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Distributed Wind Energy

Bachelor thesis 2024
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List of Acronyms and Abbreviations

Term	Description
DES	Distributed Energy System
BC	Before Christ
OpEx	Operational Expenditures
CapEx	Capital Expenditures
hh	Hub height
kW	Kilowatt
DOE	U.S. Department of Energy
NREL	National Renewable Energy Laboratory
O&M	Operations and maintenance
LCOE	Levelized cost of electricity

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1. Abstract

Renewable energy systems such as wind energy are a growing market. This thesis describes how a wind turbine works, investigates distributed wind energy systems, and develops a framework for choosing the most suitable wind turbine system for an end user with regards to technological and economic issues. The study was conducted by collecting wind speed, power demand and power output data from different wind turbines with power capacities of 110 kW, 150 kW and 250 kW which was then used to model and evaluate a use case.

The data was compared with regards to different variables such as number of turbines and hub heights, and then gathered in graphs and tables to finalize the framework. It resulted in a baseline framework which can tell most end users step by step how to do an analysis themselves and help them choose the wind turbine model that fits their use-cases. Additionally, for our analysis it resulted in the 150-kW turbine being the most suitable in a techno-economic sense. This turbine was the most viable for our use case simulation with the least fluctuations and the shortest payback period.

2. Introduction

Humans have used wind as an energy source through all of history, from powering boats 5000 years BC to the big wind farms today. It has been used for water pumps, food production, windpumps etc., and the very first wind turbines, originated in the Netherlands and called windmills, used the energy directly to grind grain or minerals. Eventually it was learned how to convert the power of the wind over to electricity, which became the start of the modern wind turbine. Today, wind power is used in a broad spectrum ranging from small/direct use to big wind electricity farms. Global climate change has sparked this technology because wind power is a renewable energy source. Non-renewables such as coal, oil and gas which were the world's primary energy sources as of 2024, have a shortage and are also very pollutant and thus contributing negatively to climate change [1].

In the European distributed energy systems, the small wind turbine market is a growing market and there is a wide range of applications which are starting to integrate Distributed Energy Systems (DESs). Distributed wind energy has the potential to provide support to the grid in the form of voltage support, frequency response, reserve power etc. Wind energy is commonly utilized on the larger utility-scale with large wind farms that provide power to the main electricity grid. To use wind in DESs, a framework is essential. Such a framework needs to include techno-economic evaluations based on the end user needs and use case for more informed decisions.

In this thesis the primary task will be to develop a framework to improve and help the decision making of end users in finding the best possible wind turbine system for different use cases. It will contribute to end users more rapidly finding the turbine which is the most suitable for their demand from both a technological and economic perspective, without having to work out all the calculations from scratch. For this thesis it is assumed that the power from the turbines can be stored and used later when the wind is insufficient. The focus of the framework will be the payback period for the system. A payback period tells how many years it will take for something such as a distributed energy system to pay back all its capital investments and operational costs by the savings in Operational Expenditure (OpEx) that come from using the DES instead of electricity from the grid. The framework will be developed by choosing a basic end user with a power demand and a small selection of turbines which are thought to be a good match for the end user. It will be developed through a trial-and-error process of finding the best system including defining and testing different variables and analysing power curves and power output and power demand graphs. The variables used are turbine models, number of turbines and hub height. Finally, based on the test results, the framework will be finished and can be used as a general instruction manual by a wide range of end users with no or limited prior engineering knowledge.

The geographical focus of this thesis is in Norway, on the west coast. The local climate at this location includes a lot of wind. This makes wind energy application one of the most reliable and available renewable energy sources, opposite to for example solar power which requires a certain amount of sun rays (of which there are in more southern parts of the earth) to be viable. Norges vassdrags- og energi direktorat (NVE) estimate that the possibility of converting wind energy to electricity is several thousand TWh/year. However, this requires massive land areas and financial investments to achieve [2].

3. Basics of wind energy

Through this chapter the basics of wind energy will be presented, from how the wind occurs to how a wind turbine functions.

3.1. Where does the energy come from?

Air in motion, what we call wind, is derived from the sun, and can therefore be called a form of solar energy, which is the fact for most renewable energy sources. Wind is caused by the sun in diverse ways. The sun is unevenly warming up the earth, causing temperature and pressure differences around the globe. These differences cause air to move, going from high pressure to low pressure, creating wind. Also, the irregularities on the earth's surface causes friction with the air in motion, causing the wind to change speed and direction. The rotation of the earth also influences the air to move, described as the Coriolis effect [4].

3.2. How does a wind turbine work?

There are two basic types of wind turbines: the horizontal-axis turbines and the vertical-axis turbine as shown in Figure 3.1, which both convert energy to electricity the same way. In this thesis, the horizontal-axis turbines are studied which also are the most common type of turbine.

As already mentioned, a wind turbine uses wind to generate mechanical power or electricity. It uses the aerodynamic forces from the rotor blades and pressure differences in the air flowing through the turbine. The pressure on one side of a rotor blade decreases as the wind flows through and creates lift and drag forces on each side of the blades, causing the rotor to spin. This rotor is connected to a generator, which creates electricity from the spinning rotor [4].

Wind turbines consist of typical main components such as the tower, which has the turbines standing. A taller tower gives a higher hub height and accessibility to stronger wind speeds. On top of the tower is the nacelle which contains the generator, gear box and components that convert the energy from the blades into electricity when the wind speed is above the cut in speed, which is the minimum wind speed a wind turbine begins to generate electricity efficiently. The rotor hub attaches the rotor blades to the main shaft. The rotor blades are attached to the rotor hub and are shaped and angled to capture the energy of the wind. The main shaft extends from the rotor hub through the nacelle and connects the gearbox to the rotor hub.

The gear box increases the rotational speed of the main shaft and converts the mechanical energy into electrical energy using a generator. The yaw system in a wind turbine makes sure the turbine faces the wind and the anemometer measures the wind speed and direction to optimize the performance [5].

If a wind speed higher than the cut-out speed occurs (the maximum speed the wind turbine can operate safely with) there are brakes who stops the rotor blades in such high winds.

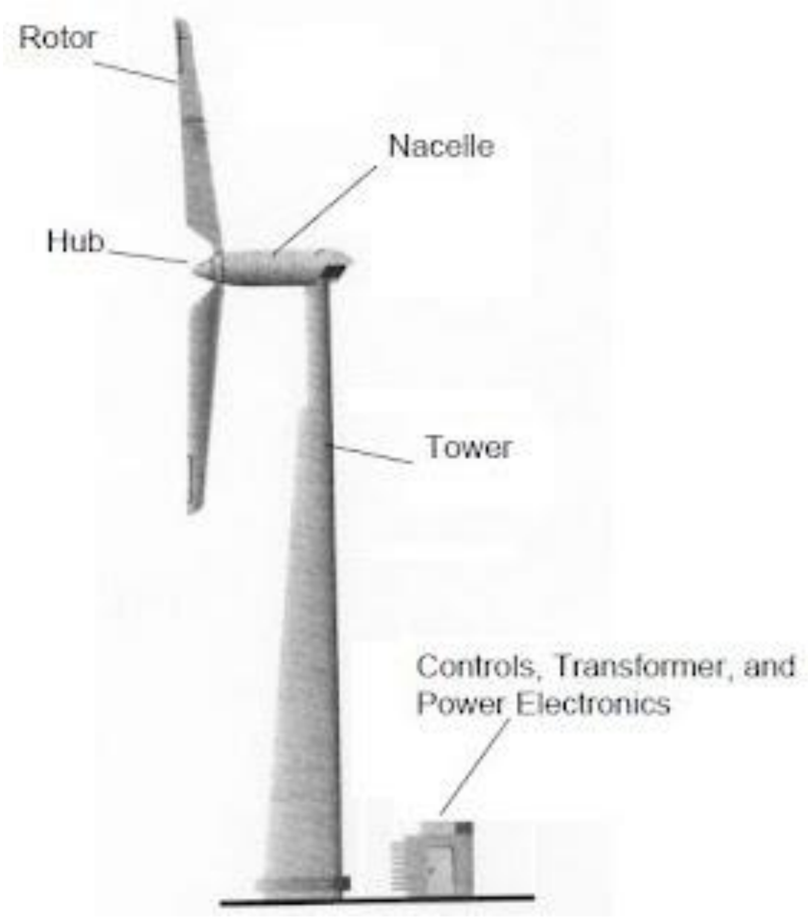


Figure 3.1: Parts of a vertical wind turbine [14]

4. Methodology

This chapter will go through the complete process of developing the framework in detail, starting with selecting an end user and ending with a completed framework. More detailed it will go through the data collection analysis and visualize the selection of power output regarding the power demand. This is done to be able to find the best fitted wind turbine for the chosen demand. Evaluation is done by comparing the different turbines with different variables such as hub height, capacity, and number of turbines. The turbines are sorted by capacities, lowest to highest.

First the power data is shown in a table for each turbine, then the generation of the power curve and the power curve equation. Later in discussions the power output with the different variables is shown in graphs together with the power demand of the supermarket and is compared to find the best in each turbine. Finally, the best fits for the turbines are compared to each other to find the most viable turbine. Figure 4.1 shows the following process in steps in a summarized and generic matter.

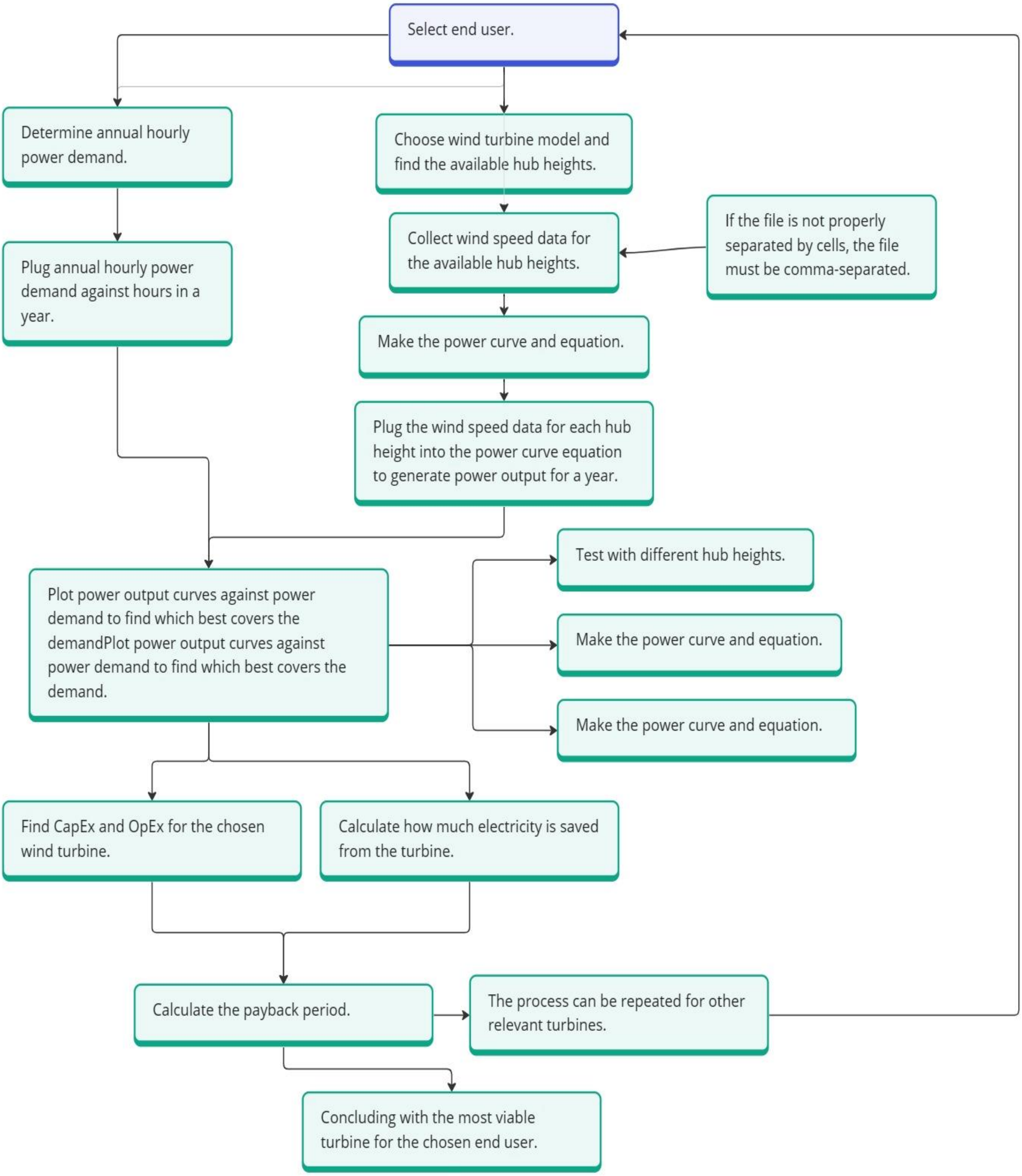


Figure 4.1: Detailed flow chart of the steps in the framework.

