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Multi-Rotor Wind Turbine: Structure and Cost analysis

(Brief Discussion)

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Abstract

The wind turbine industry has made significant strides, with current developments reaching the multi-giga range and rotor diameters of 200m. While increasing rotor diameters enables higher power output, the economic feasibility of larger blades remains a burning question. This paper explores an innovative Multi Rotor Wind Turbine (MRWT) design as an alternative to traditional single large rotors. The concept of wind turbines with multiple rotors dates to the late 1800s and has been studied by researchers due to its potential benefits of lighter weight and lower cost.

The core idea of this research is to divide a large single rotor into multiple smaller rotors while maintaining the same power output. The MRWT system offers various advantages, including ease of transportation, standardization, production, and installation. To demonstrate the mass and cost reduction benefits, this work compares a 5MW MRWT design with a baseline 5MW single rotor wind turbine (NREL 5MW).

The work begins by providing an introduction and background on wind turbine development and working principles. It then presents a historical overview of multi-rotor concepts and their potential advantages. The MRWT design is described, highlighting its proposed benefits in terms of scaling. A comparative analysis between the NREL 5MW baseline and a 5MW MRWT focuses on mass and cost reduction. Additionally, concludes with recommendations for future research and development of the MRWT design.

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1. Wind turbine Introduction

Climate change is a pressing global issue, and mitigating its impact requires a concerted effort from all nations. Scientists worldwide have emphasized the need to significantly reduce greenhouse gas emissions, particularly carbon dioxide (CO_2), by at least 70-80% by the year 2050. To achieve this ambitious target, a substantial portion of our total energy production, approximately 80-90%, must come from renewable sources by the mid-century mark. Among the various renewable energy alternatives, wind power stands out as a widely recognized and cost-effective solution. It is an abundant, renewable, and environmentally friendly energy source that does not contribute to air pollution. This has prompted many developing and emerging economies to optimistically focus their efforts on the wind energy sector, working innovatively to enhance energy production from this resource. In numerous locations, generating electricity from wind energy offers a cost-effective alternative to traditional power generation systems, such as thermal or nuclear power plants. Wind energy not only has a lower environmental impact but also contributes to greater energy independence by reducing reliance on imports of non-renewable energy sources. Additionally, it enhances energy security by diversifying the energy supply.

1.1 Wind Power around the world

Wind power has experienced remarkable growth over the past two decades, fueled by research and development efforts, supportive policies, and declining costs. The global installed wind generation capacity, encompassing both onshore and offshore installations, has multiplied by an astonishing factor of 98 since 1997, surging from a modest 7.5 gigawatts (GW) to an impressive 733 GW by 2018, according to data from the International Renewable Energy Agency (IRENA). The onshore wind sector has been a driving force behind this expansion, with capacity skyrocketing from 178 GW in 2010 to an impressive 699 GW by 2020. Although starting from a lower base, offshore wind has grown proportionately more, increasing from 3.1 GW in 2010 to 34.4 GW in 2020. Consequently, wind power production has experienced a substantial 5.2-fold increase between 2009 and 2019, reaching an impressive 1,412 terawatt-hours (TWh). Both onshore and offshore wind technologies hold tremendous potential for further deployment and improvement on a global scale. As these technologies have advanced and scaled up, costs have decreased, and capacity factors have risen. Between 2010 and 2020, the global weighted-average levelized cost of electricity (LCOE) for onshore wind fell by a remarkable 56%, from $0.089 per kilowatt-hour (kWh) to $0.039 per kWh. During the same period, the LCOE for newly commissioned offshore wind projects experienced a substantial 48% reduction. [1]

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Installed Capacity by the end of 2018 (MW)*

Country/Region1	2018	2017	2016	2015
China	221'630	195'730	168'730	148'000
United States	96'363	88'775	82'033	73'867
Germany	59'313	56'190	50'019	45'192
India**	35'017	32'879	28'279	24'759
Spain*	23'031	23'026	23'020	22'987
United Kingdom	20'743	17'852	14'512	13'614
France	15'313	13'760	12'065	10'293
Brazil**	14'490	12'763	10'800	8'715
Canada	12'816	12'239	11'898	11'205
Italy*	10'090	9'700	9'257	8'958
Rest of the World*	91'473	83'473	76'325	67'695
Grand Total	**600'278**	**546'388**	**486'939**	**435'284**

