the displacement height which is derived from the surface roughness and the total area that is occupied by buildings in the city. The height of the two locations at which the wind speeds are being measured are denoted z_1 and z_2.

The wind data collected from governments Historical Climate Data [16] measured at the Winnipeg James Armstrong Richardson International Airport was converted to take into effect the urban boundary layer and the height at the roof. This transformation of the data is an estimation of the wind characteristics on the roof of the Richardson building in downtown Winnipeg.

The displacement height, d, was selected to be 23 meters assuming 42% of the total area of the city is buildings [17]. The recorded heights of the two locations are approximately 50 meters for the measured data and 124 meters for the roof of the Richardson building [18]. The landscape type surrounding the Winnipeg International Airport is generally an agricultural area with some buildings and fences and thus is considered a roughness class 1.5 with a roughness length of 0.055 meters from the European Wind Atlas [19]. The Richardson building is located downtown with tall buildings surrounding it and thus is considered roughness class 4 with a roughness length of 1.6 meters [19]. The distance, x, between the change of roughness to the Richardson building was taken as the upper limit of 5km [17]. The variables used in the urban boundary layer calculations are summarized in Table III.

TABLE III: URBAN BOUNDARY LAYER WINNIPEG VARIABLES

Variable	Value	Reference
x	5000m	[17]
z_{01}	0.03	[19]
z_{02}	1.6	[19]
d	23	[17]
z_1	50m	[16]
z_2	124m	[18]

The new annual mean velocity taking into consideration the urban boundary layer is 6.37m/s from governments Historical Climate Data [16].

A.5 References

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Appendix B

Sensitivity Analysis Criteria

Contents

List of Figures

B.1 Introduction

Each criterion is introduced, the rationale for why it's important to urban wind farms and lastly the HAWT and VAWT are compared. The criteria are split into three main sections, the performance aspects, environmental impacts and economic aspects.

B.2 Performance Aspects

(1) Technology Development

The technology development of wind turbines refers to the maturity of the designs and implementation. The maturity of the technology is a criterion because it can indicate higher costs with respect to design and manufacturing as well as political backing and funding. HAWT is the most common wind turbines and are the turbine of choice for large scale wind farms both on and offshore. Due to the mature of HAWT, the efficiency and cost of the turbines have improved to the present day. The VAWT is not as developed as a technology compared to the HAWT.

(2) Energy Density

The energy density is a measure of the amount of energy that the turbines are rated per the swept area of the turbine. Having a larger energy density means that more energy can be harvested in a smaller space which is important for urban wind farms where space is limited. The rated capacity and swept area were collected for a variety of small wind turbines (<10kW) to determine the energy density of each [1]. The power densities of the sampled HAWT and VAWT turbines are shown in Figure 1.

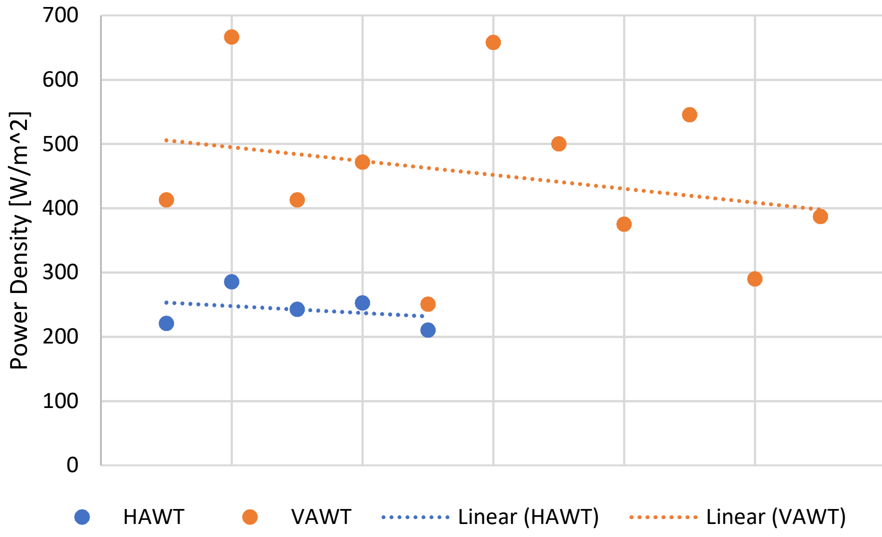

Figure 1. The power density of sampled HAWT and VAWT's.

The power density of small VAWT's are generally higher than small HAWT's and thus are more suitable for urban wind farms.

(3) Efficiency

The efficiency of the wind turbine is often determined using the coefficient of performance which is a measure of how well the wind turbine converts the winds energy into usable mechanical energy. The efficiency of the implemented wind turbine is important so that the wind farm can extract the most amount of wind energy to help supply the building. The coefficient of performance for different wind machines is shown in Figure 2.

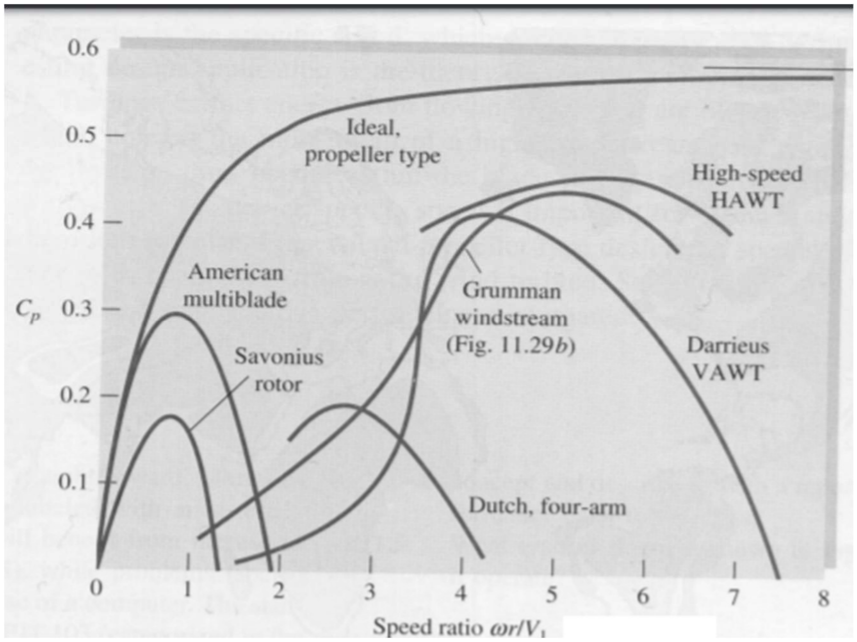

Figure 2. Performance parameters of varying machine type [2].

HAWT's have the highest efficiency usually around 0.45 compared to VAWT as shown in Figure 2.

(4) Performance in Turbulent Wind

The performance in turbulent wind describes how wind turbines performance will change when located in turbulent flow or the requirements of the incoming wind for operation. The ability to harvest energy in high turbulent flow is important for urban wind farms since the wind over buildings causes wakes of turbulent flow that the turbines may be located. HAWT's are limited to operate in flow with less than 15% turbulence intensity to control the fatigue loads on the blades [2]. With respect to an urban wind turbine, this means the HAWT will have to be installed higher above the roof to reach more laminar flow which is unwanted for urban wind farms. VAWT's can operate in turbulent flow with the performance minimally reduced at 15% turbulence intensity [3].

