Colorado Wind Farm Design

Prepared for
Dr. Sankar
AE 4701-A
Wind Engineering

Prepared by
Parth Patel
Georgia Institute of Technology

10 June, 2024

Table of Contents

Introduction……..…………………..…………………………………………………………3

Feasibility analysis…………...………………..…….……………………………………………3

Rotor Design and Performance……….………………………………………..……….…..………4

Environmental Issues……….………………..……………………………………..……….…..………7

Conclusion………………………………,.......………………………………………………9

Bibliography……………………………………..……………………………………...….…..10

Introduction

As the world continues to strive towards net-zero carbon use and develop sustainable energy solutions, wind power is one of the frontrunners for renewable technology. In this report we will be reviewing the overall outlook and feasibility of developing a wind farm in Colorado. We will be using our findings from prior research as well as consider a number of environmental issues. We will be addressing technical and social aspects of developing a windfarm with a comprehensive look at potential challenges associated with wind energy being developed in this area.

Feasibility analysis

Energy Needs of Colorado

Colorado has a very diverse geography and a growing population, with most of the population concentrated in the center of the state around the Denver area, mountains out to the West and flat plains out in the East. Currently the state consumes about 56,000 GWh of energy every year. The energy is used across various sectors and industries as follows:

- Residential: 13,500 GWh
- Commercial: 10,700 GWh
- Industrial: 15,500 GWh
- Transportation: 16,300 GWh

Colorado's population is expected to increase by over 500,000 people over the next 10 years and energy consumption is expected to rise over 65,000 GWh. Economic development, electrification of cars and trucks, and overall growth in energy use by people are all factors leading to this incrase.

Wind Resources

Colorado has a great deal of wind resources, especially out in the plains in the east where the state borders Kansas. The varied topography of the mountain regions also creates diverse wind patterns which makes it an ideal location for wind energy projects. The average annual capacity factor for wind energy resources in Colorado is about 34% which shows the states strong wind conditions.

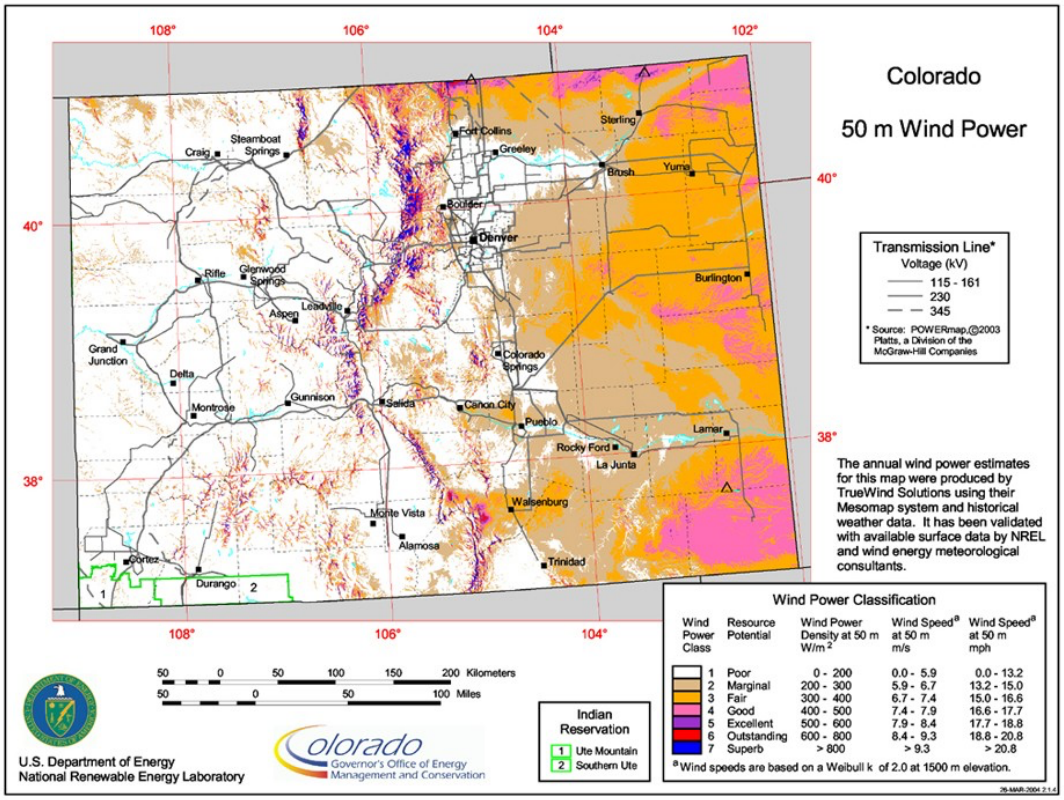

Figure 1: Wind Resource Map of Colorado

As you can see in figure 1 the eastern plains is full of consistent high speed winds which is ideal for large scale wind farms. The mountainous regions on the other hand area characterized by small-scale family based wind projects with challenges coming from the difficult terrain layout and accessibility of areas to develop turbines.