* Preliminary data
** By November 2018

Figure 1: Top 10 countries in WT Installed capacity [2]

2. Basic of Wind Turbine

Wind turbines use wind to make electricity. The wind turns the blades, which spin a generator to create electrical power. There are two main types of wind turbines - ones with blades that spin horizontally like a windmill, and ones with blades that spin vertically. Most big wind turbines have horizontal spinning blades.

In paper, I want to look at the horizontal spinning wind turbines. I want to come up with new ideas to make them better by thinking in different ways. This could mean improving the blade design, structure, controls or completely new ideas. The goal is finding ways to make horizontal wind turbines more efficient, reliable and better for the environment.

2.1 Turbine Components

Horizontal axis wind turbine (HAWT) components includes:

- **Rotor** or **Blade**, which rotates due to kinetic energy of Wind;
- a **drive train**, normally including a gearbox and a generator;

- a **tower** which gives supports to the rotor and drive train; and
- different equipment, including electrical cables, controls, interconnection equipment and ground support equipment.

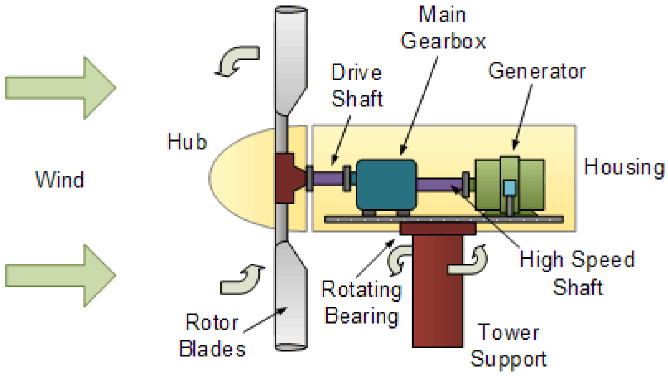

Figure 2: Turbine Components [3]

The predominant wind turbine design is the Horizontal Axis Wind Turbine (HAWT). In this configuration, the main rotor spins around a horizontal axle, typically with three blades extending from a central hub. The rotor-nacelle assembly (RNA) comprises the rotor blades, hub, drivetrain components that transfer the rotational energy, and an electrical generator. As depicted in the referenced figure, the RNA is supported by a tall tower structure with a foundation base. The turbine also has a yaw mechanism that rotates the entire RNA to face into the wind direction, allowing it to capture the maximum available wind energy and generate the highest possible power output. [3]

2.2 Working Principle of Wind Turbine

Wind turbines convert wind kinetic energy into mechanical rotation via their rotor blades, which is then used to generate electricity through a generator. The two main wind turbine designs are:

- Horizontal Axis Wind Turbines (HAWTs) - These have a horizontal rotor shaft, typically with 3 propeller-style blades.[4]
- Vertical Axis Wind Turbines (VAWTs) - The rotor shaft is vertical, perpendicular to the wind flow. [4]

The blades of a wind turbine are carefully designed with a shape that transitions from a thick cylindrical root section to a thin air foil profile at the tip. This shaping allows an optimal balance between aerodynamic performance and structural integrity. Additionally, the blades are twisted along their length to maintain a more favorable angle of attack (α) relative to the apparent wind direction at each spanwise location. As the rotor spins, aerodynamic forces are generated on the blades and converted into mechanical rotational power transmitted through the turbine shaft. These aerodynamic forces consist of lift (*L*) and drag (*D*) components, which can be resolved into normal (F_n) and tangential (F_t) force vectors acting perpendicular and parallel to the rotor's plane of rotation respectively. The referenced figure 3 visually depicts the aerodynamic lift and drag loads experienced by an airfoil cross-section along the blade.