(5) Operating Temperature Range

The operating temperature range of the wind turbine determines the minimum and maximum atmospheric temperatures that the turbine can generate electricity. This criterion is specifically important to Winnipeg because of the climate variation of cold winters and warm summers that the turbine will have to withstand. The formation of ice on the blades of the wind turbines can reduce power output and increase rotor loads [4]. Larger turbines can be installed with cold weather packages that include heating of the gearbox or de-icing or anti-icing mechanisms such as heated blades. At the small wind turbine scale, implementing cold weather packages would not be economically variable. The standard operating range of wind turbines is -20°C - 50°C [1]. Both VAWT's and HAWT's have comparable operating temperature ranges but VAWT has a slight advantage since Drag based VAWT can operate much lower since the turbine won't be affected by lost lift due to ice on the blades. Furthermore, since VAWT's generators are located on the ground, this offers the ability to heat the turbines components easier than HAWT's if required.

(6) Vibration

Vibration transmission from the wind turbine to the existing buildings structure is a concern when implementing urban wind farms. Wind turbines experience vibration due to the turbulent nature of the wind as well as the difference in aerodynamic loads on the blades [5]. The inducted vibration frequency in the VAWT is double the HAWT since the VAWT blades experience aerodynamic loads twice in the rotation, first when the blade is on the upwind side then again at the downwind location. The increased vibration frequency in the VAWT will require further investigation when implementing the wind turbine and thus is determined inferior to the HAWT.

B.3 Environmental Impacts

(7) Public Safety

Public safety refers to the risks that are acquired when implementing the different types of turbines. The risks of having wind turbines on high rise building include complete failure where parts can fall to the ground or ice being thrown from blades due to ice formation. The VAWT is considered a better choice for public safety since the VAWT have lower tip speeds than HAWT [6].

(8) Shadow Flicker

Shadow flicker from the turbines is caused when the sunlight is disturbed by the rotating blades causing rotating shadows to be cast on surroundings. This phenomenon may cause problems for people in surrounding office buildings and possibly trigger people with epilepsy. Shadow flickering between the range of 3-25 hertz will be noticed and could cause annoyance [6]. This criterion is important for urban wind farms since it is likely that the shadow cast from the roof of the high-rise building will land on the street level or surrounding office buildings in Winnipeg. The HAWTs are more likely to have problematic shadow flicker since the turbines operate mainly in the range of rotation speeds (200-500rpm) that cause the greatest sensitivity [6].

(9) Public Opinion

Public Opinion encompasses factors such as visual effects of having different urban wind farms. Public opinion occasionally contradicts viable solutions such as limiting the height of HAWT because of the aesthetic requirements of the city. The implementation of VAWT in urban areas has a high receptivity, specifically with highly educated people, compared to the intrusive HAWT [7].

(10) Noise

The noise associated with a wind turbine comes from two main sources: aerodynamic and mechanical with the former being the dominant source [6]. Since urban wind farms are located directly in the urban environment, the noise levels the turbines generate are important to consider. Wind turbines, in general, are quiet, especially in an urban environment where other forms of noise will overpower the turbine. 63% of small wind turbines produce less than 40dB with a wind speed of 5m/s which is quieter than a conversation from 5 meters away [8]. Despite the low noise level of wind turbines, VAWT is considered relatively silent due to the lower operating speeds compared to HAWT which limits the aerodynamic noise.

(11) Biodiversity

The effects of urban wind farms on the local biodiversity are through the reported bird and bat strikes responsible by the wind turbines. Even though bird kills due to wind turbines are statistically irrelevant when compared to domestic cats, building and vehicle strikes [6]; reducing the effect on biodiversity is naturally an important aspect of urban wind farms. Furthermore, mitigating strikes were reported as the most desirable future of a wind turbine to the public [7]. The VAWT is considered more desirable with mitigating strikes since the turbine has a smaller swept area for the corresponding output compared to HAWT.

B.4 Economical Aspects

(12) Annual Energy Yield

The annual energy yield considers the operating capacity of the wind turbine and represents the total amount of energy that can be displaced from the grid. The energy yield over the year will be the amount of energy and money that the customer can save and thus is an important parameter for the implementation of urban wind farms. The energy yield of the VAWT is considered favourable since the turbines can operate over a wider range of conditions such as omnidirectional wind patterns and increased turbulence.

(13) Maintenance and Operation Costs

The maintenance and operation costs are the associated expenses of operating a wind farm and is considered an annual payment. This cost is important to consider for an urban wind farm since the turbines are located on the top of the building which may be difficult to access which would increase the costs. Furthermore, the costs of operation of the turbines should be minimized to make the wind farm more economical from the electricity outputted. The maintenance required entirely depends on the wind turbines and the manufacture. Generally, all wind turbines need inspections on the blades, brushes, slip rings, seals, nuts and bolts, and joints. The VAWT is considered to have a slight advantage because the generator and components of the turbine are located closer to the ground compared to HAWT. Having the moving parts located close to the ground makes the accessibility better for maintenance and thus lowers the cost.

(14) Turbine Cost

The turbine cost refers to the upfront cost of purchasing the wind turbine. The turbine cost is important with respect to urban wind farms because since the energy yield is less than large scale wind farms, the cost should be low enough so that it can be recovered through generating electricity. The HAWT is considered more cost-effective compared to the VAWT due to the maturity of the concept which makes manufacturing costs reduced as well as the larger material costs required for some VAWT designs.

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Implementation of Urban Wind Farms in Winnipeg, MB, Canada

Final Report

Appendix C

Concepts for Quantitative Analysis

Contents

List of Figures

C.1 Introduction

A total of 10 varying VAWT designs were selected for the analysis which are introduced and discussed below. An example of an existing project that each turbine has been used are presented alongside the technical specifications for each.

(1) Ropatec WRE-030

The Ropatec WRE 0.30 is the 3kW model, savonius type VAWT offered by the company Ropatec and is shown in Figure 1.

Figure 1. Ropatec WRE-030 wind turbine [1].

The turbine has been used in multiple small operations such as the Monte Cimone Research station located in Italy [2].

The technical specifications of the turbine are shown in Figure 2.

Ropatec S.p.a.

VAWT from 0,75 kW to 6 kW.