4.1. Selection of End User

The chosen end user is a fictional commercial supermarket. One of the main reasons this is the chosen one is because the supermarket has less fluctuations in demand over 24 hours. There are also several supermarkets in Randaberg, which are chosen as the location to find the wind speed data from, so it should be a realistic end user. The graph for the annual power demand for the supermarket is shown in Figure 4.2.

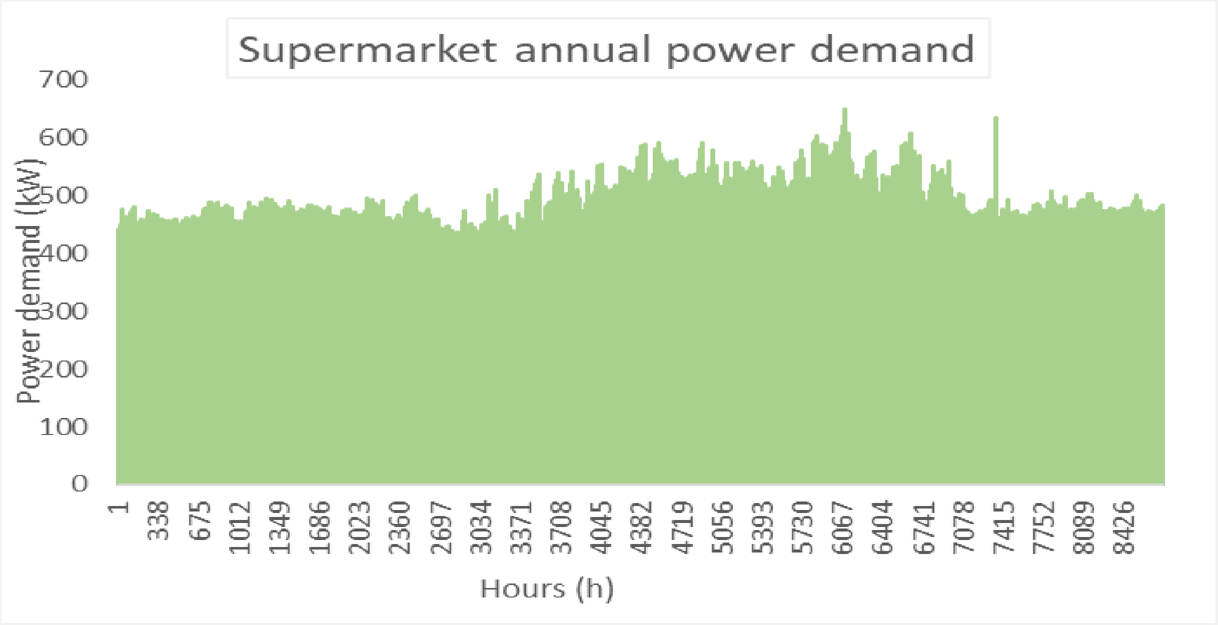


Figure 4.2: Hourly annual power demand for the supermarket.

The fictive power demand data is found in Mendeley Data [8]. The dataset includes 24 representative hourly load profile sets from various end users. The supermarket is simulated and adapted to the state of New Jersey, U.S., with a tool capable of capturing the buildings functionalities. It is used by many researchers to model energy systems such as our distributed wind energy system for engineering, economic and environmental analyses [9].

4.2. Turbine one: Danish Wind Power AS (DWP) D110/19

The power curve data for the DWP 110/19 turbine is made in excel and shown in Table 4.1. A power curve for a wind turbine shows how much power the turbine produces at a given wind speed, and where the cut-in and cut-out speed is (4 and 25 m/s). The output power is taken from wind-turbine-models.com [6].

Table 4.1: Power curve data for the DWP D110/19 wind turbine.

	Power Curve - wind-turbine-models.com
Wind Speed (m/s)	**Output Power (kW)**
4	1
5	8.5
6	18
7	30
8	46
9	60.5
10	75
11	89.5
12	100
13	107
14	109.5
15	111
16	112
17	112.5
18	112
19	111.5
20	110
21	106
22	105.5
23	105
24	105
25	106

From the data in Table 4.1 the power curve for the 110-kW wind turbine is generated in excel by making a polynomial trendline equation of order 5, which was the maximum size of the polynomial, and as many decimal points as possible. These should be high to achieve the best accuracy possible and if not all the decimal points are included, the accuracy will be reduced.

The trendline and power curve is shown in Figure 4.3 and the power curve equation made from this power curve is in Equation 4.2.

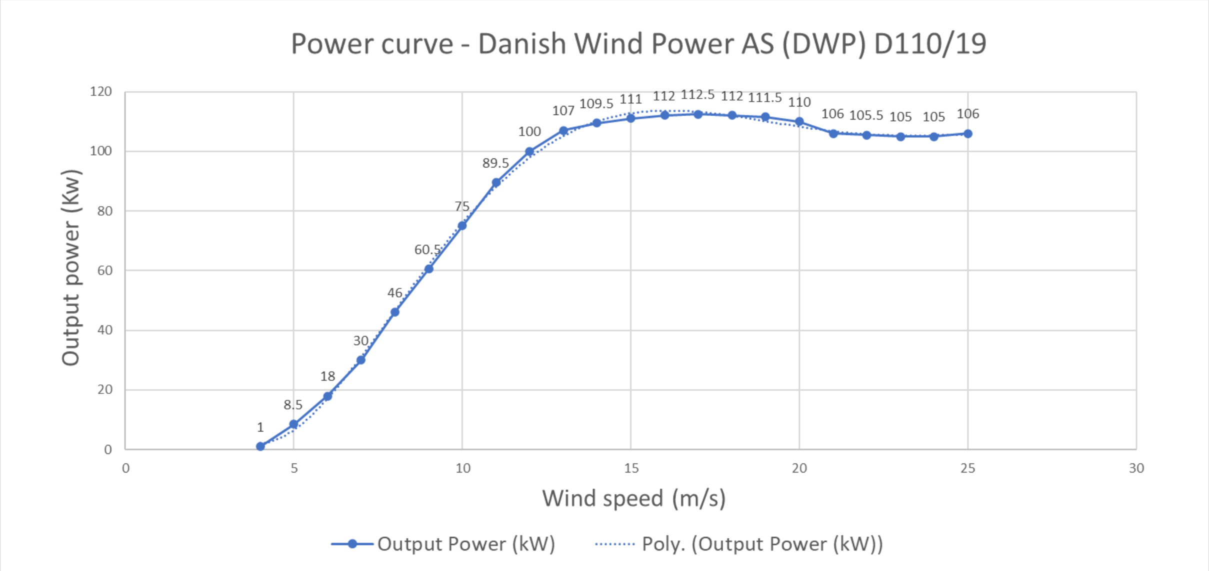


Figure 4.3: Power curve for the 110-kW turbine from Danish Wind Power (DWP) D110/10

Equation 4.1: Power curve equation DWP D110/19

$$\begin{aligned} y = {} & 0.000003449320233x6 - 0.000674550272588x5 + 0.041960160889850x4 \\ & - 1.164247609390830x3 + 14.989629031153400x2 \\ & - 73.507987656742400x + 120.754454774362000 \end{aligned}$$

By using this power equation, the actual annual power output for the turbine is generated by putting in the hourly wind speed data for a year. The wind speed data is taken from windatlas.xyz [7] which is a data site where you can find wind speed data sets at different hub heights and locations, compiled by a study done by the Australian National University [9].

4.3. Turbine two: Nordex group N27 turbine 150 kW

For the wind turbine N27 150 kW the output power was available both on windatlas.xyz [7] and windturbinemodels.com [6]. The power curve for the N27 turbine is made with the data from windturbinemodels.com. In Table 4.2 below the output power per wind speed for this N27 wind turbine is shown.

Table 4.2: Power curve data for N27 150 kW turbine.

Wind Speed (m/s)	**Power Curve - wind-turbine-models.com**
	Output Power (kW)
4	8
5	19
6	31
7	55
8	83
9	110
10	136
11	160
12	170
13	176
14	180
15	175
16	172
17	164
18	155
19	150
20	145
21	145
22	140
23	135
24	130
25	130

By using the power output data from the table above, the power curve is generated in excel. This power curve is shown in Figure 4.4.

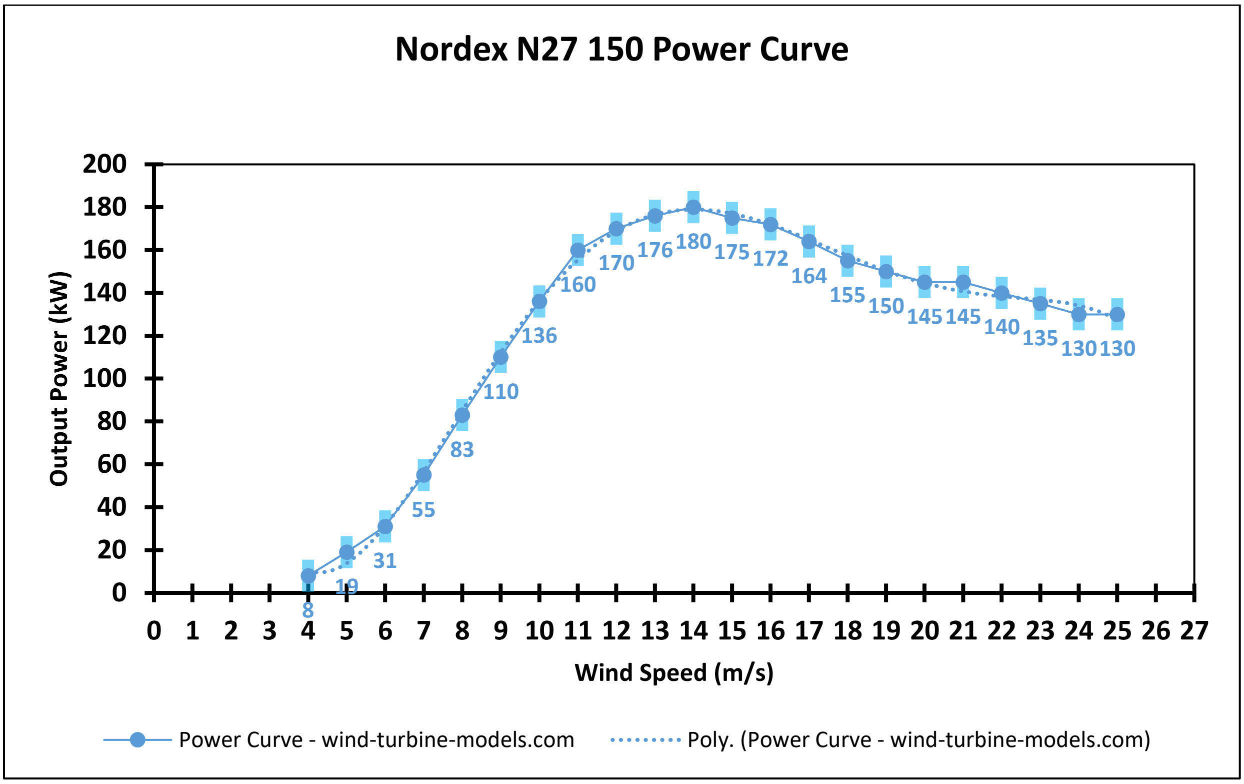


Figure 4.4: Power curve for Nordex N27 150 kW turbine.

Again, the power curve equation is generated from the power curve. The power curve equation is generated with 14 decimal points to get the most accurate data when we later put in the wind speed data. With any fewer decimal points, there would be several small errors throughout the calculations. The power curve equation for the N27 150 kW turbine is shown in Equation 4.2.

Equation 4.2: Power curve equation for the N27 150 kW turbine.

$$y = -0.00117567674846x^5 + 0.09349148630518x^4 - 2.75251377379152x^3 + 35.7341197371566x^2 - 182.345072912157x + 321.508990548777$$

The power curve equation is then used to generate the power output at all the different hub heights. Other variables such as the number of wind turbines and different capacities are also considered. This is to compare the power output for the different variables and discover which combination of hub height and number of turbines is the most viable.

In Table 4.3 the difference between the power output from the N27 wind turbines at different hub heights and the demanded power is calculated.

Table 4.3: Comparison of the difference between the power demand and the output for four N27 wind turbines in each hub height.

	N27 30m hub height [kW]	N27 36m hub height [kW]	N27 40m hub height [kW]	N27 50m hub height [kW]
Demand	4 012 145.9	4 012 145.9	4 012 145.9	4 012 145.9
Power output	1 992 903.698	2 083 331.111	2 141 109.061	2 273 427.451
Difference	2 019 242.202	1 928 814.789	1 871 036.839	1 738 718.449

4.4. Turbine three: Nordex group N29 turbine 250 kW

The data in Table 4.4 shows the output power at different wind speeds for the wind turbine N29 250 kW.

Table 4.4: Power curve data N29.

	Power Curve - wind-turbine-models.com
Wind Speed (m/s)	**Output Power (kW) N29 250 kW**
4	6
5	17
6	30
7	51
8	75
9	101
10	130
11	158
12	186
13	206
14	233
15	246
16	250
17	248
18	245
19	238
20	228
21	220
22	215
23	210
24	210
25	210

From this table the power curve for the N29 250 kW wind turbine is made. The equation made from the power curve is then used to generate the power output for the different hub heights that are available for the wind turbine in question. The power curve is shown in Figure 4.5.