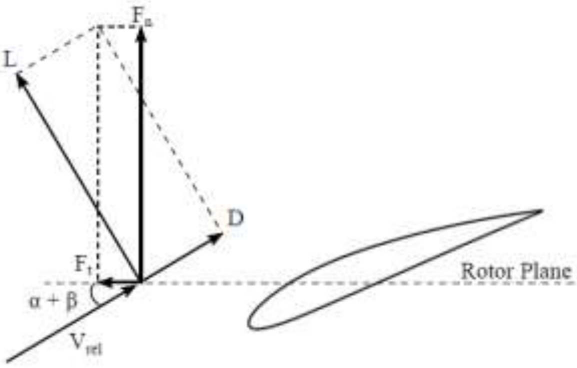

Figure 3: Aerodynamic loads experienced on an airfoil section of the blade [4]

The torque (Q) and thrust (T) produced by the normal and tangential forces, which determine the overall outcome of a wind turbine. In order to compare various designs, the thrust and torque of wind turbines can be non-dimensional zed. The following equations define the coefficients of thrust (C_T) and torque (C_Q), respectively.[4]

$$C_T = \frac{T}{1/2\rho A {V_0}^2}$$

$$C_Q = \frac{Q}{1/2\rho RA {V_0}^2}$$

where V_o is the incoming wind speed, ρ is the fluid density, A is the swept area of the rotor (i.e., $A = \pi R^2$) and *R* is the radius of the rotor.

Another crucial non-dimensional parameter for wind turbine performance is the coefficient of power (C_P). This coefficient represents the ratio of the actual power output extracted by the turbine to the theoretical maximum power (P_{max}) available in the wind stream. The maximum theoretical power is defined by an equation that assumes the wind velocity could hypothetically be reduced to zero. [5]

$$P_{max} = 1/2\rho A {V_0}^3$$

However, “This is not physically possible because the air must continue flowing past the turbine rotor to maintain steady-state conditions.” As a result, wind turbines can only capture a fraction of the total kinetic energy in the wind stream. This limiting fraction is known as the power coefficient C_p. The idealized maximum value of C_p is 16/27 or approximately 59.26%, termed the **Betz Limit**. Therefore, the mechanical power generated by a wind turbine with rotor radius *R* operating in a wind speed v is given by the expression shown, which involves the air density, rotor swept area, wind speed, and C_p value. [5]

$$P_{mech} = C_P 1/2 \rho A {V_0}^3$$

$$P_0 = \eta_0 C_P 1/2 \rho A {V_0}^3$$

Where, where η_0 is the drive train’s mechanical efficiency.[5]

3. Overview to Multi rotor wind turbine

The concept of multi-rotor wind turbine (MRWT) arrays has been quietly present for over a century. Unlike conventional single modern wind turbines with one rotor, MRWTs feature multiple rotors installed on a single tower or structure. Initially, the need for multi rotors arose from the challenge of producing larger blades, largely due to technological limitations. However, the advent of modern glass composites, which are lighter and stronger than conventional materials, addressed this limitation, leading to a decline in interest in the multi-rotor concept.

Now, with rotor diameters exceeding 200 meters, it's time to reconsider the MRWT system. The emergence of materials like fiber-reinforced polymers, boasting high strength-to-weight ratios, has made manufacturing very large rotor blades feasible. The multi-rotor concept, once considered too complex and unnecessary, deserves renewed attention in light of these advancements. The primary focus of current research is to reduce the Cost of Energy (CoE) associated with wind energy systems. The CoE is defined as the unit cost of energy ($/KWh) generated by the wind energy system.[6] Challenges such as offshore installation with existing vessels and cranes, transportation limitations, and economic feasibility suggest that single-rotor designs may not be practical on a large scale beyond 150m blades.[7]

COE = (Total annualized costs) / (Annual energy production)

3.1 Literature Review

The origins of multi-rotor systems trace back to 1873 in Denmark, where Danish twin mills were employed for containment and drying projects.[8] This innovation replaced steam with three Dutch mills, two of which were twin-mills, each featuring 6-winged flap sailing rotors mounted atop mill houses.