Contact name: Hannes Riegler
Address: Via Siemens 19
Telephone: +39 0471 568 180
Country : **Italy**

Ropatec WRE.30 references

Site	Use	Country
Monte Cimone	Research station	Italy
Foggia	Support for electrical pumps	Italy
Sennes	Refuge	Italy
Marchetti	Refuge	Italy

WRE.030 / 3 kW

Technical information

POWER		Unit
1) Rated power	3	kW
2) Rated wind speed	14	m/s
3) Cut-in wind speed	2	m/s
4) Cut-out wind speed	None	m/s
5) Maximum wind speed the turbine can withstand	> 150	Km/h
DIMENSIONS		
6) Rotor weight	~430	kg
7) Rotor diameter	3.3	m
8) Rotor height (for VAWT only)	2.2	m
9) Swept area	7.26	m^2
10) Height of the mast	Not relevant	m
OTHER INFORMATION		
11) Maximum rpm	100 to 120	At rated wind speed
12) Gear box type	No gear box – direct driven	
13) Brake system	Not required	
14) Number of blades	2	
15) Blades material	Aluminium	
16) Output voltage	0 - 220	V
17) Minimum operation temperature	- 30	°C
18) Maximum operation temperature	+ 50	°C
19) Acoustic levels at a distance of 20 m ? at nacelle ? (wind = 5 m/s)	Not audible	DB
20) Lifetime	15/20	Years
21) Is the machine self-starting	Yes	
22) Use of an asynchronous generator	No	
23) Yaw control system	Independent of wind direction	
24) Upwind or downwind	Upwind turbine	

Calculated power curve

Wind speed (m/s)	Power* (kW)
1	0.01
2	0.02
3	0.03
4	0.06
5	0.12
6	0.22
7	0.35
8	0.52
9	0.74
10	1
11	1.3
12	1.7
13	2.2
14	2.8
15	

* electrical output, sea level, temp. 15°C

Power curve:

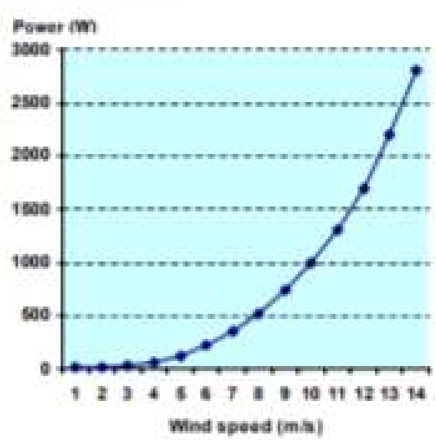


Figure 2. Technical specifications for Ropatec WRE-30 [2].

(2) Ropatec WRE-060

The Ropatec WRE 0.60 is the 6kW model, savonius type VAWT offered by the company Ropatec and is shown in Figure 3.

Figure 3. Ropatec WRE-060 wind turbine [3].

The turbine has been used in multiple small operations such as a water heating system in the Valley of Aeste located in Italy [2].

The technical specifications of the turbine are shown in Figure 4.

Ropatec S.p.a.

VAWT from 0,75 kW to 6 kW.

Contact name:	Hannes Riegler
Address:	Via Siemens 19
Telephone:	+39 0471 568 180
Country :	**Italy**

Ropatec WRE.060 references

Site	Use	Country
Valley of Aoste	Water heating system	Italy
Hallau	On-grid system	Switzerland
Townsville	Demonstration unit	Australia

WRE.060 / 6 kW

Technical information

POWER		Unit
1) Rated power	6	kW
2) Rated wind speed	14	m/s
3) Cut-in wind speed	2	m/s
4) Cut-out wind speed	None	m/s
5) Maximum wind speed the turbine can withstand	> 150	Km/h
DIMENSIONS		
6) Rotor weight	750	kg
7) Rotor diameter	3,3	m
8) Rotor height (for VAWT only)	4,4	m
9) Swept area	14,52	m^2
10) Height of the mast	Not relevant	m
OTHER INFORMATION		
11) Maximum rpm	110	At rated wind speed
12) Gear box type	No gear box – direct driven	
13) Brake system	None	
14) Number of blades	2	
15) Blades material	Aluminium	
16) Output voltage	220	V
17) Minimum operation temperature	- 30	°C
18) Maximum operation temperature	+ 50	°C
19) Acoustic levels at a distance of 20 m ? at nacelle ? (wind = 5 m/s)	Not audible	DB
20) Lifetime	15/20	Years
21) Is the machine self-starting	Yes	
22) Use of an asynchronous generator	No	
23) Yaw control system	independent of wind direction	
24) Upwind or downwind	Upwind turbine	

Calculated power curve

Wind speed (m/s)	Power*(kW)
1	0
2	0
3	0.05
4	0.10
5	0.25
6	0.40
7	0.70
8	1
9	1.5
10	2
11	2.7
12	3.5
13	4.5
14	5.6
15	6
* electrical output, sea level, temp. 15°C	

Power curve:

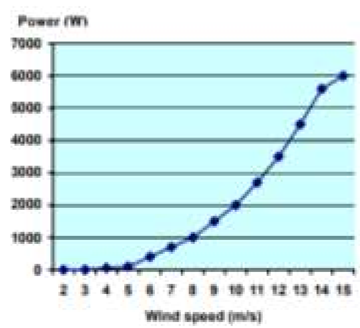


Figure 4. Technical specifications for Ropatec WRE-60 [2].

(3) Ropatec SA40

The Ropatec SA40 is the 10kW model, darrieus H type VAWT offered by the company Ropatec and is shown in Figure 5.

Figure 5. Ropatec SA40 wind turbine [4].

The SA40 is a turbine in the new phase of ropatec wind turbines and has been installed in many locations such as the Mario Zucchelli Station located in Antarctica which utilizes three SA40 turbines to be completely self-reliant [5].

The technical specifications of the turbine are shown in Figure 6.