Initial Economic Analysis

To evaluate the cost-effectiveness of wind energy in Colorado, we conducted a comprehensive economic analysis. From this analysis we found that the average cost of wind energy is 0.503 cents/kWh which makes It the most cost efficient energy resource in the entire state. This clear economic advantage shows the viability of developing new wind energy projects in this state. As you can see in the data from table 1 below, wind energy is the least expensive resource to the consumer.

Table 1: Current Energy Sources and Costs in Colorado

Energy Source	Average Cost (cents/kWh)
Coal	3-5
Natural Gas	4-6
Wind	2-4
Solar	3-6
Hydropower	3-5

Rotor Design and Performance

Aerodynamic Data

In order to optimize our wind turbine design specifically for Colorado, we selected several aerodynamic parameters for our simulation. The following average data for Colorado was considered when selecting our turbine parameters due to the high-altitude of the state:

- Air density (Rho): 1.08 kg/m^3
- Kinematic air viscosity: 1.46e-5 m^2/s

These values reflect the high altitude atmosphere of Colorado as the air density is clearly lower than what it is at sea level. This is a necessary concern for our turbine design to ensure it is optimal for our environment.

Turbine Specifications

Several parameters were chosen and considered for our wind turbine design to ensure a balance between power, efficiency, reliability, and noise reduction.

The chosen specifications are shown below:

- Number of blades: 3
- Rotor radius: 15 meters
- Hub radius: 0.75 meters
- Precone angle: 2 degrees
- Shaft tilt: 5 degrees
- Yaw error: 0 degrees
- Hub height: 30 meters

A three bladed design was chosen as it is the industry standard and balances aerodynamic efficiency and mechanical stability. We chose a 0.75 meter hub radius as this was the optimal value for our design on WT_PERF and it also minimizes hub loss as well as providing enough structural support. The precone angle was chosen to be 2 degrees as it reduces bending moment on the blades from gravity and also improves the overall structural integrity of the turbine. The shaft tilt was chosen to be 5 degrees as it can help reduce the gyroscopic loads that are coming upon the turbine. Finally, we chose our hub height of 30 meters and rotor radius of 15 meters purely based on testing several different values for this input in increments of 15 meters and this is what outputted the highest energy and efficiency (Cp) from our tested designs on WT_PERF.

Simulation Results

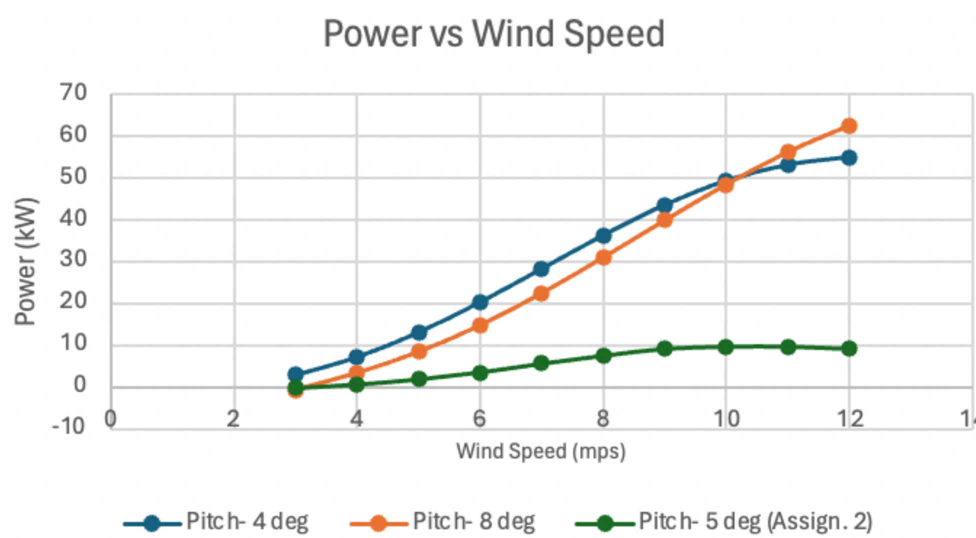

Figure 2: Wind Turbine Design Simulation Power Results

As we can see in figure 2, we tested the turbine at both 4 degree pitch and 8 degree pitch, and the data shows that our turbine performs better at 4 degree pitch for most wind speeds. Additionally, we can see that compared to assignment 2 our design shows significant improvement in power output while maintaining a similar efficiency.