In 1930, German engineer Hermann Honnef proposed a multi-rotor concept [9] that involved a 430m high tower with three contra-rotating rotors intended to generate 20 MW.

During the 1980s in the Netherlands, Henk Lagerweij of Lagerwey Wind constructed several multi-rotor turbines, including the Sixmaster [10], the Quadro [11], and the Twinmaster. These turbines featured 6, 4, and 2 rotors respectively, all mounted on a single tower, as depicted in Figure 6. Each rotor had a capacity of 75 kW. However, these turbines encountered challenges such as vibration and control system issues, leading to their eventual decommissioning.

Figure 4: (Left to right) Twinmaster, Quadro [11] and Sixmaster [10] built by Lagerwey Wind

4. Scaling Relation

To enhance the power output of wind turbines, larger rotor diameters are necessary. However, challenges such as transport, installation, and manufacturing limitations may hinder further increases in rotor size. Hence, the concept of multi-rotor systems is introduced. To improve cost-effectiveness while maintaining the same power output, the idea of scaling a larger rotor into smaller ones with the total swept area remaining constant is considered. This chapter will explore various approaches to scaling relations.

4.1 Scaling Method

4.1.1 Geometric Scaling

The first scaling method is the simplest, involving multiplying the dimensions of the model by a known factor uniformly. This approach assumes geometric and aerodynamic similarity, meaning a fixed tip speed ratio. It's also referred to as 0^{th} order scaling or geometric scaling.[12]

According to the area-volume relationship, the area and volume of any 3D object scale as the square and cube of its given length, respectively. This implies that even a small increase in rotor size would have a significant effect on the cost and mass of the blade. Jamieson incorporated this relationship into his work to demonstrate that multiple small rotors, each generating a portion of the total power output, are more cost and mass-effective than a larger single-rotor system with the same power output. The advantage in terms of mass and cost is particularly observed in the rotor nacelle assembly (RNA).[13]

$$\frac{nm}{M} = n\left(\frac{d}{D}\right)^3 = \frac{1}{\sqrt{n}}$$

As described, when comparing smaller rotors to a larger rotor, the smaller ones would be approximately $1/\sqrt{n}$ times lighter, and consequently, less expensive. Mathematically, if the rotor diameter is halved, the swept area (and thus the total wind captured) is quartered. However, the mass will be decreased by an eighth. In simpler terms, the mass decreases much faster than the power with a smaller diameter.

4.1.2 Dynamic Scaling

In a geometric scaling scenario, certain physical characteristics such as load, size, weight, etc., always vary with the scale factor. However, in dynamic scaling, one select predefined ratios or numbers as relationships among these physical characteristics in a manner that these ratios or numbers remain unchanged regardless of the scale factor. For instance, in a strength-to-weight problem, one can limit stress so that it does not exceed the predefined ratios or numbers. This approach allows stresses to be used as the driving factor in design, enabling changes in dimensions and offering flexibility corresponding to geometric scaling because stress values depend on material properties. This method is known as the 1st order of scaling.[13]

4.1.3 Empirical Upscaling

Geometric upscaling provides valuable insights, but it may not encompass all aspects of operating large wind turbines. To achieve a more comprehensive upscaling process based on industry observations, the 2nd order of scaling is utilized. This approach, also known as 2nd order scaling, relies on published design and cost data of wind turbines, which are derived from successful designs already in use. This scale combines both geometric and dynamic upscaling methods and is favored by major manufacturers and researchers due to its reliance on proven designs and available data.[14]

The Wind Partnership for Advanced Component Technology (WindPACT) project, led by the United States Department of Energy (DoE), conducted research aimed at technological improvements to decrease the Cost of Energy (CoE) associated with wind energy.[14] This project analyzed various successful wind turbine designs to assess the impact of increasing component size on the CoE, based on publicly released data. The National Renewable Energy Laboratory (NREL)'s National Wind Turbine Center (NWTC) developed a spreadsheet model based primarily on the WindPACT data of rotor studies.

For the rotor blade, research gives two types of empirical relations.