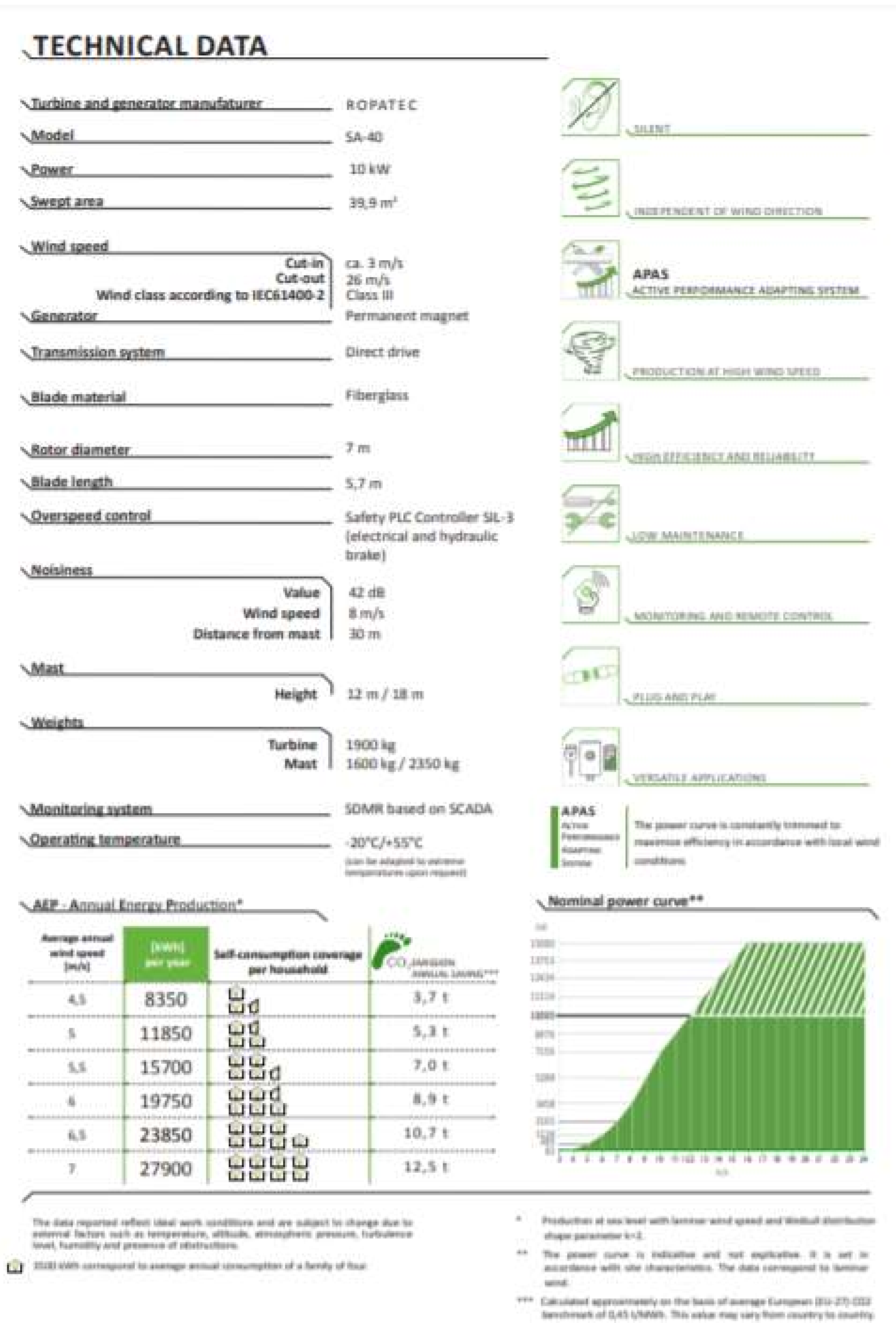


Figure 6. Technical specifications for Ropatec SA40 [6].

(4) Ropatec T30proS

The Ropatec TA30proS is the 30kW model, darrieus H type VAWT offered by the company Ropatec and is shown in Figure 7.

Figure 7. Ropatec T30proS wind turbine [7].

The T30proS turbine is the keystone turbine that Ropatec is producing and has the most installations out of the company's fleet. The T30proS turbine has been utilized for an off-shore application in Sweden [8].

The technical specifications of the turbine are shown in Figure 8.

Figure 8. Technical specifications for Ropatec T30proS [9].

(5) OY Windside Production Ltd WS-12

The Windside WS-12 is the 8kW model, savonius type VAWT offered by the Finland based company Oy Windside Production Ltd. and the turbine is shown in Figure 9.

Figure 9. Windside WS-12 wind turbine [10].

A notable installation of this turbine is in the shopping mall tower in Raisio Finland where two turbines were installed in 2001 [11].

The technical specifications of the turbine are shown in Figure 10.

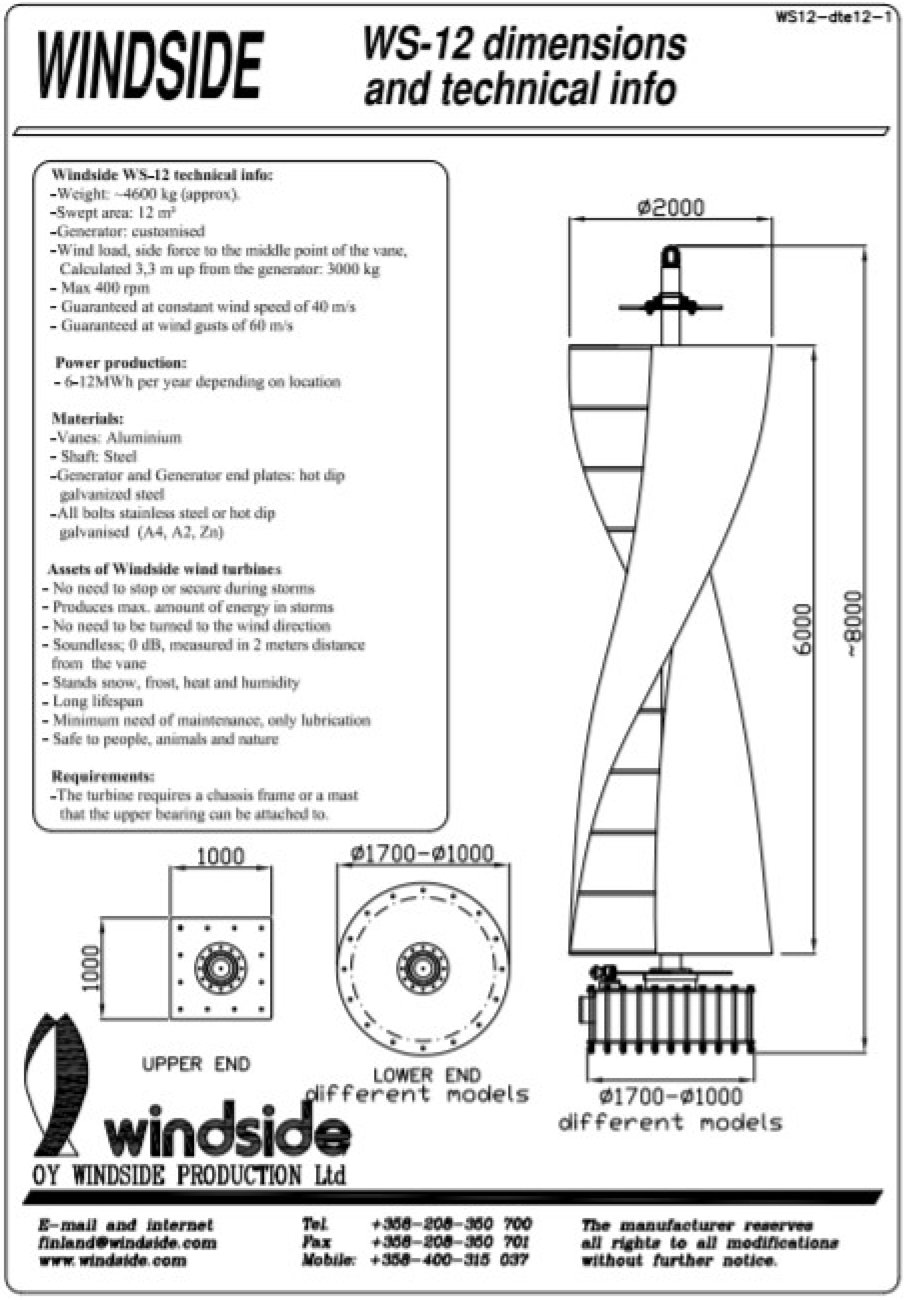


Figure 10. Technical specifications for Windside WS-12 [12].

(6) HEA Energy Ball V100

The HEA Energy Ball V100 is the 0.5kW model, alternative HAWT offered by the Netherland based company Home Energy and the turbine is shown in Figure 11.