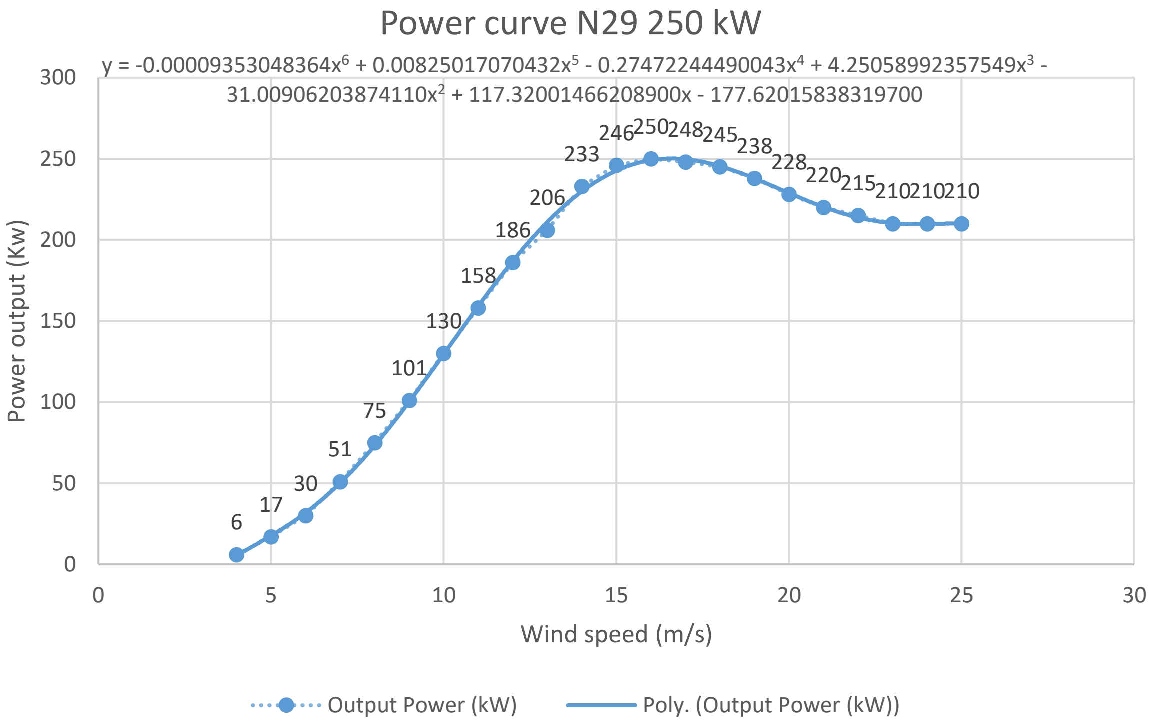


Figure 4.5: Power curve for the N29 250 kW turbine.

The power curve equation for the N29 250 kW turbine is shown in Equation 4.2:

Equation 4.3: Power curve equation for the N29 250 kW turbine.

$$y = -0.00009353048364x^6 + 0.00825017070432x^5 - 0.27472244490043x^4 + 4.25058992357549x^3 - 31.0090620387411x^2 + 117.320014662089x - 177.620158383197$$

Here in Table 4.5 the difference between the demanded power and the power output of the turbines is calculated.

Table 4.5: Comparison of the difference between the power demand and the output for four N29 wind turbines in each hub height.

	N29 30m hub height [kW]	N29 36m hub height [kW]	N29 41,5m hub height [kW]	N27 50m hub height [kW]
Demand	4 012 145.9	4 012 145.9	4 012 145.9	4 012 145.9
Power output	1 233 342.331	1 378 436.892	1 505 745.553	1 654 308.84
Difference	2 778 803.569	2 633 709.008	2 506 400.347	2 357 837.06

4.5. Economic assessment

For the economic evaluation of the project the payback period is focused on, and therefore different costs regarding the wind energy system must be found. The formula for the payback period (shown later in chapter 5.5) includes the electricity grid savings, the annual operational expenditures, and the capital investment. Therefore, these costs must be found.

Described more in detail in chapter 5.5, the OpEx and CapEx were found to be generic numbers based on how many kilowatts the wind turbine in question has as capacity. Then the electricity costs if connected to the grid are calculated, and lastly the savings - the costs that would have been spent on the grid if it were not for the connected DES (Distributed Energy Systems).

5. Results and discussion

In this thesis we have developed a framework for helping end users make important and effective decisions about a distributed wind energy system and finding the most viable system for their use cases. It has been developed using a systematic trial-and-error process with simulating our own case with choosing a demand, location, and turbines. It has consisted of manually generating graphs and comparing numbers both in the technical and economical experiment.

To visualize and make the decision easier the power output graphs are made for each of the chosen capacities with both different hub heights and number of turbines. With this visualization of the power output versus the power demand, and the calculations of difference between the power output and demand, the decision making is a lot easier to do and to be sure that it is the right one. Later, the economic part is discussed, and calculations are done with respect to the payback time.

5.1. Turbine one: Danish Wind Power AS (DWP) 110 kW

The annual power output for the 110-kW turbine is compared to the annual power demand in Figure 5.1.

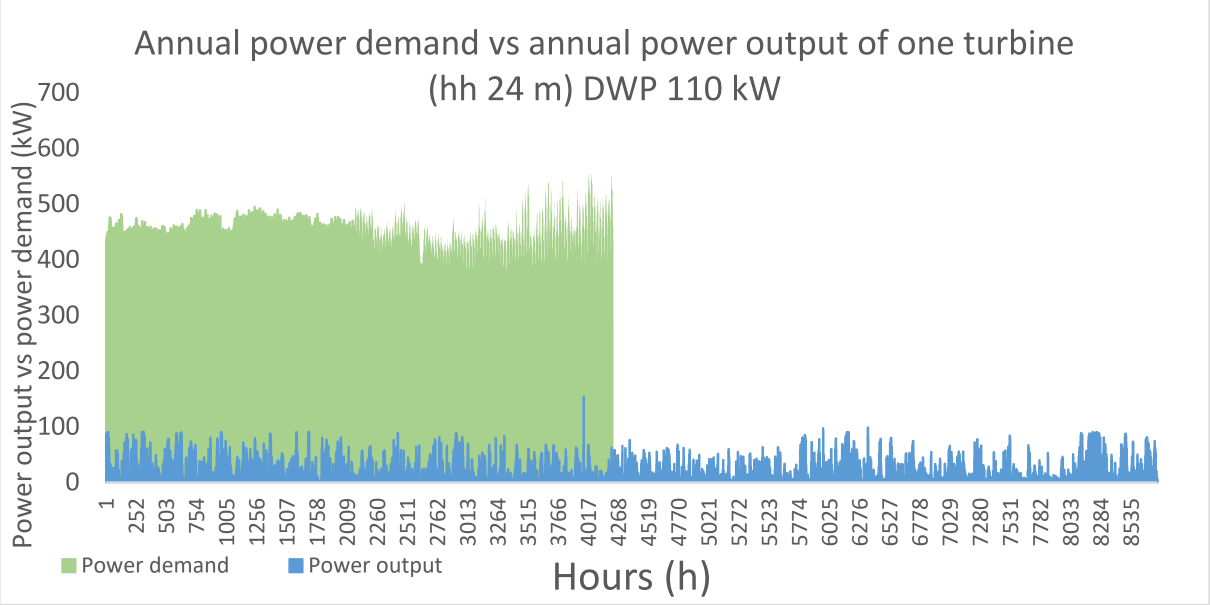


Figure 5.1: Hourly annual power demand vs annual power output for one turbine DWP D110/19 at hub height 24 meters.

The graphics in Figure 5.1 show that one turbine alone does not come close to covering the demand. This turbine only has one hub height option, so to try to cover the demand, the next step is to add more turbines to the system. In Figure 5.2 the power output from eight wind turbines is generated by multiplying the annual power output from Figure 5.1 with eight and then compare to the power demand.

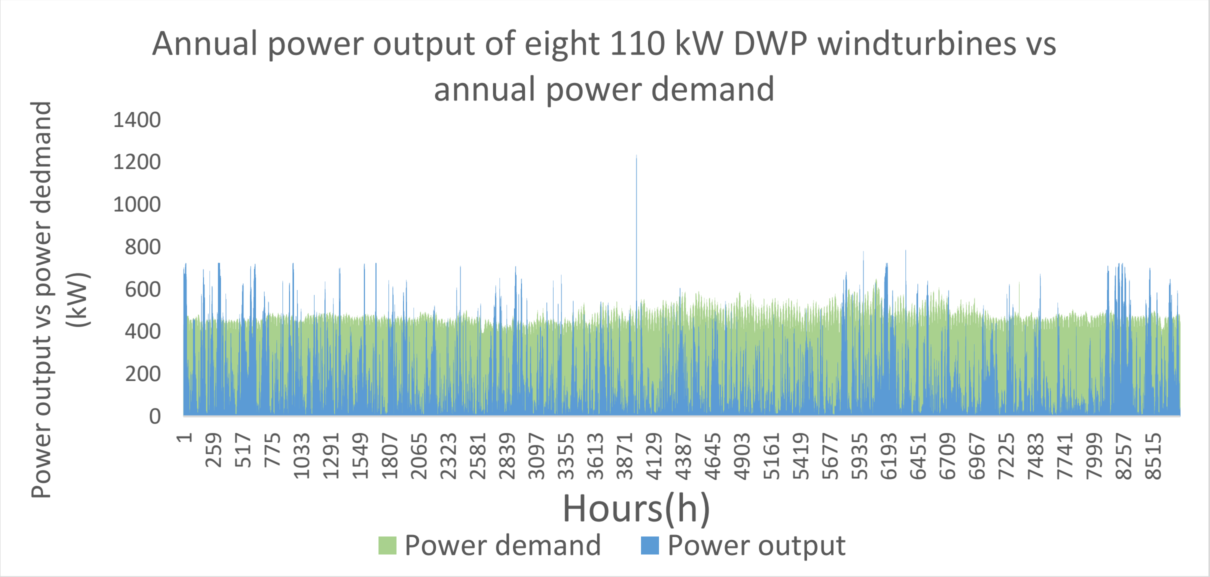


Figure 5.2: Hourly annual power demand vs hourly annual power output for eight DWP D110/19 turbines with 24 meters hub height.

There is still a big discrepancy between power output and demand, and it is concluded that this wind turbine will not be viable for the supermarket. This is because the price increases for each turbine added, and even eight turbines cannot cover half of the power demand. Another argument is that since this is a sole use case energy system, it would be a stretch to have so many turbines, and optimally it should be maximum a couple of them to cover the energy demand (or part of) of this system.

5.2. Turbine two: Nordex group N27 turbine 150 kW

The figures underneath show one and four turbines in hub height 30 meter visualized in Figure 5.3 and Figure 5.4, respectively.

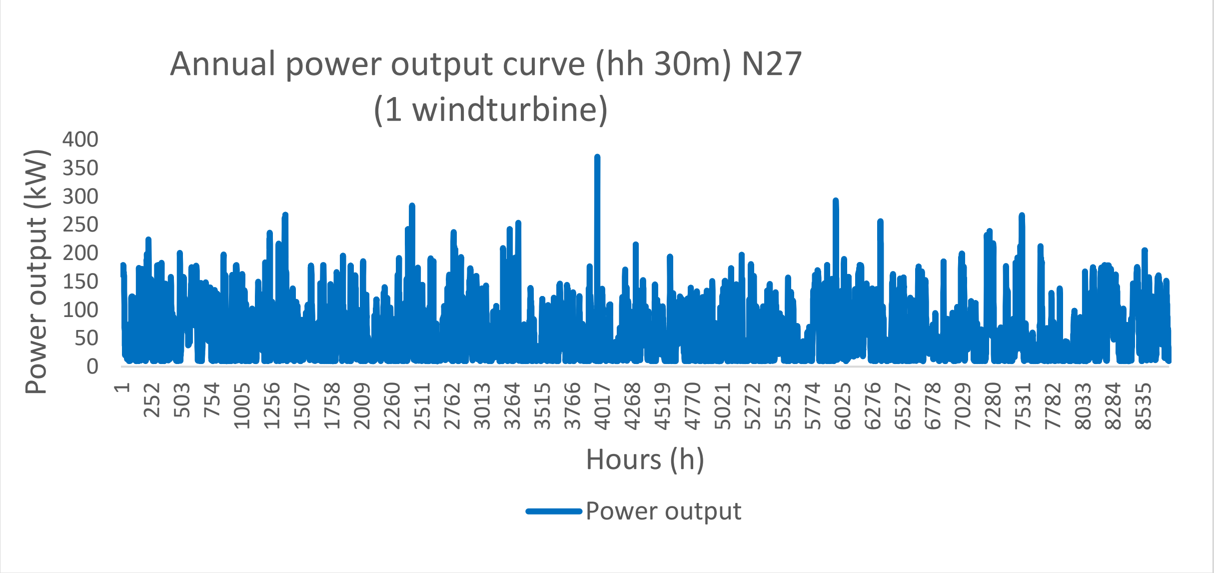


Figure 5.3: Hourly annual power output from one N27 150 kW turbine, at 30 meters hub height.