Cost of Energy Analysis

We then conducted an economic analysis of our wind turbine to determine the cost of energy utilizing an excel model. To calculate the cost of energy for a 1 MW wind farm in Colorado we estimated the total installed cost per kW and the fixed energy costs while taking into account inflation. Table 3 below shows the cost for the components needed to functionally operate a wind turbine.

Table 3: Economic Analysis of Wind Turbine Systems

Component	Cost (USD)
Blades	3,222
Hub	27,832
Pitch mechanism	7,461
Drive train, nacelle	251,705
Tower	629
Foundations	1,989
Transportation	33,010
Roads, civil works	57,210
Assembly & installation	154
Permits, engineering	21,304

The total installed cost for a 1 MW turbine was calculated to be $495,778 per kW. The fixed energy costs were determined to be $77.46/kWh adjusted for inflation to $135/kWh. While there is a high cost of installation the turbine design is still technically feasible. There are however several economic challenges that need to be looked at. Further optimization of design, exploring different areas, and leveraging financial incentives such as subsidies can all be utilized to help reduce this cost.

Environmental Issues

Noise

Noise is a serious issue that needs to be considered when installing wind turbines, especially in residential areas. However, our site selection is in Colorado, particularly in the eastern part of the state where there is not much population density and wide open fields of space which will cause a lower risk of noise disturbance. Yet it is still important that noise assessments are completed so that local regulations are complied with, To mitigate this noise we can also implement several strategies such as using quieter turbine models, installing noise barriers, and scheduling maintenance of the turbines at less noise sensitive times of day.

Noise level varies based on several factors such as turbine size, wind speed, and the terrain around the turbine. The primary source for this noise comes from wind turbines and aerodynamic drag noise coming from blades as well as mechanical noise coming from the gearbox and generator. Aerodynamic noise which comes from blade/wind interaction can be reduced with the optimization of blade design and surface of the blade. Mechanical noise can be reduced can be mitigated through routine maintenance and oiling of the parts as well as using soundproofing materials around the parts.

Avian Issues

Birds around a wind turbine are also a major concern especially those that frequently collide into them during migration periods. Colorado is particularly known for its bird migration routes passing through the state. We can implement several technologies such as bird detection and deterrent systems as well as choose locations to place the turbine to minimize the impact on their habitats which can mitigate the risk of collision during migratory periods. Routing monitoring and collaborating with wildlife experts on these issues is also critical to protect the avian population.

Turbine design can also impact the effect it has on bird population varying from factors such as turbine size and rotor speed. Particular bird species common to Colorado are known to be more susceptible to these collisions. To mitigate this we can implement the following measures:

- Bird friend turbine designs which are less hazardous to birds with lower rotor speeds and bladeless turbines
- Planning locations away from known bird migration paths, nesting and feeding areas
- Monitoring and researching the area by conducting regular bird surveys as well as utilizing radar technology to monitor their movement
- Adjusting turbine operations to adapt to peak migration periods to minimize rate of collision

Public Policy

Colorado has implemented several public policies to increase the renewable energy sector, especially wind energy projects. The state has several tax credits and incentives already in place. However those seeking to develop a wind farm must comply with local zoning laws as well as conduct routine environmental impact assessments. The Renewable Portfolio Standards (RPS) mandate that at least 30% of annual electricity sales come from strictly renewable sources, which even further encourages the implementation of wind energy. The state also provides tax credits for investment and production of renewable energy products to incentivize their development. Key policies that support this wind energy development in Colorado are as follows:

- Renewable energy standards that maintain a certain percentage of energy to be derived from renewable resources
- Grants and funding that area offered for low interest loans to develop these energy projects
- Permits and regulations that streamline the ground up and operation process so that environmental regulations area complied with
- Community engagement which promotes public participation and addressing community concerns of wind turbines to ensure a transparent planning process

Public Acceptance

A often looked past aspect is public acceptance of the project to ensure success. Info sessions and local community engagement is necessary to address public concerns such as noise, visual impact, and ecological effects. Transparency is essential in project planning so that public support can be leveraged for economic benefits. Incentives can also be put into place such as profit sharing arrangements and community ownership to help build local support and involvement. Various factors need to be taken into consideration for public acceptance such as:

- Concerns of visual and aesthetic impact of wind turbines on the local landscape. This can be addressed through careful site selection, using smaller turbines, and utilizing design elements which can easily blend in with the environment
- Demonstrating the economic benefits to the local community such as job creation, increased property value, and community investment
- Addressing health and safety concerns such as noise-related sleep disturbance and shadow flicker. We can provide clear information and research to communities to help alleviate these concerns
- Highlighting the environmental benefits of utilizing wind energy such as reducing greenhouse gas emissions and decreasing the use of fossil fuels. By showing the community that we can engage in environmental conservation efforts and collaborating with local wildlife organizations we can demonstrate our commitment to environmental stewardship

Conclusion

The feasibility study and design analysis conducted for a wind turbine project to be developed in the state of Colorado reveals a promising potential for wind energy production in the state. High wind resource availability, supportive public policies, and growing demand for energy needs in Colorado make it one of the most ideal locations for wind farms in the United States of America. However our economic analysis did reveal the need for further design optimization for cost reduction. Additionally, we need to address environmental concerns such as noise and avian impacts, ensure public acceptance, and promote community engagement to achieve sustainable and economically viable wind energy production in Colorado.

Bibliography

Malcolm, D J, & Hansen, A C. *WindPACT Turbine Rotor Design Study*: June 2000--June 2002 (Revised). United States. https://doi.org/10.2172/15000964

Giguere, P, & Selig, M S. *Design of a Tapered and Twisted Blade for the NREL Combined Experiment Rotor*. United States. https://doi.org/10.2172/750919

Reports. Reports I Colorado Energy Office. (n.d.). United States. https://energyoffice.colorado.gov/about-us/reports

Fogleman, J. (2024, March 18). *Fast facts about electricity in Colorado in 2023* - Independence Institute. Independence Institute - Think Freedom. https://i2i.org/fast-facts-about-electricity-in-colorado-in-2023/

U.S. Energy Information Administration - EIA - independent statistics and analysis. State Energy Profile Data. (n.d.). https://www.eia.gov/state/data.php?sid=CO

Weiser Scott., S. (2023, December 1). *Carbon capture isn't ready for prime time, Colorado's energy chief says. Denver Gazette.* https://denvergazette.com/news/carbon-capture-isnt-ready-for-prime-time-colorados-energy-chief-says/article_a2852b08-4670-11ec-b43e-0382b5982a03.html

Wikimedia Foundation. (2023, November 30). *Wind power in Colorado.* Wikipedia. https://en.wikipedia.org/wiki/Wind_power_in_Colorado

Appendix A

LWST Baseline (2002) Turbine Calculations - Class 4

10 m windspeed	4	m/s		**P/Prated**	**Efficiency**
Weibull K parameter	2.00			0.00001	0.0%
Rated power	1000	kW		0.05	54.5%
Rotor Dia.	70	meters		0.1	74.5%
Hub height	30	meters		0.15	81.2%
Altitude	1600	meters		0.2	84.5%
Air Density	**1.080**	kg/m^3		0.25	86.5%
Rotor Cp	0.3			0.3	87.8%
Cut-in windspeed	3	m/s		0.35	88.8%
Cut-out windspeed	26	m/s		0.4	89.5%
Power law shear exponent	0.143			0.45	90.1%
Hub height windspeed	**4.68**			0.5	90.5%
Rated windspeed	**12.01**	m/s		0.55	90.9%
Conversion Efficiency	0.95	0.015		0.6	91.2%
	0.005	0.005		0.65	91.4%
Soiling Losses	3.5%			0.7	91.6%
Array Losses	5.0%			0.75	91.8%
Availability	98.0%			0.8	92.0%
	Turbine	Weibul Cp	Weibul betz	0.85	92.1%
Energy capture (MWh/year)	**758.78**	**1016.00**	**2112.55**	0.9	92.3%
Capacity Factor	**8.66%**			0.95	92.4%
Energy capture ratio	**74.68%**			1	92.5%