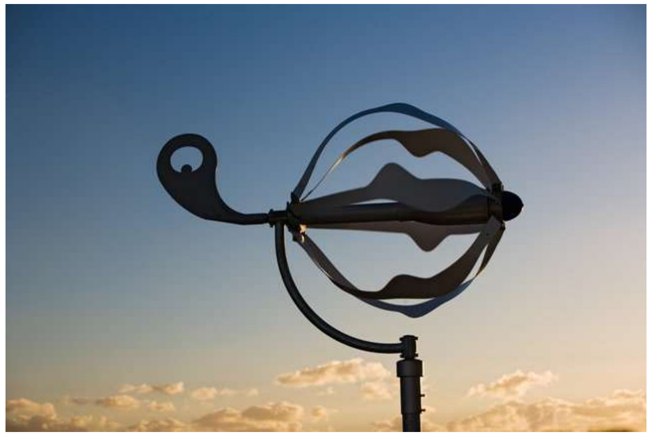


Figure 11. Home Energy V100 wind turbine [13].

The previous installations of the V100 are generally for residential purposes or other applications that require little energy due to the low capacity of the wind turbine.

The technical specifications of the turbine are shown in Figure 12.

HEA Energy Ball® V100 Specification Sheet

Name	Energy Ball®	**Metric**
Type	V100	
Power		
Maximum power	500 W	500 W
Cut in wind speed	4.5 mph	2 m/s
Survival wind speed	90 mph	40 m/s
Dimensions		
Rotor diameter	3.6 ft	1.1 meters
Rotor weight	66 lbs	30 kg
Rotor surface	10.76 ft^2	1 square meters
Height of mast	30 - 36 ft	9 or 11 meter (incl.V100)
Generator		
Type	Permanent Neodymium magnet	
Number of poles	12	
Number of phases	3	
Other information		
Maximum rotation speed at 40 m/s	2100 rpm	
Transmission	None	Direct driven, no gearbox needed
Brake system	Electrical	
Number of blades	6	
Blades material	Reinforced Glass Fiber Polyester	
Output voltage	120 V	230 V
Output frequency	60 Hz	50 Hz
Minimum operation temperature	-13° F	-25° C
Maximum operation temperature	122° F	50° C
Acoustic level	Below discernable background noise	
Minimum lifetime	25	years
Starting procedure	None	(V100 is self starting)
Yaw control system	None	(V100 yaws itself in the wind)

Figure 12. Technical specifications for Home Energy V100 [14].

(7) HEA Energy Ball V200

The HEA Energy Ball V200 is the 2.5kW model, alternative HAWT offered by the Netherland based company Home Energy and the turbine is shown in Figure 13.

Figure 13. Home Energy V200 wind turbine [15].

Similar to the V100 model, the V200 wind turbine has limited previous installations for small scale projects.

The technical specifications of the turbine are shown in Figure 14.

HEA Energy Ball® V200 Specification Sheet

Name	Energy Ball®	**Metric**
Type	V200	
Power		
Maximum power	2500 W	2500 W
Cut in wind speed	6.7 mph	3 m/s
Survival wind speed	90 mph	40 m/s
Dimensions		
Rotor diameter	6.5 ft	1.98 meters
Rotor weight	198 lbs	90 kg
Rotor surface	40.9 ft^2	3.8 square meters
Height of mast	40 – 50 ft	12 or 15 meter (incl.V200)
Generator		
Type	Permanent Neodymium Magnet	
Number of poles	12	
Number of phases	3	
Other information		
Maximum rotation speed at 40 m/s	700 rpm	
Transmission	None	Direct driven, no gearbox needed
Brake system	Electrical	
Number of blades	5	
Blades material	Reinforced Glass Fiber Polyester	
Output voltage	120 V	230 V
Output frequency	60 Hz	50 Hz
Minimum operation temperature	-13° F	-25° C
Maximum operation temperature	122° F	50° C
Acoustic level	Below discernable background noise	
Minimum lifetime	> 15	years
Starting procedure	None	(V200 is self starting)
Yaw control system	None	(V200 yaws itself in the wind)

Figure 14. Technical specifications for Home Energy V200 [14].

(8) Quiet Revolution Qr6

The Quiet Revolution Qr6 is the 7.5kW model, helical Darrius VAWT offered by the United Kingdom-based company Quiet Revolution and the turbine is shown in Figure 15.

Figure 15. Quiet Revolution Qr6 wind turbine [16].

Two qr6 wind turbines were installed in 2015 for the German Soccer League team Rot-Weiss Essen Football Clubs new stadium [17].

The technical specifications of the turbine are shown in Figure 16.

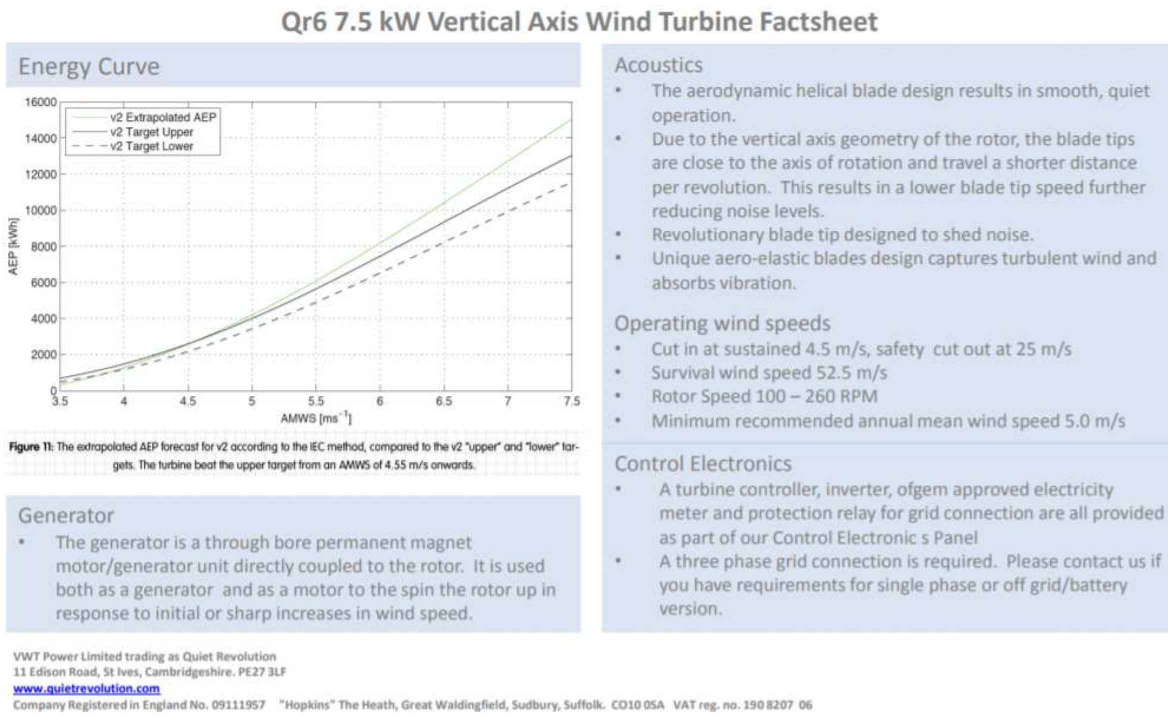


Figure 16. Technical specifications for Quiet Revolution Qr6 [18].