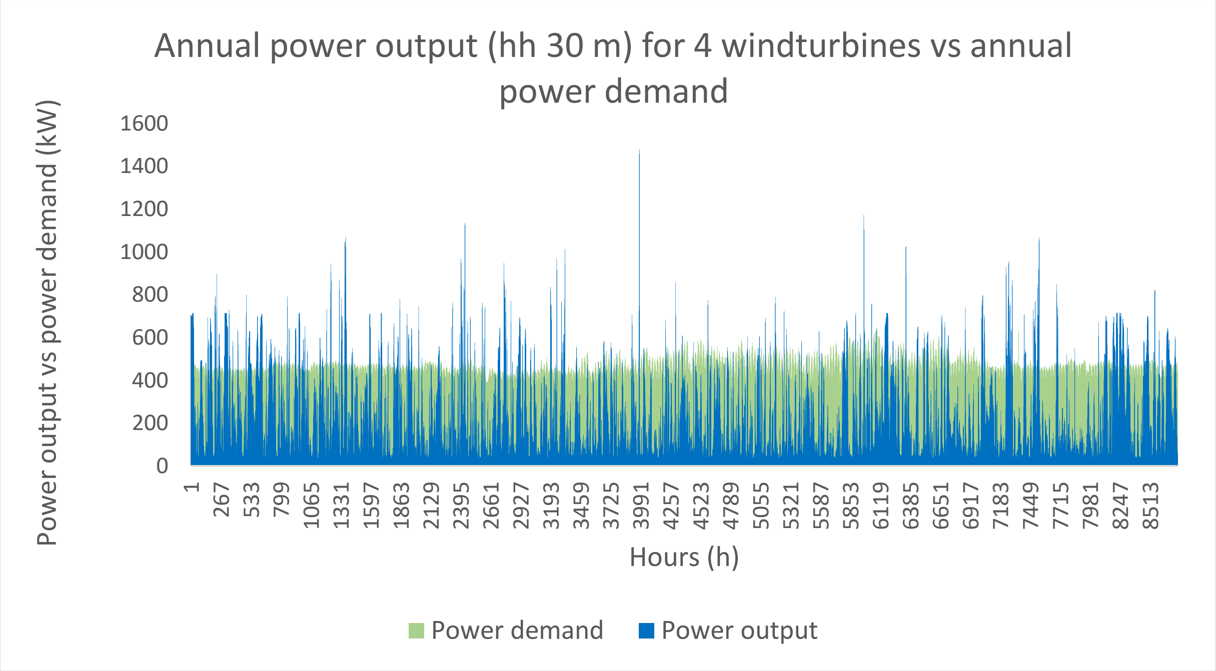


Figure 5.4: Hourly annual power output from four N27 turbines at 30 meters hub height vs hourly annual power demand.

The demand shows that it needs at least a stable power output of 500 kW per day to be covered. By looking at the output, any less than four wind turbines (visualized in Figure 4.8) will not cover the power demanded from the supermarket. Since there is still a lot of power demand that is not covered, the other hub heights for the N27 150 kW turbine (36, 40 and 50 meters) must be evaluated.

For the 36 meters hub height, the power output is visualized for one and four turbines in Figure 5.5 and Figure 5.6, respectively.

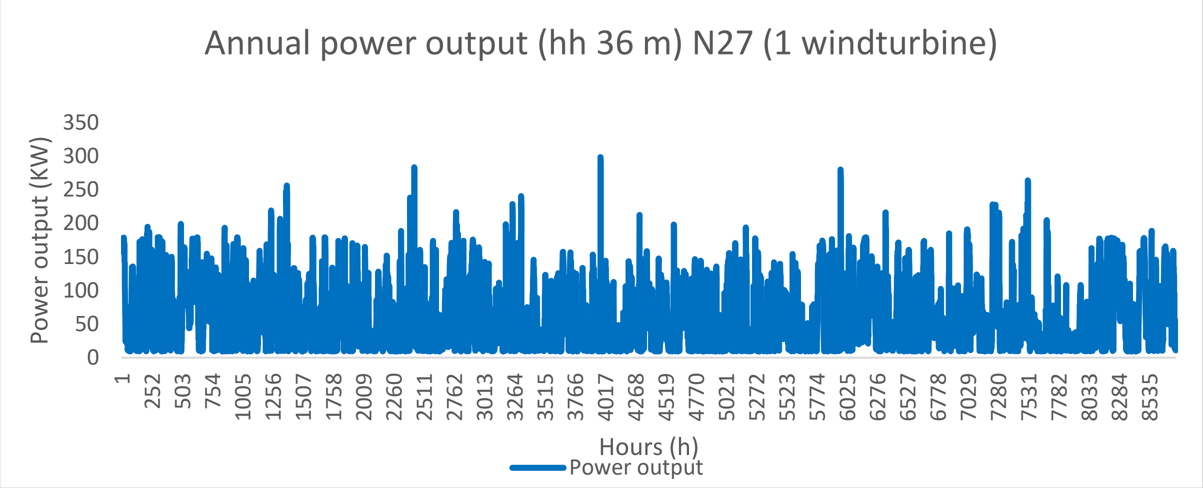


Figure 5.5: Hourly annual power output for one N27 turbine at 36 meters hub height.

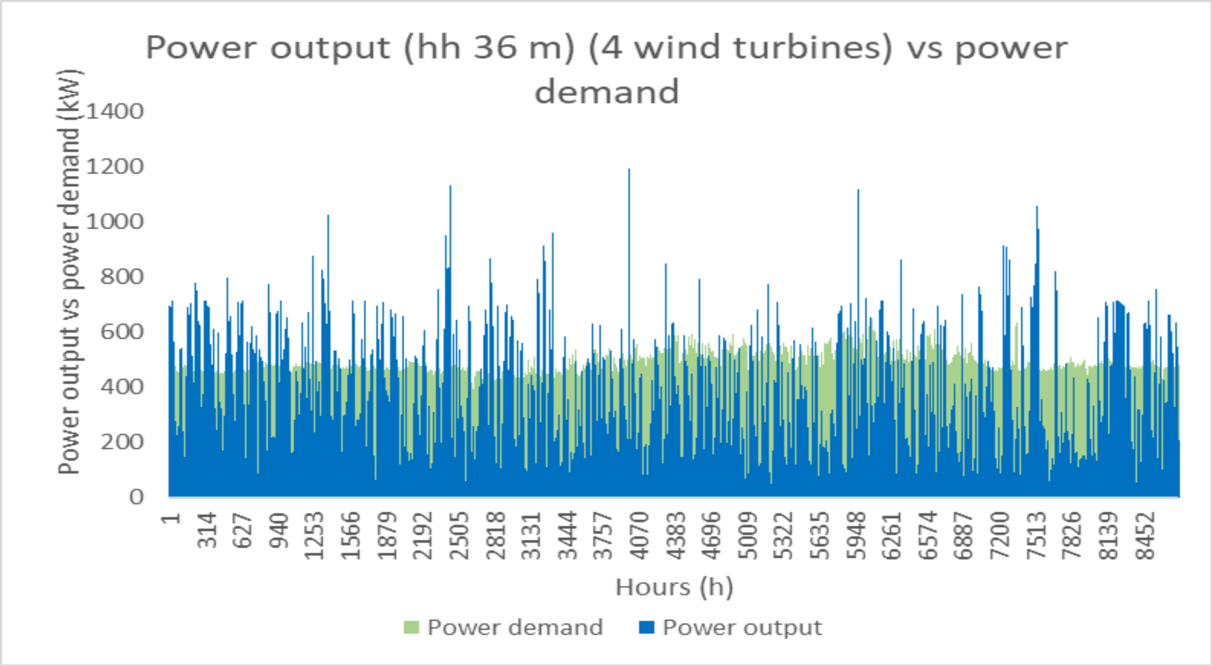


Figure 5.6: Hourly annual power output from four N27 turbines at 36 meters hub height vs hourly annual power demand.

The gaps are still too big, meaning the power output is still not sufficient to be considered as viable for the power demand.

The power output for one and four turbines are visualized in Figure 5.7 and Figure 5.8.

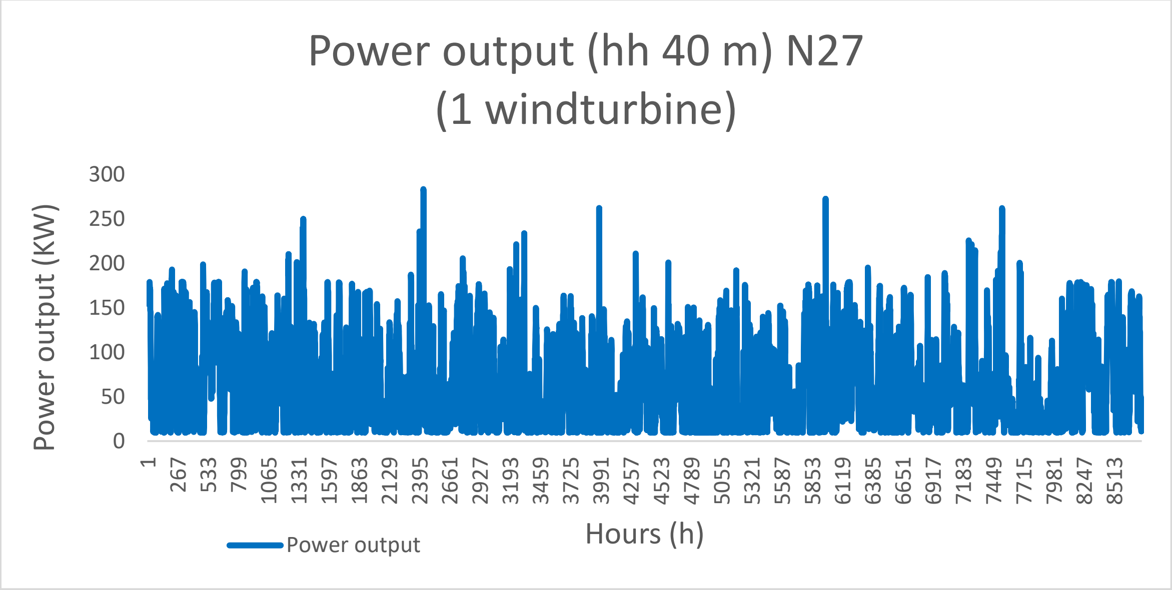


Figure 5.7: Hourly annual power output from one N27 turbine at 40 meters hub height.

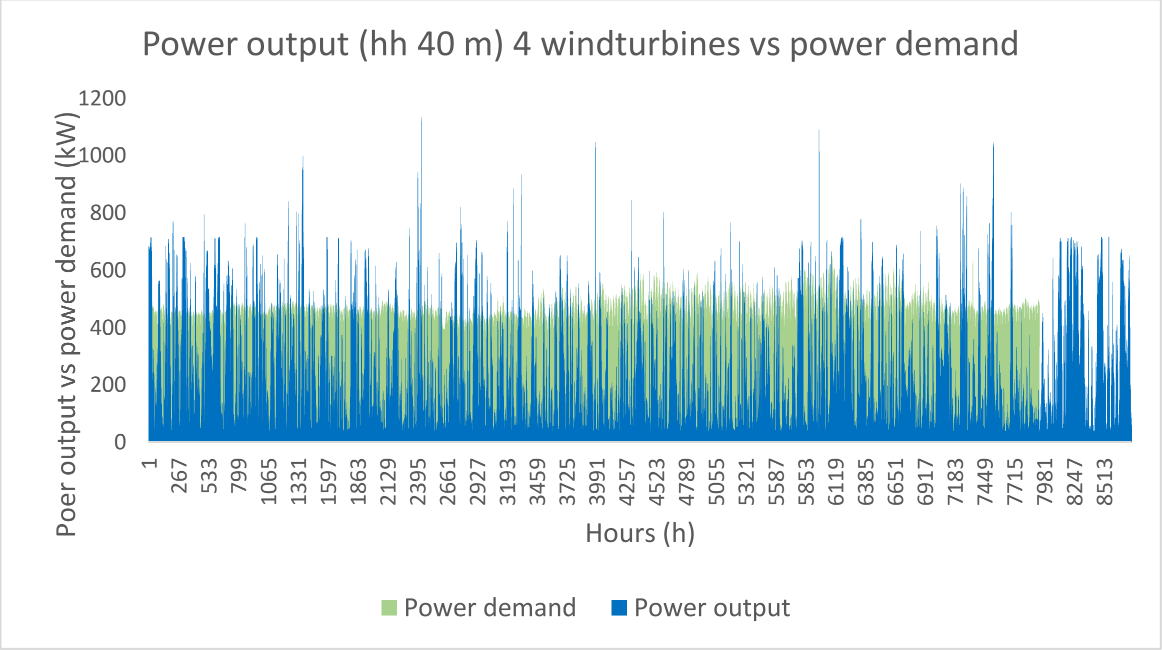


Figure 5.8: Hourly annual power output from four N27 turbines at 40 meters hub height vs hourly annual power demand.