Appendix B

Component	Baseline
Rotor	**38,515**
Blades	3,222
Hub	27,832
Pitch mchnsm & bearings	7,461
Drive train,nacelle	**251,705**
Low speed shaft	7
Bearings	173
Gearbox	29,668
Mech brake, HS cpling etc	1,989
Generator	65,000
Variable spd electronics	79,000
Yaw drive & bearing	6
Main frame	8,476
Electrical connections	40,000
Hydraulic system	12,000
Nacelle cover	15,386
Control, safety system	**10**
Tower	**629**
TURBINE CAPITAL COST (TCC)	**290,859**
Foundations	1,989
Transportation	33,010
Roads, civil works	57,210
Assembly & installation	154
Elect interfc/connect	91,090
Permits, engineering	21,304
BALANCE OF STATION COST (BOS)	**204,757**
Project Uncertainty	**162**
Initial capital cost (ICC)	**495,778**
Installed Cost per kW for 1MW turbine	**495,778**
(cost in $)	
Turbine Capital per kW sans BOS	**290,954**
(cost in $)	
NET 4 m/s ANNUAL ENERGY PRODUCTION MWh (AEP)	**758.78**
Fixed Charge Rate	11.85%
COE at 4 m/s $/kWh	**77.4645**

Appendix C

Wind Turbine Component Cost Calculations

Number of Blades: 3
Rotor Radius: 15 m
Hub Radius: 0.75 m
Hub Height: 2 m
Calculation Type: Baseline
Machine Rating: 1000 kW

Calculations

Blades

Blade Mass:
mass = 0.1452 * R^2.9158
R = 15 m
mass = 0.1452 * 15^2.9158 = 0.1452 * 6109.945 ≈ 887.03 kg
Blade Cost:
Cost = (0.4019 * R^3 - 955.24 + 2.7445 * R^2.5025) / (1-0.28)
Cost = (0.4019 * 15^3 - 955.24 + 2.7445 * 15^2.5025) / (1-0.28)
Cost = (0.4019 * 3375 - 955.24 + 2.7445 * 350.9) / (1-0.28)
Cost = (1355.92 + 963.92) / 0.72 ≈ 2319.84 / 0.72 ≈ 3221.72 USD

Hub

Hub Mass:
mass = 0.954 * Blade Mass + 5680.3
mass = 0.954 * 887.03 + 5680.3 ≈ 6548.97 kg
Hub Cost:
Cost = Hub Mass * 4.25
Cost = 6548.97 * 4.25 ≈ 27832.12 USD

Pitch Mechanism and Bearings

Total Pitch Bearing Mass:
Mass = 0.1295 * Total Blade Mass + 491.31
Mass = 0.1295 * (3 * 887.03) + 491.31
Mass = 0.1295 * 2661.09 + 491.31 ≈ 835.72 kg
Total Pitch System Mass:
Mass = (Total Pitch Bearing Mass * 1.328) + 555
Mass = (835.72 * 1.328) + 555 ≈ 1665.25 kg
Total Pitch System Cost:
Cost = 2.28 * (0.2106 * Rotor Diameter^2.6578)
Rotor Diameter = 2 * 15 = 30 m
Cost = 2.28 * (0.2106 * 30^2.6578) ≈ 2.28 * 3273.11 ≈ 7460.69 USD

Low-Speed Shaft

Low-Speed Shaft Mass:
mass = 0.0142 * Rotor Diameter^2.888
mass = 0.0142 * 30^2.888 ≈ 0.0142 * 703.44 ≈ 9.99 kg
Low-Speed Shaft Cost:
Cost = 0.01 * Rotor Diameter^2.887
Cost = 0.01 * 30^2.887 ≈ 0.01 * 703.44 ≈ 7.03 USD

Bearings

Bearing Mass:
mass = (Rotor Diameter * 8/600 - 0.033) * 0.0092 * Rotor Diameter^2.5
mass = (30 * 8/600 - 0.033) * 0.0092 * 30^2.5
mass = (0.4 - 0.033) * 0.0092 * 1581.14 ≈ 0.3367 * 14.54 ≈ 4.89 kg
Total Bearing System Cost:
Cost = 2 * Bearing Mass * 17.6
Cost = 2 * 4.89 * 17.6 ≈ 172.89 USD

Gearbox (Three-Stage Planetary/Helical)

Gearbox Mass:
mass = 70.94 * Low-Speed Shaft Torque^0.759
Low-Speed Shaft Torque = 703.44
mass = 70.94 * 703.44^0.759 ≈ 70.94 * 98.76 ≈ 7008.62 kg
Total Cost:
Cost = 16.45 * machine rating^1.249
Machine Rating = 1000 kW
Cost = 16.45 * 1000^1.249 ≈ 16.45 * 1803.4 ≈ 29667.83 USD