1. **Baseline** – Primarily based on the data acquired from WindPACT design

2. **Advance** – Mainly based on LM Glassfiber blade design

In terms of rotor radius R, the blade mass relation can be given as follows:[15]

$$\text{Baseline: Blade Mass} = 0.1452 * R^{2.9158}$$

$$\text{Advanced: Blade Mass} = 0.4948 * R^{2.53}$$

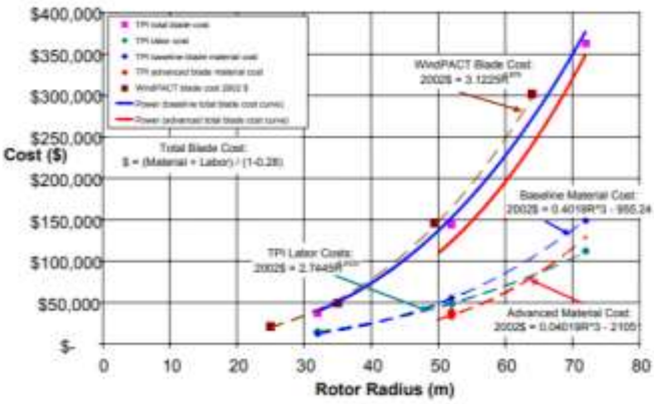

Figure 5: Blade Cost scaling relation [16]

4.2 Effect of Scaling on Wind turbine design

Downscaling larger wind turbines into smaller ones is indeed an intriguing subject. While empirical scaling provides valuable data on mass and cost, it doesn't cover all the necessary aspects for building scaled wind turbines. There are certain design considerations that empirical scaling laws overlook. Some other important scaling effects to consider include:

1.**Tip Speed Ratio (λ):** The tip-speed ratio, λ, or TSR for wind turbines is the ratio between the tangential speed of the tip of a blade and the actual speed of the wind. [17]

$$\text{Tip Speed Ratio } (\lambda) = \frac{Tip\ speed\ of\ blade}{Wind\ speed} = \frac{\omega R}{v}$$

While upscaling a wind turbine, primarily idea is to maintain the ratio constant. This idea preserves the relation between wind speed and rotor speed at any given operating speed of wind turbine. Maintaining a constant tip speed ratio at a given wind speed make sure that in up-scaling, Rotor diameter D must inversely vary with the rotor angular velocity ω. Rotor diameter should decrease with increasing angular velocity.

2. Self-Weight load scaling: In wind turbine design, the self-weight of the blade affects bending loads. This bending load scales with the mass of the blade (D^3) and the moment arm (D), resulting in a scaling factor of D^4 for blade bending moments. When considering upscaling, the increased blade weight leads to higher bending moments, necessitating attention to stress levels and recommending a higher factor of safety.

3. Lift and Drag coefficient: As the blade is shaped aerofoil, we cannot neglect effect of boundary layer over the aerofoil section of blade. Reynold number indicates the boundary layer effect and a research shows that lift and drag coefficient not only on the shape but it also depends on the size of the blade. For a medium range wind turbine of 850KW to 1.5MW for land-based, this effect is minor and can easily neglected. [18].

4. Wind Shear: Wind shear or Wind gradient simply means change in wind speed or direction over a short distance in atmosphere. At a certain height, the wind speed is given by the:

$$v_2 = v_1 \left(\frac{z_2}{z_1}\right)^{\alpha}$$

Where v1 is velocity at z1 height and v2 is velocity at z2 height. α is wind shear exponent. Researcher can estimate the wind speed at any given height by taking a normal approach of wind shear used in wind energy industry. The shear exponent α is normally assumed to be 0.2.[19]

As the hub height increases, wind speed and consequently wind power also increase. Wind shear, the variation of wind speed with height, implies that upscaling can result in greater power production. However, it's important to note that increasing the hub height isn't always beneficial, as it also leads to increased loads on the turbine structure. Since wind shear effect is directly related to the dimensions of the wind turbine, it will be considered in the design of the Multi-Rotor Wind Turbine (MRWT).[19]

5. Multi Rotor 5MW wind turbine RNA cost analysis

This chapter will include general framework of the Rotor Nacelle assemble of the multi rotor assembly depends on the scaling fundamentals. The mass data of the RNA is obtained from the NREL scaling studies.