By analysing the peaks from the 36 meters hub height with four turbines and compare this to the peaks for the one with 40 meters hub height, we note that the peaks from the lower hub height are higher and produce more power at certain times. However, when analysing the whole picture, the turbine with higher hub height has a more consistent output, nevertheless is still not sufficient to cover the power demand.

Below the graphs for 50 meters hub height are visualized for one and four turbines in Figure 5.9 and Figure 5.10, respectively.

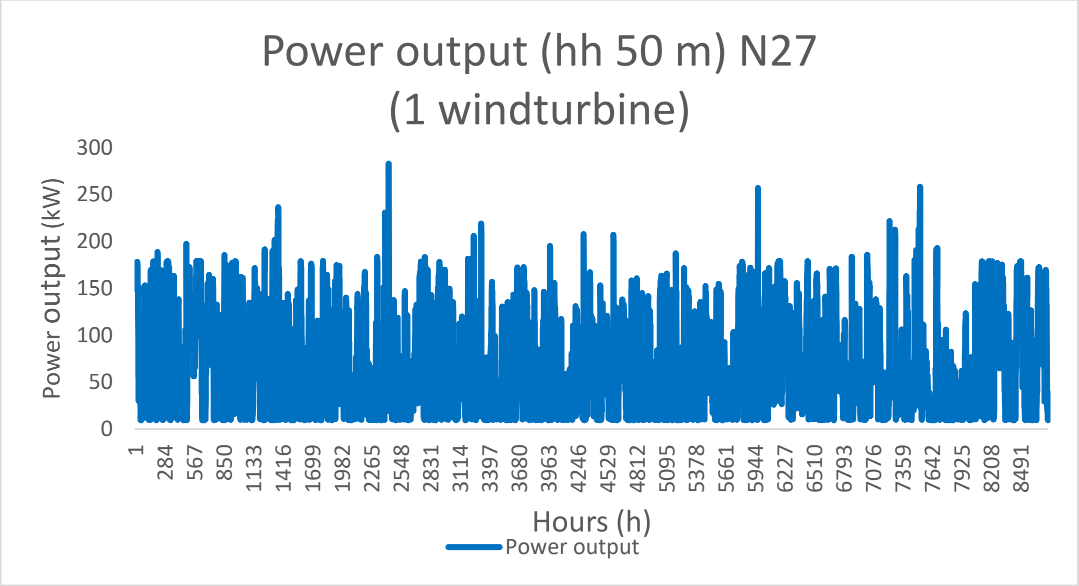


Figure 5.9: Hourly annual power output from one N27 turbine at 50 meters hub height.

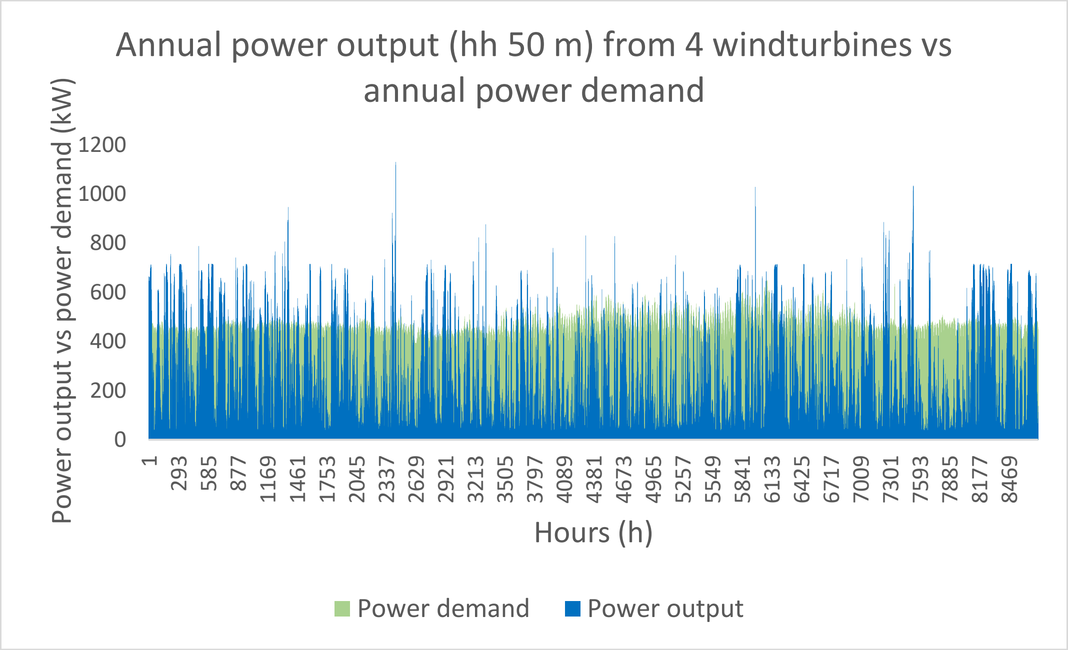


Figure 5.10: Hourly annual power output from four N27 turbines at 50 meters hub height vs hourly annual power demand.

The power output from the four turbines with 50 meters hub height has an even better consistency than the turbines with lower hub heights. However, it still does not generate enough power to completely cover the demand.

From this data it seems that the system with 4 turbines at 50 meters hub height each is the best alternative as it seems to cover most of the demand. In

In Table 4.3 the difference between the power output from the N27 wind turbines at different hub heights and the demanded power is calculated.

Table 4.3 one can view the calculation of the difference between the power demand and the power output for each N27 model with four turbines at the different hub heights. The table shows that the turbine with the highest hub height (50 meters) has the lowest discrepancy (1 738 718.449 kW) between power demand and output. From this we can conclude that it is the most viable from a pure technological point of view, as less demand needs to be powered from the grid than for the other alternatives. Still, this model only covers a bit more than half of the demand and may be improved by adding more turbines. We will come back to this in the discussion.

5.3. Turbine three: Nordex group N29 turbine 250 kW

In this chapter, the same procedure as in the previous chapters is followed, comparing the output from N29 250 kW turbine at different hub heights towards the power demand. Figure 5.11 and Figure 5.12 shows the power output for one and four turbines at 30 meters hub height.

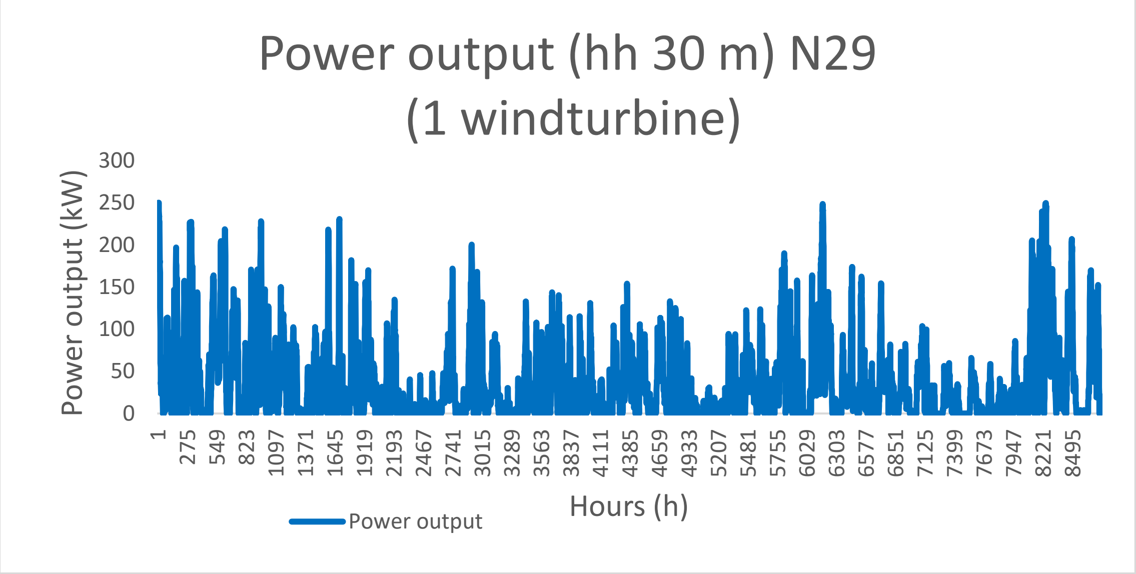


Figure 5.11: Hourly annual power output for one N29 250 kW turbine, 30 meters hub height.

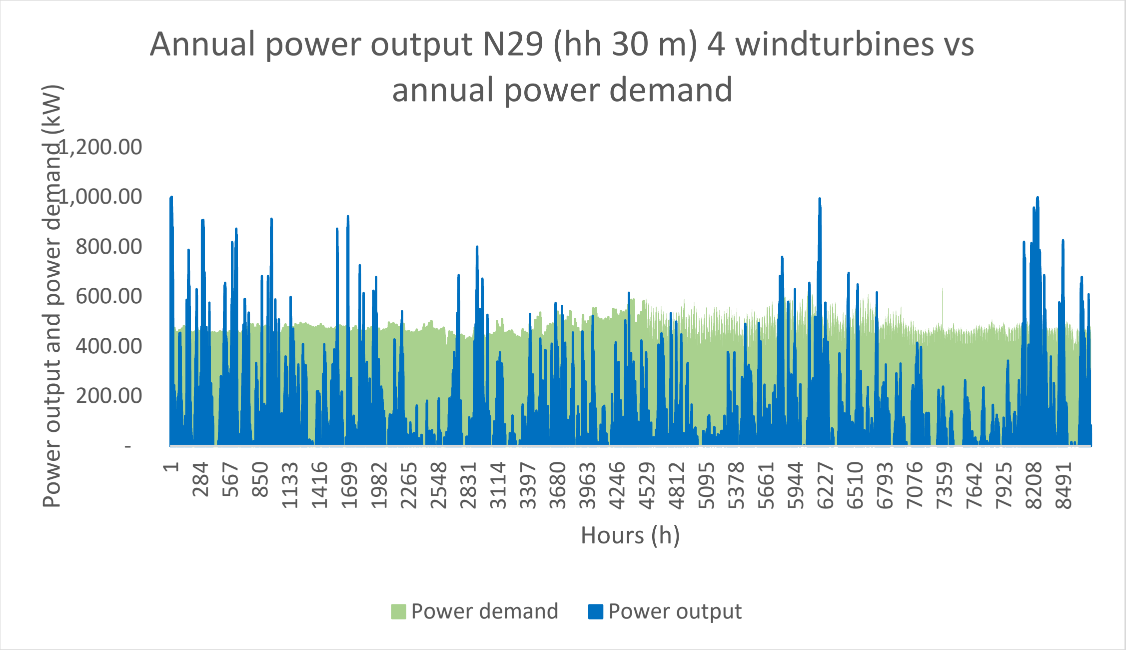


Figure 5.12: Hourly annual power output from four N27250 kW turbines at 30 meters hub height vs hourly annual power demand.

These figures above show that the power output does not cover the power demand.

Figure 5.13 and Figure 5.14 shows the power output for one and four turbines at 36 meters hub height.

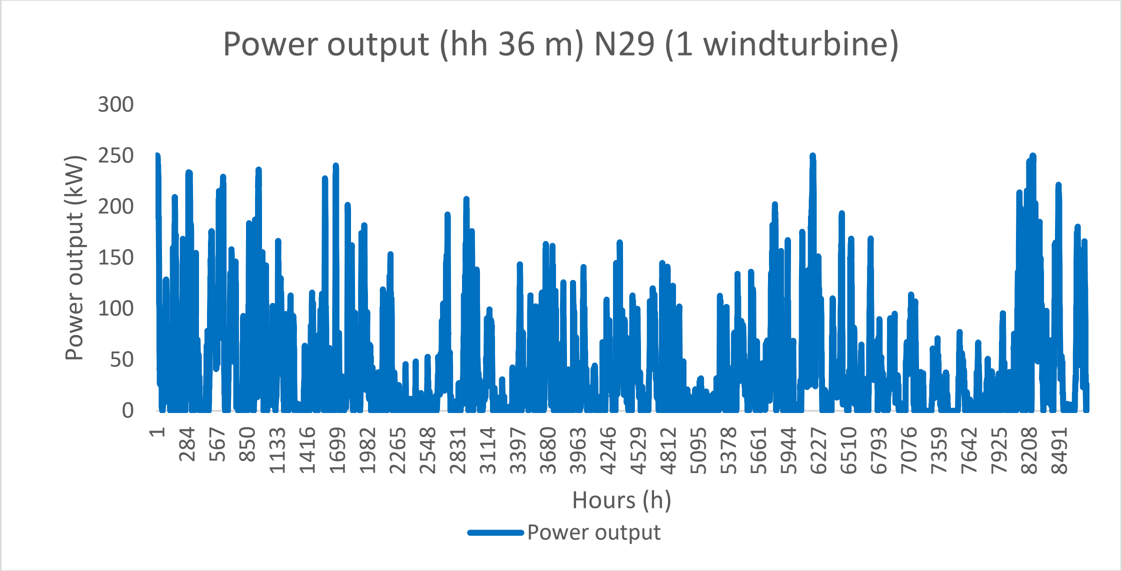


Figure 5.13: Hourly annual power output for one N29 205 kW turbine at 36 meters hub height.