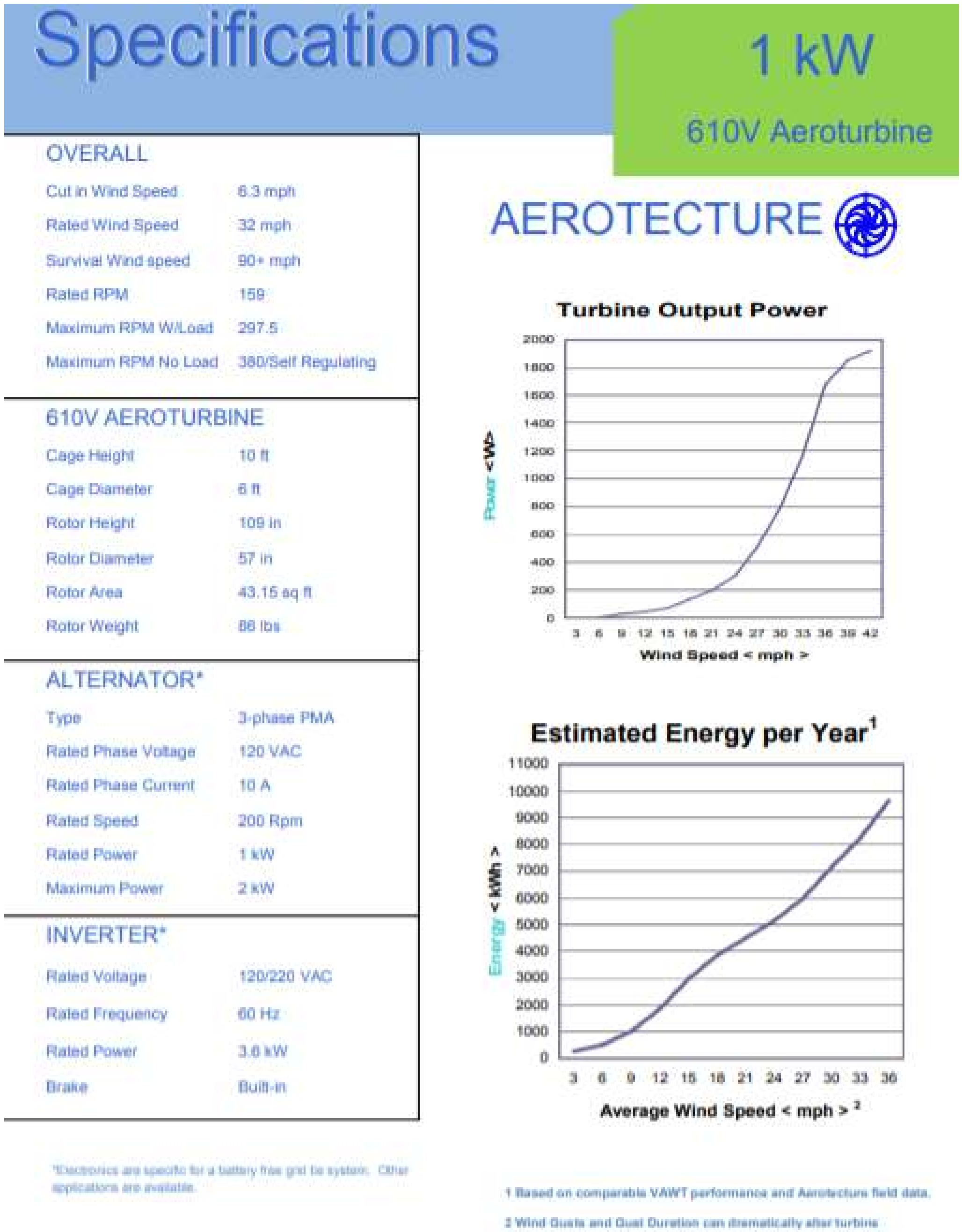
(9) Aerotecture 610V

The Aerotecture 610V is the 1kW model, Darrius VAWT offered by the United States-based company Aerotecture International Inc. and the turbine is shown in Figure 17.

Figure 17. Aerotecture 610V wind turbine [19].

The company has 11 major projects that their turbines have been used including the two 610V turbines located on the IBEW Local Union 701 in Warrenville, IL.

The technical specifications of the turbine are shown in Figure 18.



Specifications

1 kW

610V Aeroturbine

AEROTECTURE

OVERALL	
Cut in Wind Speed	6.3 mph
Rated Wind Speed	32 mph
Survival Wind speed	90+ mph
Rated RPM	159
Maximum RPM W/Load	297.5
Maximum RPM No Load	380/Self Regulating
610V AEROTURBINE	
Cage Height	10 ft
Cage Diameter	6 ft
Rotor Height	109 in
Rotor Diameter	57 in
Rotor Area	43.15 sq ft
Rotor Weight	86 lbs
ALTERNATOR*	
Type	3-phase PMA
Rated Phase Voltage	120 VAC
Rated Phase Current	10 A
Rated Speed	200 Rpm
Rated Power	1 kW
Maximum Power	2 kW
INVERTER*	
Rated Voltage	120/220 VAC
Rated Frequency	60 Hz
Rated Power	3.6 kW
Brake	Built-in

*Electronics are specific for a battery free grid tie system. Other applications are available.

1 Based on comparable VAWT performance and Aerotecture field data.

2 Wind Gusts and Gust Duration can dramatically alter turbine

Figure 18.Tecnhical specifications for Aerotecture 610V [20].

(10) Aerotecture 712V

Figure 19. Aerotecture 712V wind turbine [21].

A project worth noting from the many projects Aerotecture wind turbines have used is the four 712V wind turbines were installed in the company's first every high-rise installation on the Harold Washington Social Security Center located in Chicago [22].

The technical specifications of the turbine are shown in Figure 20.

Figure 20. Technical specifications for Aerotecture 712V [23].

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UNIVERSITY OF WATERLOO

Implementation of Urban Wind Farms in Winnipeg, MB, Canada

Final Report

Appendix D

Quantitative Criteria

Contents

List of Figures

List of Tables

D.1 Introduction

Each criterion used in the quantitative analysis is presented in this section with the main equations used. The calculations for each criterion for all ten turbines are presented for the two criteria sections and each turbine is ranked with respect to the others with the larger magnitude indicating the better performing turbine in that case.

D.2 Performance Aspects

The performance aspects selected were used in the decision matrix to rank the turbines in order of the best performing to worst. The performance criteria that was used in this section included the non-dimensional parameters of the tip speed ratio, power coefficient and power specific tip speed. Furthermore, the capacity factor and wind potential dependent efficiency coefficient was determined for each turbine.

Performance Coefficient (C_p)

The power coefficient, C_p, of each VAWT was determined from equation (1), using the rotor power, P_{rotor}[kW] as specified in the power curve, swept area, A $[m^2]$, wind velocity from power curve, u, and density of air, $\rho = 1.225 kg/m^3$ [1].

$$C_p = \frac{P_{rotor}}{\frac{1}{2}\rho A u^3} \tag{1}$$

Turbines with larger coefficients of power represent machines that have lower losses and thus capture more energy. The decrease in power is due to three main effects, wake rotation behind the rotor, finite number of blades and associated tip losses, and non-zero aerodynamic drag [2].