Mechanical Brake, High-Speed Coupling

Cost:
Cost = 1.9894 * Machine Rating - 0.1141
Cost = 1.9894 * 1000 - 0.1141 ≈ 1989.29 USD
Mass:
mass = Brake/Coupling Cost / 10
mass = 1989.29 / 10 ≈ 198.93 kg

Generator (Three-Stage Drive with High-Speed Generator)

Mass:
mass = 6.47 * Machine Rating^0.9223
mass = 6.47 * 1000^0.9223 ≈ 6.47 * 759.38 ≈ 4912.48 kg
Total Cost:
Cost = Machine Rating * 65
Cost = 1000 * 65 ≈ 65000 USD

Variable-Speed Electronics

Total Cost:

Cost = Machine Rating * 79
Cost = 1000 * 79 ≈ 79000 USD

Yaw Drive and Bearing

Total Yaw System Mass:
mass = 1.6 * (0.0009 * Rotor Diameter^3.314)
mass = 1.6 * (0.0009 * 30^3.314) ≈ 1.6 * 196.79 ≈ 314.86 kg
Total Yaw System Cost:
Cost = 2 * (0.0339 * Rotor Diameter^2.964)
Cost = 2 * (0.0339 * 30^2.964)
Cost = 6.02 USD

Main Frame

Main Frame Mass:
mass = 2.233 * Rotor Diameter^1.953
mass = 2.233 * 30^1.953 ≈ 1996.2 kg
Main Frame Cost:
Cost = 9.489 * Rotor Diameter^1.953
Cost = 9.489 * 30^1.953 ≈ 8475.6 USD

Electrical Connections

Cost = Machine Rating * 40
Cost = 1000 * 40 ≈ 40000 USD

Hydraulic System

Hydraulic System Mass:
mass = 0.08 * Machine Rating
mass = 0.08 * 1000 ≈ 80 kg
Hydraulic System Cost:
Cost = Machine Rating * 12
Cost = 1000 * 12 ≈ 12000 USD

Nacelle Cover

Cost = 11.537 * Machine Rating + 3849.7
Cost = 11.537 * 1000 + 3849.7 ≈ 15386.7 USD

Tower

Tower Mass:
mass = 0.3973 * Swept Area * Hub Height - 1414
Swept Area = π * R^2 = π * 15^2 ≈ 706.86 m^2
Hub Height = 2 m
mass = 0.3973 * 706.86 * 2 - 1414 ≈ 419.6 kg
Tower Cost:
Cost = mass * 1.50
Cost = 419.6 * 1.50 ≈ 629.4 USD

Foundations

Cost = 303.24 * (Hub Height * Swept Area)^0.4037
Cost = 303.24 * (2 * 706.86)^0.4037 ≈ 303.24 * 1455.3^0.4037 ≈ 303.24 * 6.56 ≈ 1989.2 USD

Transportation

Cost = Machine Rating * (1.581E-5 * Machine Rating^2 - 0.0375 * Machine Rating + 54.7)
Cost = 1000 * (1.581E-5 * 1000^2 - 0.0375 * 1000 + 54.7)
Cost = 1000 * (15.81 - 37.5 + 54.7) ≈ 1000 * 33.01 ≈ 33010 USD

Roads, Civil Works

Cost = Machine Rating * (2.17E-6 * Machine Rating^2 - 0.0145 * Machine Rating + 69.54)
Cost = 1000 * (2.17E-6 * 1000^2 - 0.0145 * 1000 + 69.54)
Cost = 1000 * (2.17 - 14.5 + 69.54) ≈ 1000 * 57.21 ≈ 57210 USD

Assembly & Installation

Cost = 1.965 * (Hub Height * Rotor Diameter)^1.1736
Cost = 1.965 * (2 * 30)^1.1736 ≈ 1.965 * 60^1.1736 ≈ 1.965 * 78.63 ≈ 154.48 USD

Electrical Interface/Connections

Cost = Machine Rating * (3.49E-6 * Machine Rating^2 - 0.0221 * Machine Rating + 109.7)
Cost = 1000 * (3.49E-6 * 1000^2 - 0.0221 * 1000 + 109.7)
Cost = 1000 * (3.49 - 22.1 + 109.7) ≈ 1000 * 91.09 ≈ 91090 USD

Permits, Engineering

Cost = Machine Rating * (9.94E-4 * Machine Rating + 20.31)
Cost = 1000 * (9.94E-4 * 1000 + 20.31)
Cost = 1000 * (0.994 + 20.31) ≈ 1000 * 21.304 ≈ 2130