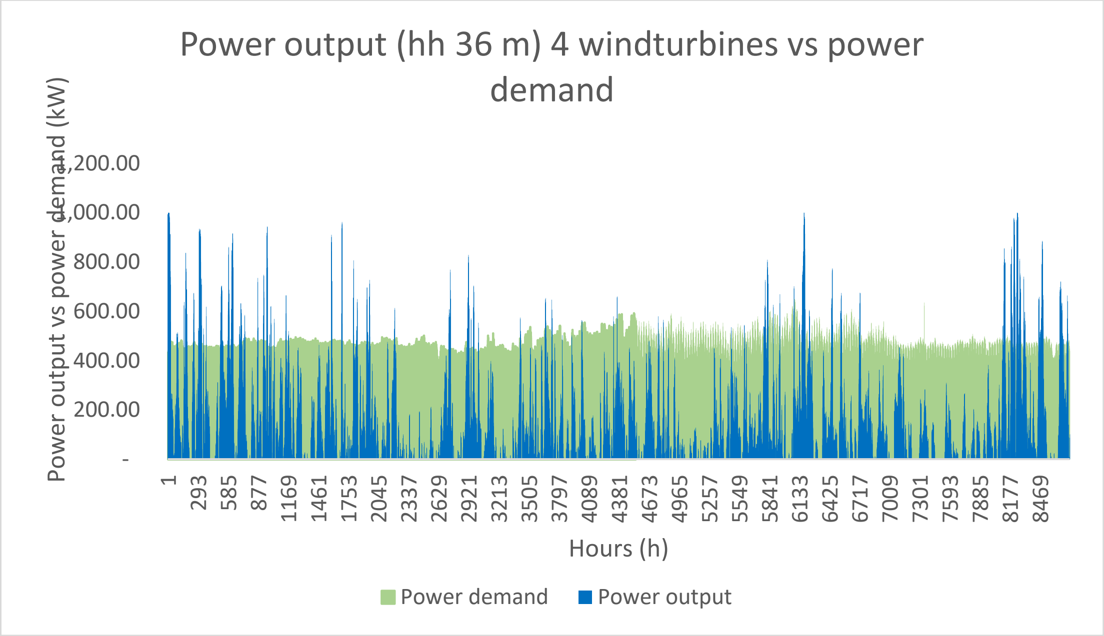


Figure 5.14: Hourly annual power output from four N27 turbines at 36 meters hub height vs hourly annual power demand.

These figures above also visualize that neither this power output can cover the power demand.

Figure 5.15 and Figure 5.16 shows the power output for one and four turbines at 41.5 meters hub height.

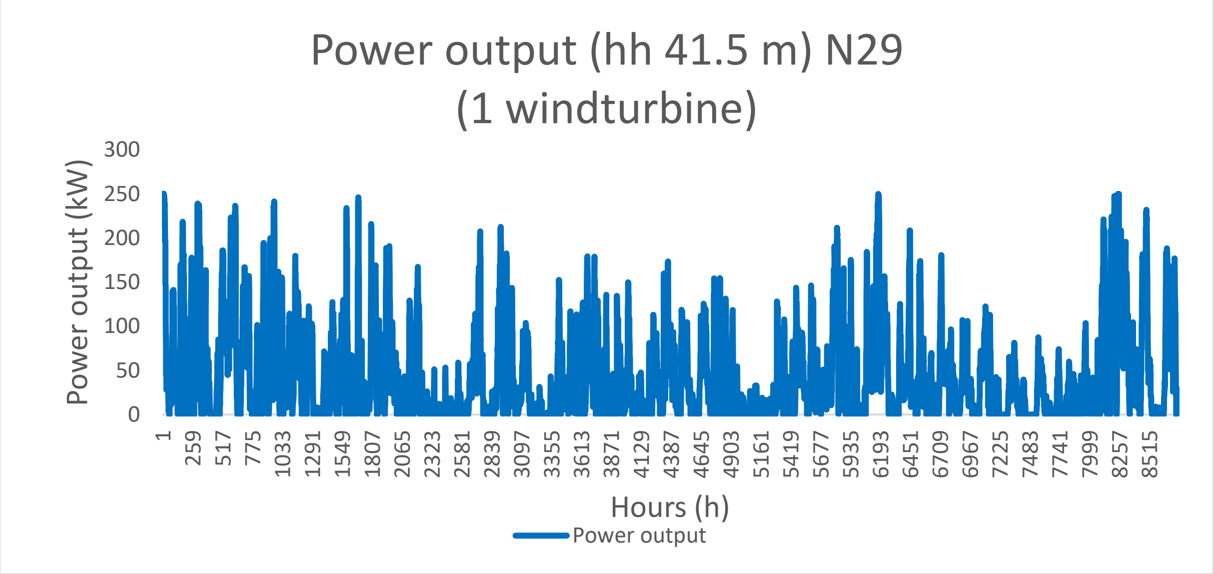


Figure 5.15: Hourly annual power output for one N29 turbine, 41.5 meters hub height.

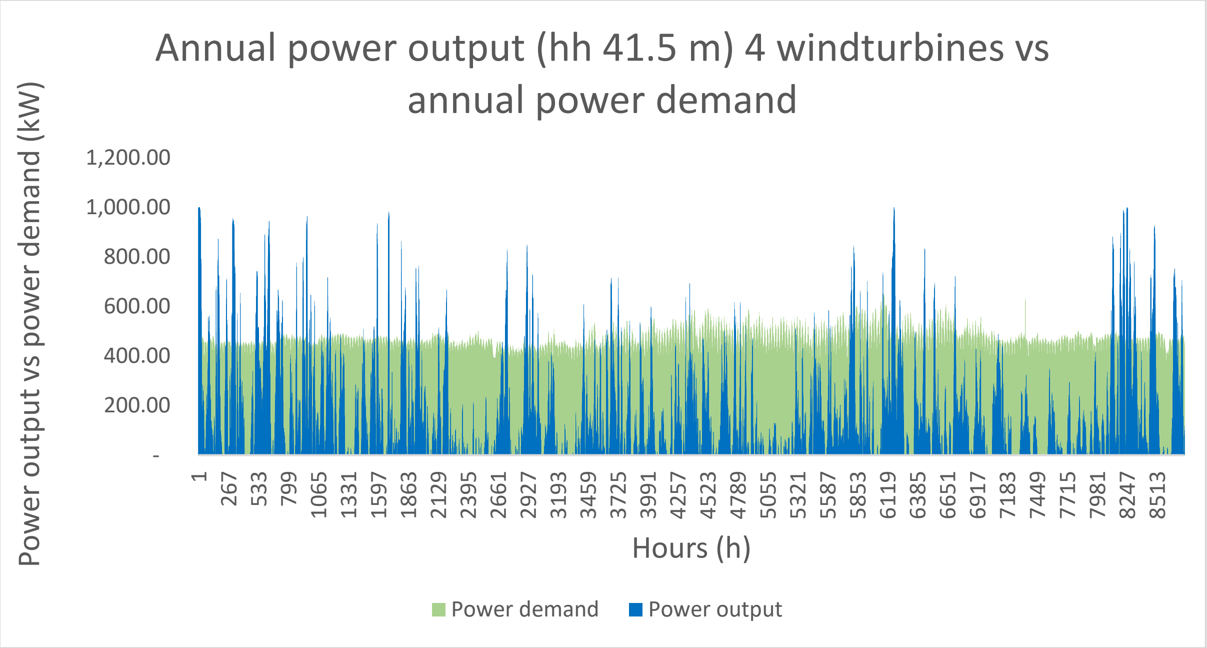


Figure 5.16: Hourly annual power output from four N27 turbines at 41.5 meters hub height vs hourly annual power demand.

The figures above show that the power output again cannot cover enough of the demand.

Figure 5.17 and Figure 5.18 shows the power output for one and four turbines at 50 meters hub height.

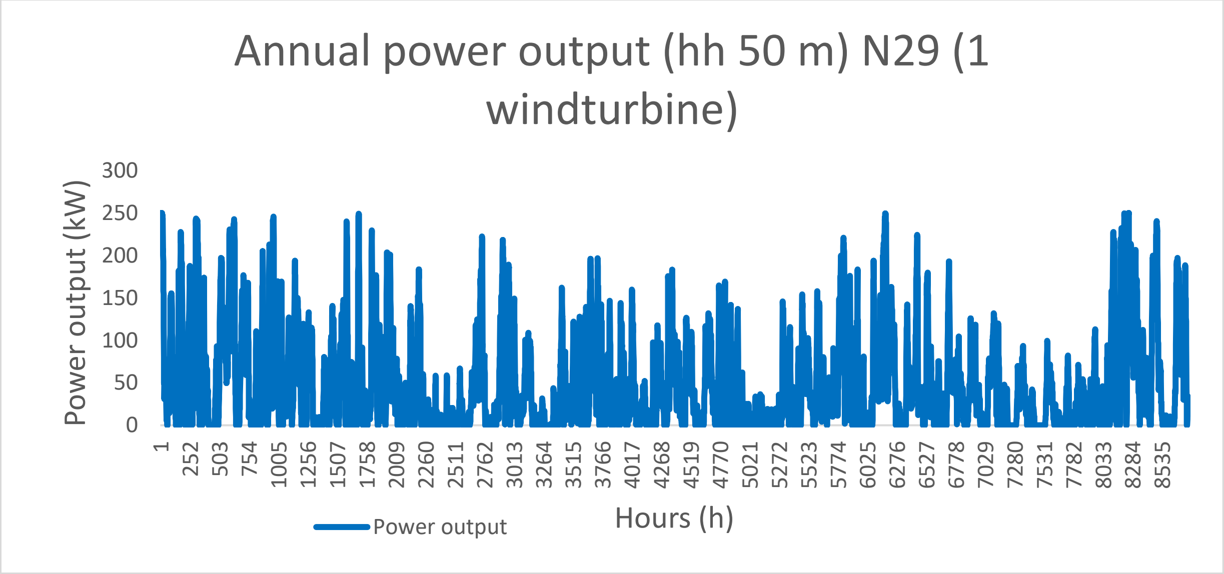


Figure 5.17: Hourly annual power output for one N29 250 kW turbine, at 50 meters hub height.

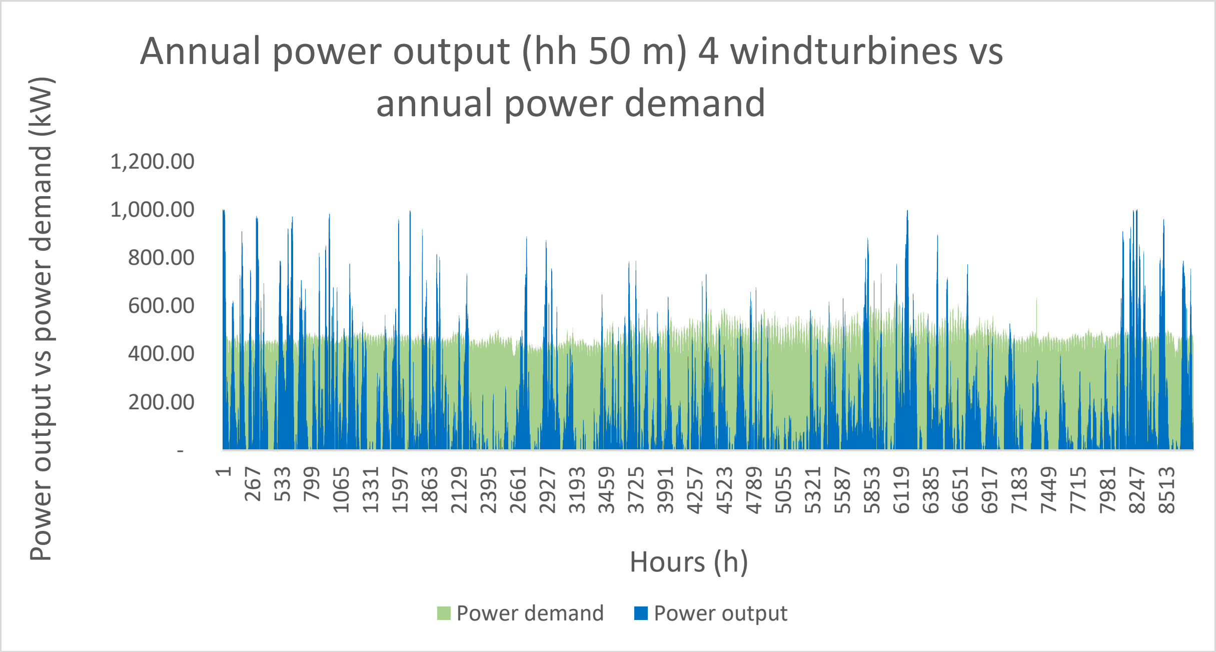


Figure 5.18: Hourly annual power output from four N27 250 kW turbines at 50 meters hub height vs hourly annual power demand.

Lastly, these figures above show that the power output again does not cover enough of the power demand.

From this data we can see that none of the N29 models seems to cover enough of the power demand. The best one appears to be the 50 meters hub height model with four turbines, but even this one has a lot of gaps compared to the demand. In Table 4.6, the difference in the demand and the power output for the four hub heights when using four turbines are calculated. Again, the difference should be as small as possible, and this holds for the turbines with 50 meters hub heights with the difference (2 357 837.06 kW).