Down-scaled RNA property

For the design of the 3 Rotor wind turbine, chosen 'NREL 5 MW baselined wind turbine' [22]. This is conventional, upwind type, three rotor multi megawatt turbine. It also has variable blade pitch and variable blade speed with feather controlled. Due to excessive information available online I have opted to choose this turbine as a reference.

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m

Hub Height	90 m
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Cut-In, Rated, Cut-Out Wind Speed	3m/s, 11.4m/s, 25m/s
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Pre-cone	5 m, 5º, 2.5º
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2m, 0.0m, 64.0m)

Table 5.1 NREL 5 MW turbine Property[22]

For the design purpose, the NREL 5 MW turbine is downscaled into 3 small rotors, each with a power capacity of 1.67 MW. These downscaled rotor properties are provided in Table 5.2. This new multi-rotor system is based on the exact design considerations of the NREL 5 MW reference's baseline design, including, Power Coefficient (Cp) – 0.467, Mechanical Efficiency (η0) – 100%, Electrical Efficiency – 94.4%, Rated Wind Speed – 11.40 m/s. [21]

Rating	1.67 MW
Rotor Orientation, Configuration	Upwind, 3 Bladed
Rotor, Hub Diameter	72.75 m, 2 m
Rotor, Hub Diameter	3 m/s, 11.4 m/s, 25 m/s
Cut-in, Rated Rotor Speed	5.51rpm, 20.94rpm
Designed Tip Speed Ratio (λ), Rated Tip speed	7, 80 m/s

Table 5. 2 Three rotor downscaled wind turbine property

Item	Mass	Cost
Blade	$M_{blade} = 0.1452R^{2.9158}$	$C_{blade} = \frac{0.4019R^3 - 955.24 + 2.7445 * R^{2.5025}}{0.72}$
Hub	$M_{hub} = 0.954M_{blade} + 5680.3$	$C_{hub} = 4.25M_{hub}$
Pitch bearing	$M_{pitch\ bearing} = (0.1295)(3) M_{blade} + 491.31$	N/A
Pitch system	$M_{pitch\ system} = 1.328M_{pitch\ bearing} + 555$	$C_{pitch\ system} = 0.40817D^{2.6578}$
Nose cone	$M_{nose\ cone} = 18.5D - 520.5$	$C_{nose\ cone} = 5.57M_{nose\ cone}$
Low speed shaft	$M_{LSS} = 0.0142D^{2.888}$	$C_{LSS} = 0.01D^{2.888}$
Bearing system	$M_{bearing\ system} = 0.00024543D^{3.5} - 0.0006072D^{2.5}$	$C_{bearing\ system} = 17.6M_{bearing\ system}$
Gearbox	$M_{gearbox} = 393.27(P_R/N_R)^{0.759}$	$C_{gearbox} = 16.45P_R$
Brake	$M_{brake} = C_{brake}/10$	$C_{brake} = 1.9794P_R - 0.1141$
Generator	$M_{generator} = 6.47P_R^{0.9223}$	$C_{generator} = 65P_R$
Electronics	0	$C_{electronics} = 79P_R$
Electrical	0	$C_{electrical} = 40\ P_R$
Yaw system	$M_{yaw} = 0.000144D^{3.314}$	$C_{yaw} = 0.0678D^{2.964}$
Hydraulics	$M_{hydraulics} = 0.08P_R$	$C_{hydraulics} = 12P_R$
Nacelle cover	$M_{cover} = C_{cover}/10$	$C_{cover} = 11.537P_R + 3849.7$
Main frame	$M_{main\ frame} = 2.233D^{1.953}$	$C_{main\ frame} = 9.489D^{1.953}$
Railings	$M_{railings} = 0.125M_{main\ frame}$	$C_{railings} = 8.7M_{railings}$

Figure 6: Mass and Cost scaling equations from Fingersh et al.[16]

After using all data and information from Table 5.1 and Table 5.2, updated the NREL 5 MW baselined turbine to 3 small rotor multi rotor turbine. After carefully considering all equations and mathematical formula from Figure 6, I compared the cost summary at below table.