Tip Speed Ratio

The tip speed ratio for the VAWT's was determined by using the operating angular velocity, ω [rad/s], rotor radius, R [m] and the wind velocity, v [m/s]. The tip speed ratio was determined by equation (2) [3].

$$TSR(\lambda) = \frac{tangential\ speed\ of\ blade\ tip}{wind\ speed} = \frac{\omega R}{v} \tag{2}$$

Turbines with higher speed ratios are favourable since higher ratios indicate that the rotor operates at higher speeds which means it will have less blade area than a slower rotor. Less blade area is advantageous since it indicates fewer blades, lower cost, and less weight. Furthermore, high-speed turbines use lower torque for the corresponding power outputs which means the turbine can be self-starting [2].

The performance coefficients and tip speed ratios for the concepts are shown in Figure 1 overlaid other machines general performance.

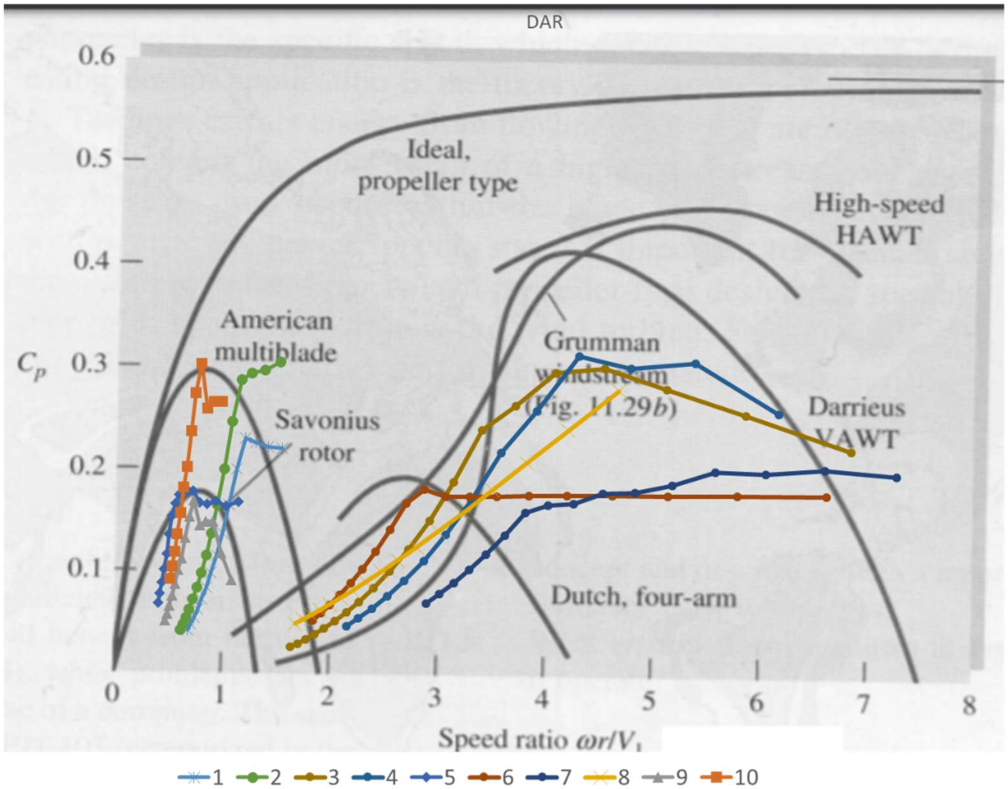

Figure 1. Performance coefficient and the tip speed ratio of VAWT' s concepts [4].

The different operating ranges of the turbines are clear in Figure 1. The Darrius VAWT turbines match closely with the average turbine line, but none reach the expected coefficient of performance with the closest being the Ropatec T30proS at 0.309. The Savonius VAWT line matches the results of the WindSide Production WS-12 well while the other Savonius turbines show improved performance.

Power Specific Tip Speed

The power specific tip speed for the VAWT's was determined from equation (3) and substituting the maximum power coefficient, C_p and corresponding tip speed ratio, λ.

$$N_{ts} = C_p\lambda^2 \tag{3}$$

Larger power specific tip speeds indicate that the turbines are performing more efficiently but compromise with tip speed. The power specific tip speeds for the corresponding tip speed ratio for the design concepts are shown in Figure 2 overlaid with other machines general performance.

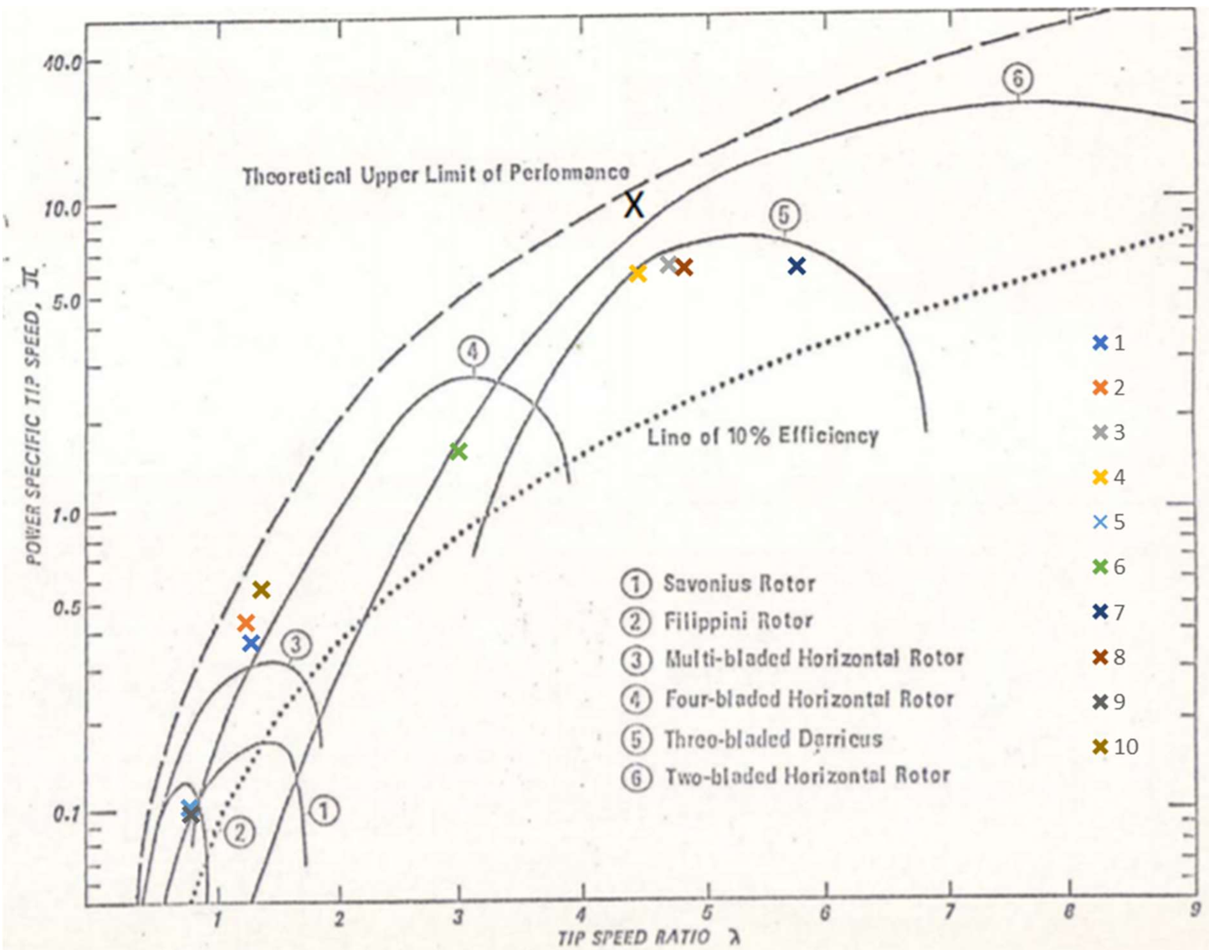

Figure 2. Power specific tip speed for VAWT design concepts [4].