5.4. Comparison of the best models

After the three chosen capacities have been analysed and the data visualized, comparing them is easier. When looking for the best turbine fit for the supermarket, the power output of the turbine is important. It should be as stable as possible without any big gaps.

Figure 5.19, Figure 5.20 and Figure 5.21 shows that the N27 seems to provide a more stable output than the N29 and DWP 110 kW and it covers more of the demand with less fluctuations.

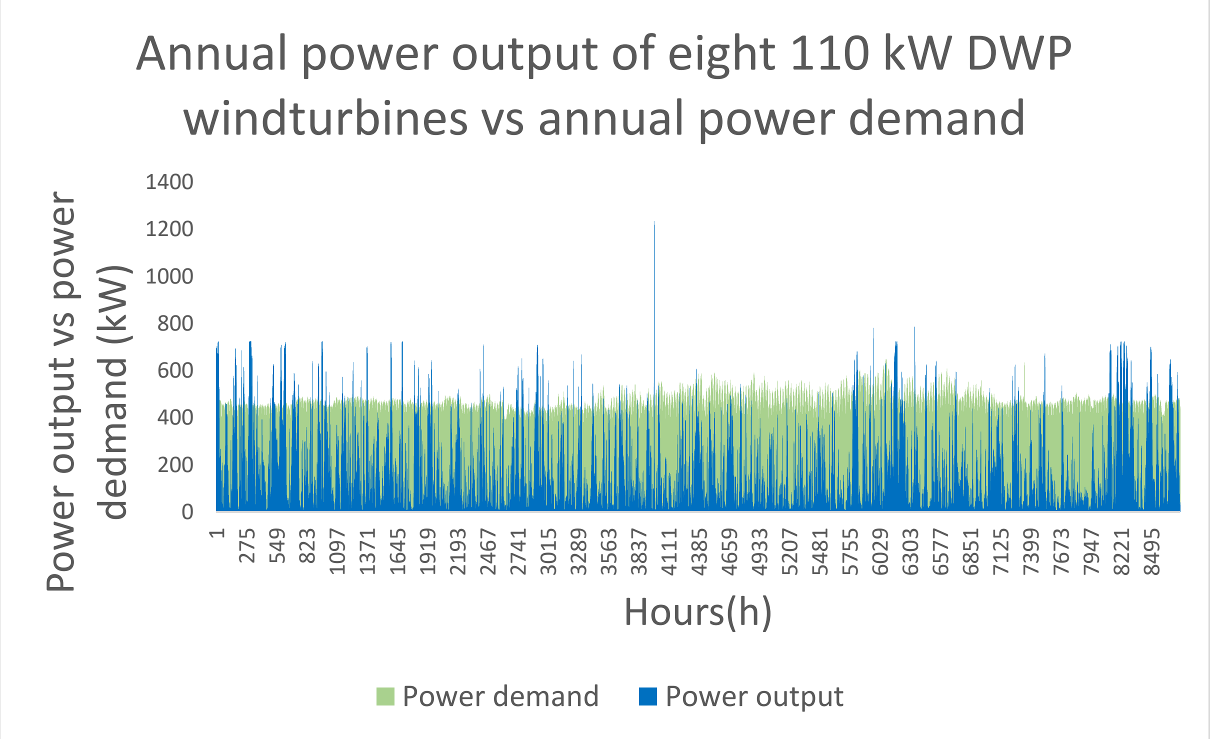


Figure 5.19: Hourly annual power output from eight DWP 110 kW turbines at 24 meters hub height vs hourly annual power output.

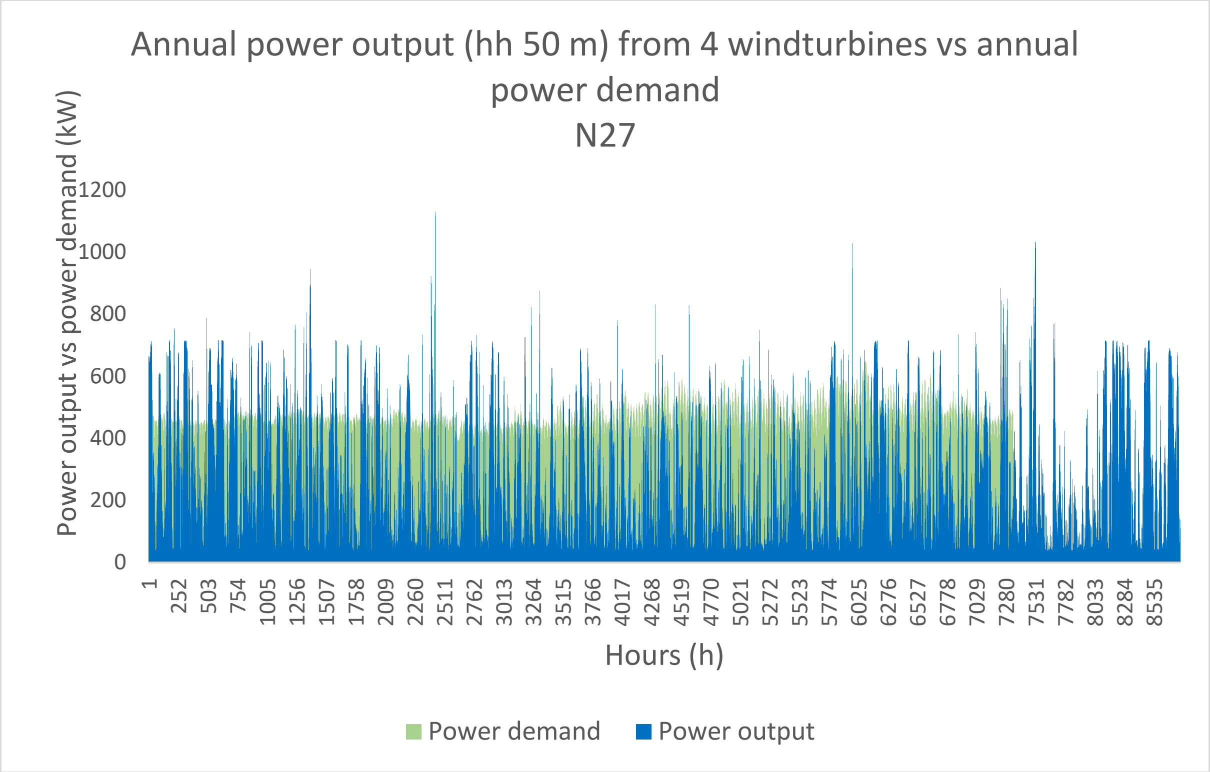


Figure 5.20: Hourly annual power output from four N27 150 kW turbines vs hourly annual power demand.

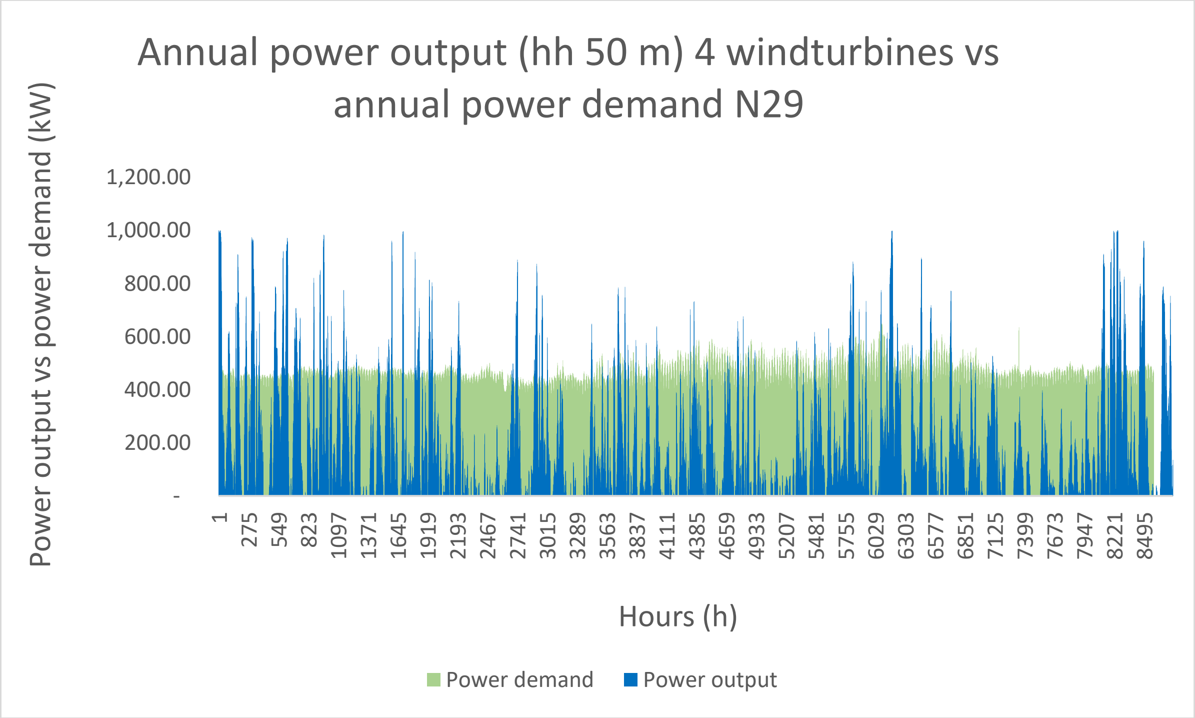


Figure 5.21: Hourly annual power output from four N29 250 kW turbines vs hourly annual power demand.

In addition to looking at the graphs, the difference between demand and output for the turbines at their best hub height has been calculated and now presented in Table 4.7 for comparison purposes. The table shows that N27 covers a lot more of the demand than both the N29 and DWP, which supports the theory that N27 is the best turbine for our model supermarket, and the other ones will not be viable because of the lack of power output.

Table 5.1: Comparison of the difference between the power demand and the output for eight DWP 110 kW at hub height 24 meters and four N27 and N29 turbines at the hub height 50 meters.

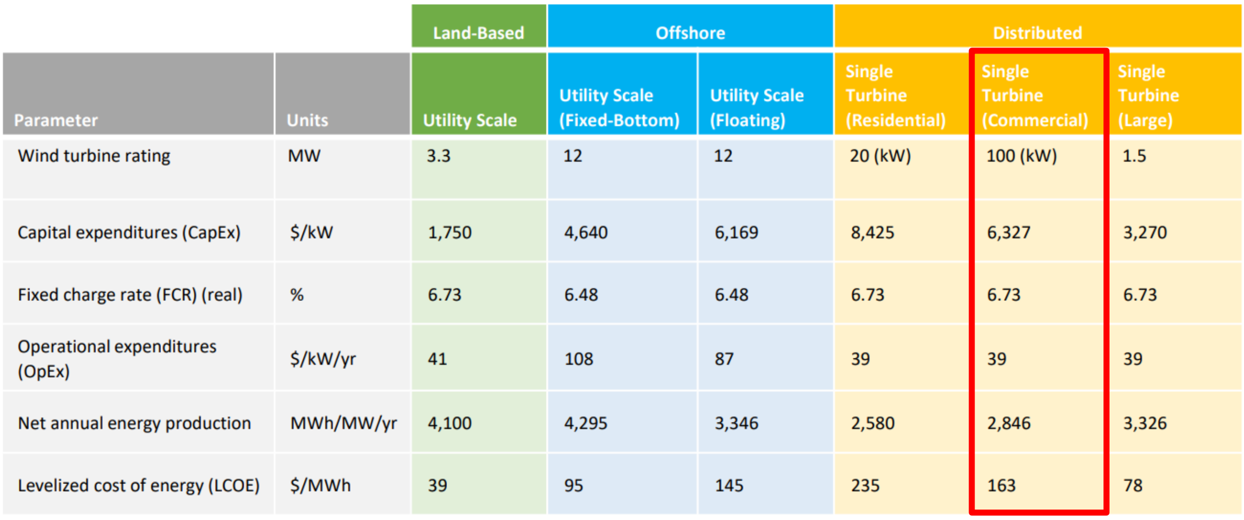
	DWP 110 kW [kW] 8 turbines 24 meters hub height	N27 150 kW [kW] 4 turbines 50 meters hub height	N29 250 kW [kW] 4 turbines 50 meters hub height
Demand	4 012 145.9	4 012 145.9	4 012 145.9
Power output	1 526 574.79	2 273 427.451	1 654 308.84
Difference	**2 485 571.11**	**1 738 718.449**	**2 357 837.06**

5.5. Economic Analysis

The variable price contracts for services were found on “Statistisk sentralbyrå” ssb.no where all official statistics are presented, and the price was found to be 122.1 øre/kWh [10]. Assuming the price for this year is representative also for the future, the total electricity price per year for the supermarket if the supermarket were connected only to the grid is calculated by multiplying the electricity price with the yearly power demand of the supermarket. This calculation will be used to compare the economics of partly using wind turbines versus solely being connected to the main grid.