Component	**Cost Summary ($)**		**Weight Summary (Kg)**	
	Single Rotor	Multi Rotor	Single Rotor	Multi Rotor
Rotor Blades	778,745	506,087	76,842	46,473
Hub	127,995	135,233	30,117	31,819
Pitch	183,552	127,908	14,422	11,612
Nose	10,084	13,793	1,812	2,476
Total	**1,100,375**	**783,014**	**123,194**	**92,385**
Nacelle Shaft	11,582	7,115	16,525	10,147
Bearing	95,050	41,095	5,403	2,334
Gearbox	685,773	521,778	36,607	31,20
Brake	9,948	9,948	997	997

Generator	325,000	325,065	16,690	18,180
Power Electronics	395,000	395,078		
Yaw System	113,955	113,955	13,153	13,151
Electrical Systems	200,000	200,040		
Hydraulics	60,000	60,013	400	400
Nacelle cover	61,536	69,245	6,152	6,923
Mainframe/Railing	150,733	154,690	31,774	32,609
Total	**2,108,570**	**1,898,020**	**127,700**	**115,945**
Total RNA	3,208,945	2,681,06	250,895	208,327

Table 5. 1 Single vs 3 -Rotor mass and cost scaling comparison

When comparing the total mass of the RNA (Rotor Nacelle Assembly) of the NREL baseline model (350 tonnes) from Table 5.1 to the downscaled model (250 tonnes) from Table 5.3, there's a difference of 100 tonnes. Most of this difference is observed in the nacelle mass, while the mass of the rotor is similar in both cases. To address this disparity, the WindPACT scaling study was utilized to properly estimate the nacelle mass using the WindPACT equation.

From the data, it's evident that the MRWT system's RNA will be almost 25% cheaper and 37% lighter than the NREL single-rotor 5MW baseline turbine RNA.

Despite requiring additional support systems for all three rotors, the multi-rotor wind turbine (MRWT) system remains lighter and more cost-effective than the single 5MW machine. The cost and mass of the Yaw system in the multi-rotor system were not considered in the preliminary analysis. However, this should be the final step, as the total weight of the support system and the load drive the selection of the yaw bearing.

From the preliminary data, it is evident that the multi-rotor turbine is more feasible both in terms of weight and economics. The main advantage of the multi-rotor system lies in its ability to overcome the challenges associated with producing a single large blade. Instead, it utilizes mass production of smaller blades, ultimately making it even cheaper.

Conclusion:

This paper provides an important idea of how different scaling systems work and how we can scale large rotor wind turbine into the smaller wind turbine array with same power output. This model also helps to find the weight and cost of the wind turbine.

The multi-rotor wind turbine (MRWT) design offers several advantages compared to conventional single-rotor turbines:

1. It is possible to develop an MRWT system with significantly lower production and installation costs than an equivalent single-rotor system.

2. Although the total mass of the MRWT including the support structure exceeds that of a single-rotor, the overall system cost is lower, providing a strong economic incentive for commercial-scale MRWT deployment.

3. Baseline turbine models are valuable tools for optimizing MRWT parameters, validated against real turbines like the 1.5MW WindPACT.

4. Wind drag forces impacting the MRWT structure must be considered for design life and survival in extreme wind conditions.

Overall, the MRWT concept leverages mass production and scaling effects to reduce costs while maintaining performance, making it an economically viable alternative to conventional turbine architectures.

Future R&D

- Prototype field testing and validation of performance, loads, and operational behavior
- Innovative structural configurations and materials for larger, lighter MRWT scalability
- Grid integration, energy storage coupling, and power electronic topologies for MRWTs
- Environmental impact assessments (noise, visual, wildlife)
- Logistical studies for large-scale transportation, assembly, and installation
- Collaboration with industry on certification, regulations, and commercialization pathways

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