The results of the power specific tip speed are all within the expected ranges for the turbine types. The Home Energy Energy Ball V100 which is a modified HAWT concept matches the two-bladed horizontal rotor line.

The results and ranking of the concepts for the first three criteria are summarized in Table I.

TABLE I: PERFORMANCE CRITERIA RANKING

Code	Rated Power [kW]	Performance Coefficient (C_p)	Rank	Tip Speed Ratio	Rank	Power Specific tip speed	Rank
1	3	0.229	5	1.234	4	0.350	3
2	6	0.287	7	1.196	3	0.410	4
3	10	0.297	8	4.561	8	**6.176**	**10**
4	30	**0.309**	**10**	4.320	7	5.770	7
5	8	0.178	2	0.748	1	0.100	2
6	0.5	0.179	3	2.891	6	1.499	6
7	2.5	0.196	4	**5.582**	**10**	6.094	9
8	7.5	0.275	6	4.689	9	6.049	8
9	1	0.169	1	0.753	2	0.096	1
10	2.5	0.302	9	1.318	5	0.524	5

Capacity Factor

The capacity factor of a wind turbine is the ratio of the energy produced over the energy that could have been produced if the machine was operating at the rated power. The factor is determined from equation (4) using the annual energy production calculated and the rated power of each turbine [2].

$$CF = \frac{Annual\ Energy\ Production}{Rated\ Annual\ Potential} * 100 \quad (4)$$

Larger capacity factors receive a higher ranking because this indicates that the turbine is operating close to the rated power which will result the largest energy yield. Small capacity factors indicate that the turbine is operating at a lower power output which may mean the wind speed is consistently lower than the rated wind speed for the turbine.

Wind Potential Dependent Efficiency Coefficient (C_E)

Differing from the performance coefficient, the wind potential dependent efficiency coefficient represents the fraction of power extracted by the turbine by the wind potential that is present at the location of the wind turbine. The coefficient is calculated using the annual energy production and annual wind potential as shown in equation (5) [5].

$$C_E = \frac{Annual\ Energy\ Production}{Annual\ Wind\ Potential} * 100 \quad (5)$$

The annual wind potential was determined by equation (6).

$$P_{wind} = \frac{1}{2}\rho A u^3 \quad (6)$$

Larger efficiency coefficients rank higher because this shows that the turbine is extracting more energy from the wind than other turbines. Higher coefficients may be a result of the wind speeds being in the optimal range of the wind turbines to produce most power or lower cut-in speeds.

The final two criteria under the performance aspects are ranked and the results summarized in Table II.

TABLE II: CAPACITY AND EFFICIENCY COEFFICIENT RANKING

Code	**Rated Power [kW]**	**Power [kWh]**	**Power Density [kWh/m^2]**	**Power in Wind [kWh]**	**Capacity Factor [%]**	**Rank**	**Efficiency Coefficient (C_E) [%]**	**Rank**
1	3	4140	570.30	19305	16%	6	21%	6
2	6	10965	755.21	38611	21%	7	28%	9
3	10	22431	562.18	106101	26%	9	21%	5
4	30	77384	586.25	351014	**29%**	**10**	22%	7
5	8	5512	459.38	31910	8%	1	17%	3
6	0.5	453	453.95	2659	10%	3	17%	2
7	2.5	1919	505.04	10104	9%	2	19%	4
8	7.5	14025	876.59	42547	21%	8	**33%**	**10**
9	1	1332	332.36	10660	15%	5	12%	1
0	2.5	3330	593.78	14917	15%	4	22%	8

D.3 Economic Aspects

The economic criterion was used to rank the turbines in order of the most economically viable order. The criterion selected for the economic analysis was the Levelized cost of energy which was determined for each turbine.

Levelized Cost of Energy

The Levelized Cost of energy represents the cost of energy for the specific turbine over the lifetime of the system [6]. The cost was determined from equation (7) using the net present value (NPV) and the annual energy production (AEP) for each turbine in the units of $/kWh.

$$COE_L = \frac{NPV}{AEP} \tag{7}$$

The net present value of each turbine was calculated conservatively from the cost of each turbine and the energy the benefit of reducing energy consumption per year. The net present value of the project is estimated using equation (8)

$$NPV = -CCWT + \sum_{n=1}^{N} \frac{ENC}{(1+i)^n} \tag{8}$$

Where CCWT is the capital cost of the wind turbine, ENC is the annual savings from displacing grid electricity, i is the rate of inflation, and N is the lifespan of the turbine [7]. The cost and lifespan data for each turbine is presented in Table III.

TABLE III: TURBINE COST AND LIFESPAN DATA

Code	Rated Power	Cost	Reference	Lifespan	Reference
1	3	$12909	[8]	15	[9]
2	6	$21166	[10]	15	[9]
3	10	$43000	*	25	[11]
4	30	$138360	[12]	25	[11]
5	8	$422964	[13]	50	[9]
6	0.5	$2390	[14]	25	[15]
7	2.5	$4915	[16]	15	[15]
8	7.5	$62113	[17]	30	[18]
9	1	$15000	[19]	30	[20]
10	2.5	$25000	[21]	30	[20]

A summary of the economic criteria calculations and results are shown in Table IV.

TABLE IV: ECONOMIC CRITERIA SUMMARY AND RANKING

Code	Lifespan [yrs.]	Annual Energy Yield [kWh]	Cost ($CAD)	ENC [$/year]	NPV [$CAD]	Levelized Cost of Energy	Rank
1	15	4140	$ 12,909.12	$ 336.58	-$ 8,584.29	2.07	6
2	15	10965	$ 16,063.03	$ 891.45	-$ 4,608.50	0.42	8
3	25	22431	$ 43,000.00	$ 1,823.64	-$ 7,396.24	0.33	9
4	25	77384	$ 138,360.38	$ 6,291.32	-$ 15,532.08	**0.20**	**10**
5	50	5512	$ 422,963.71	$ 448.13	-$408,881.99	74.18	1
6	25	453	$ 2,389.59	$ 36.83	-$ 1,670.56	3.69	4
7	15	1919	$ 4,915.03	$ 156.01	-$ 2,910.36	1.52	7
8	30	14025	$ 62,113.39	$ 1,140.23	-$ 36,576.22	2.61	5
9	30	1332	$ 15,000.00	$ 108.29	-$ 12,574.65	9.44	2
10	30	3330	$ 25,000.00	$ 270.73	-$ 18,936.63	5.69	3

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