From the technical analysis, the graphs revealed gaps in the power output, but also peaks that would give energy profit. There is a possibility to save this electricity and store it for later use. For this to be realistic it would require a bit more investigation in both the economic and technical part. Adding batteries to store this extra energy would increase the costs, but the saved power could be enough to cover the gaps where the output from the wind turbine did not cover the demanded power and the system could be independent from the grid. The other possibility for this energy profit could be to sell the power back to the grid. This would also be a way of decreasing the payback time and increasing the savings over time. However, through the calculations of this economic part, the energy profit from the wind turbine was neglected.

For the economic analysis of the N27 150 kW turbine, we first need to understand the incremental operational expenditures “OpEx” and capital expenditures “CapEx” from using the turbine(s). These were found on the 2022 Cost of Wind Energy Review [11] which uses representative wind power projects to estimate costs. The data are obtained from 2022 commissioned plants and applies to both utility-scale and distributed wind energy projects, for both land-based and offshore power plants. In this thesis, the data used is collected from the distributed wind energy projects with a single turbine of 100 kW capacity for commercial use, because this is the closest to the 150-kW turbine. Therefore, these will be reference numbers that might differ slightly from the actual numbers in such a project. We acknowledge that such numbers will always vary due to different variables such as different manufacturers, prices, point-in-time, electricity demand etc. However, we believe the analysis will still be representative.



		Land-Based	Offshore		Distributed		
Parameter	Units	Utility Scale	Utility Scale (Fixed-Bottom)	Utility Scale (Floating)	Single Turbine (Residential)	Single Turbine (Commercial)	Single Turbine (Large)
Wind turbine rating	MW	3.3	12	12	20 (kW)	100 (kW)	1.5
Capital expenditures (CapEx)	$/kW	1,750	4,640	6,169	8,425	6,327	3,270
Fixed charge rate (FCR) (real)	%	6.73	6.48	6.48	6.73	6.73	6.73
Operational expenditures (OpEx)	$/kW/yr	41	108	87	39	39	39
Net annual energy production	MWh/MW/yr	4,100	4,295	3,346	2,580	2,846	3,326
Levelized cost of energy (LCOE)	$/MWh	39	95	145	235	163	78

Figure 5.22: Cost of wind energy [11].

The OpEx and CapEx for the distributed wind power system of the N27 turbine with the sizing of four turbines and electricity grid costs were calculated in Table 5.1. Only the calculations for the N27 turbine simulation with four turbines is shown, because this was stated to be the only technological viable simulation. The annual operational cost is 63,180 kr/year. In the calculations, inflation is neglected due to the minimal effect this will have on the price over the turbine's lifespan. The conversion factor, 10.80, to convert USD to NOK is taken from Valutakalkulator.no on March 25th, 2024 [12]. The capital expenditure is then calculated in excel and is 10,249,740 kr. This is a cost which is assumed to be paid as a one-time payment at the start of the project when purchasing and installing the turbines. When installing four turbines - which is found to be the best in the technical part - the costs are multiplied by four. The annual electricity cost when covering the total power demand from the grid is calculated and is 4,898,830.14 kr/year.

Table 5.2: OpEx, CapEx and costs if connected to the electricity grid for one N27 turbine.

OpEx in USD/kW/year	**kW**	**USD/year**	**USD to NOK**	**NOK/year**	**4 wind turbines [NOK/year]**
39.00	150.00	5,850.00	10.80	63,180.00	252,720.00
CapEx USD/kW	**Capacity [kW]**	**Capex N27 [USD]**	**USD to NOK**	**Capex N27 [NOK]**	**4 wind turbines [NOK]**
6,327.00	150.00	949,050.00	10.80	10,249,740.00	40,998,960.00
Electricity grid					**Total**
Demand Power [kWh/year] supermarket	**kr/kWh (2023)**				**kr/year**
4,012,145.90	1.22				4,898,830.14

In Table 5.2 the calculations for the payback period are shown. The payback period is calculated by using Equation 5.1.

Equation 5.1: Payback period

$$Payback\ period\ (years) = \frac{Grid\ savings - annual\ OpEx}{CapEx}$$

Table 5.2: Payback period N27, four turbines of 50 meters hh.

4 turbines	**[NOK]**
CapEx [NOK]	40,998,960.00
OpEx [NOK]	252,720.00
Grid payment	2,122,975.23
Grid savings	2,775,854.92
Total cost	40,598,800.31
Difference between savings and OpEx	2,523,134.92
Payback period [years]	16.24921431

In this chapter, the different prices and payback periods for the Nordex N27 model have been analysed regarding different variables such as hub height, turbine models and number of turbines. In the appendix it is shown that because of all the factors multiplying when an additional turbine is added to a model, the payback period is the same for any number of the same turbine at the same hub height. So, the payback period for the N27 turbine is 16.25 years regardless of how many turbines there are installed.

5.6. Discussion of results

During the process of finding the best suitable wind turbine model for our fictional end user and use case, we have developed a framework. The framework is shown in Figure 4.1 This framework is created as a basic assessment tool for distributed wind energy systems based upon open-source data and can benefit others in shortening the process of selecting and evaluating a wind turbine model to their use case/power demand.

In the simulation exploited in this thesis, the Nordex N27 150 kW turbine was found to be the better fit for the supermarket demand. This was because this was the turbine giving the largest and most reliable output power throughout the entire year and having the lowest payback period (16.25 years). The other turbines were either giving too little output power or having an unrealistic and big payback period.

Although the goal of the thesis was achieved, we have stumbled upon several challenges. The different challenges include the order of the approach, finding sources, which variables to take account for and which to neglect, the possibility to cover the rest of the demand with another electricity source etc. In the progress of making the framework we started with choosing the different wind turbines first, but later understood that for this to be a reliable framework used by developers they usually have the demand first and choose the capacity of the wind turbines from this demand. Originally, we started with the end user as a farm/agriculture, but even though there are lots of such farms in our location, Randaberg, it became difficult to find power demand data for this. Then we ended up with the supermarket instead because this was easier to find data for.

A supermarket demands stable power over time, and this is not the power output case for a wind turbine. This is because the wind varies a lot over time and in different seasons and therefore the power output is not stable, and gaps will occur. We tried with different hub heights and number of turbines to see if this affected the stability of power output. We did see a pattern that the higher hub heights gave little bit smaller gaps, but not enough to cover the power demanded at the point. To make the outcome of our chosen scenario better, we could add more wind turbines to cover the whole demand. This would on the other hand give a lot of extra power output when the demand is low. And as mentioned before, we did not consider storing or selling the extra power output because it was too advanced for this thesis. Nonetheless, the outcome could be different if this was the case. We did also discuss the possibility of covering the rest of the demand with solar power such as a hybrid system but did not take this any further due to time management and to keep the scope in a level that could be delivered complete within time constraint set by university. This exploration would mark the possibilities of the distributed wind systems and how to cover the different energy demands. We instead decided to cover the power gaps with power from the grid. The grid is a reliable source of power and is also integrated into the infrastructure from before but might be a more expensive option than the other mentioned.

For this framework, the technical and economic parts of a wind turbine are considered. For further investigation it could consider both the environment due to the pollution during production and decomposition of the turbine and the location of the wind farm due to the noises and vibrations from the turbines that adversely affect wild animals. The framework can also be used whether it is a horizontal or a vertical axis turbine. The vertical axis turbines have a potential with different advantages like that it receives wind equally from every direction and then do not need the yaw system to orientate the turbine towards the wind like the horizontal turbine. It has been found that the vertical axis turbine also is more convenient for maintenance. The vertical axis turbine is not considered in this development because it is still under research and the market of vertical turbines is still very small [15].

In the economic part of the thesis, we found that the N27 wind turbine with the hub height of 50 meters was the most viable with respect to payback period. We did have a thought early in the project that the turbine with smaller hub heights could be the best, but this was untrue through our calculations. By looking at the payback periods it was shown that by increasing the hub height, the payback period decreased. Therefore the 50 meters hub height was the best solution. The CapEx, however, can be influenced by the hub height of a wind turbine, but this is not considered in this thesis. Higher hub heights may enable turbines to capture stronger and steadier winds but require taller towers and stronger foundation structures leading to increasing CapEx. Although steadier winds can lead to higher annual electricity yields and potentially decrease the LCOE, the increasing tower CapEx may outweigh the gains in yield [13].

The opportunity to combine two turbines was considered after analysing the three turbines with different capacities. This is because just by looking at the graphs the smallest turbine could be able to cover the gaps of the big turbine, but there are a lot of challenges connected to combining two turbines with different capacities. The control systems must be integrated to manage the different wind variations and optimize the power generation. The costs will also increase due to design work and customizations that must be done. If the turbines have different control and monitoring systems, the price will be increased to ensure a seamless operation that might require even more software development. Therefore, the development of combining two different turbine models was not considered in this project due to the complexity, cost, and the risk of compatibility issues [3].

6. Conclusion

In summary, this thesis project has developed a baseline framework; a general approach in evaluating a wind energy system for any end user using open-source data. It evaluates both the technical and economic feasibility of the wind turbines for DES applications. By considering using different variables such as economics, sizing and use cases, this framework is made to ease the decision-making process.

Creating the framework was a step-by-step process from choosing the turbines and hub heights to generating the power curves etc. On the other hand, the economic part of the framework takes into consideration the cost due to operational and capital expenditures and calculates the possible payback period and savings.

With the neglection of some factors, the economic analysis did reveal that higher hub heights do not always result in higher expenditures. The capital expenditure may increase but due to the increased efficiency in power generation the payback period will be shortened. By this analysis it is shown how important it is to carefully consider both the technical and economic parts in such an analysis for distributed wind energy systems. We both were surprised when we observed the power outputs and the payback periods. We did think that the highest capacity would have higher and better power output than the smaller one, but by looking at both the power output and payback period we could conclude with the N27 as the most viable and best turbine for this use case. We have learnt a lot during the writing and research process.

In conclusion this study and framework can contribute to the growing market of the distributed wind energy systems by bringing attention to the technical and economic considerations and challenges and showing a general approach to utilize a system like this. Lastly, this framework can contribute to strengthening decision-making and efficiency.

7. References

[1] Energy information administration. (20.04.2023). Wind explained. In *EIA (Energy Information Administration)*. Retrieved 22.04.2024: https://www.eia.gov/energyexplained/wind/history-of-wind-power.php

[2] Miljødirektoratet. (28.11.2023). Vindkraft. In *Miljødirektoratet*. Retrieved 07.03.2024: Vindkraft - Miljødirektoratet (miljodirektoratet.no)

[3] Stanley, P.J. (2022). Turbine scale and siting considerations in wind plant layout optimization and implications for capacity density. In *Elsevier*. Retrieved 06.05.2024: Turbine scale and siting considerations in wind plant layout optimization and implications for capacity density - ScienceDirect

[4] Energy government. How do wind turbines work? In *Energy.gov*. Retrieved 04.03.2024: https://www.energy.gov/eere/wind/how-do-wind-turbines-work

[5] Gill. (10.11.2021). The parts of a wind turbine. In *Energyfollower*. Retrieved 04.03.2024: https://energyfollower.com/parts-of-a-wind-turbine/#google_vignette

[6] Wind-turbine-models. Retrieved 05.02.2024: https://en.wind-turbine-models.com/turbines?kwrange=0%2C220

[7] Windatlas. Retrieved 05.02.2024: http://windatlas.xyz/download/

[8] Angizeh, F., Ghofrani, A., & Mohsen, A. J. (21.08.2020). Dataset on Hourly Load Profiles for a Set of 24 Facilities from Industrial, Commercial, and Residential End-use Sectors. Mendeley Data, V1, doi: 10.17632/rfnp2d3kjp.1. Retrieved 07.03.2024: https://data.mendeley.com/datasets/rfnp2d3kjp/1

[9] Hayes, L., Stocks, M., Blakers, A. (08.2021). Accurate long-term power generation model for offshore wind farms in Europe using ERA5 reanalysis. Retrieved 05.02.2024: Accurate long-term power generation model for offshore wind farms in Europe using ERA5 reanalysis (windatlas.xyz)

[10] Statistisk sentralbyrå. Retrieved 16.03.2024: https://www.ssb.no/en/statbank/table/09366/tableViewLayout1/

[11] Stehly, T., Duffy, P., & Mulas Hernando, D. (2023). 2022 Cost of Wind Energy Review. In *NREL*. Retrieved 16.03.2024: 2022 Cost of Wind Energy Review (nrel.gov)

[12] DNB. Retrieved 25.03.2024: https://www.dnb.no/markets/valuta-og-renter/valutakalkulator

[13] Satymov, R., Bogdanov, D., & Breyer, C. (01.09.2022). Global-local analysis of cost-optimal onshore wind turbine configurations considering wind classes and hub

heights. In *Elsevier*. Retrieved 16.03.2024: https://www.sciencedirect.com/science/article/pii/S0360544222015328#:~:text=CAPEX%20is%20also%20influenced%20by%20the%20hub%20height,and%20stronger%20foundation%20structures%20leading%20to%20increasing%20CAPEX.

[14] Useful project. Retrieved 2.05.2024: Useful Project: The Wind Turbine

[15] Vanek, F. M., Albright, L. D. & Angenent, L. T. (2016). *Energy systems Engineering, Evaluation and implementation* (third edition). Mc Graw Hill Education

Appendix

- Wind power curves new.xlsx