Advancing Urban Energy: A Transition to Segmented Micro or Macro Grid Systems via Vertical Axis Wind Turbines with Integrated Energy Storage

A design project report submitted in fulfilment of the requirements for the degree

Master of Design

by

LESLIE TERENCE DAVIDS: 198043082

in the Faculty of Informatics and Design at the Cape Peninsula University of Technology

Supervisor: Dr. Monica Di Ruvo

Date submitted: (7 November 2025)

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Signed **Date: 7** November **2025**

Acknowledgements

I want to thank the following individuals:

- To Jesus, King of kings, thank you for granting me this opportunity and giving me the strength to see this through. I could not have done it without You.
- My mom for always allowing me to follow my own path and trusting me to make the right decisions in life. This is for you.
- My blompot and sterretjie, Angelique, I appreciate your patience during this period. Thank you for always believing in me. SHMILY.
- My rockstar colleagues in the Product Design department for your continuous encouragement and support.
- DRAW team members for their continuous efforts to reduce complexity.
- Last but most definitely not least, my shining light supervisor, Dr Monica Di Ruvo, for your unquantifiable guidance. Thank you for your support by pushing and challenging me. Your knowledge is immense.

Abstract

In recent years, the energy supply in Cape Town has gradually changed from coal generation to renewable energy sources. Ratshilengo, Sigauke, and Bere (2021:1) emphasise that "renewable energy forecasts are critical to renewable energy grids and backup plans, operational plans, and short-term power purchases." This design project aimed to develop a set of design principles for the City of Cape Town but needed to be adaptable to similar cities globally. I investigated whether the urban integration of energy storage systems within a microgrid was viable as a renewable energy source in Cape Town for microgrid applications.

The aim of the design project is to develop a design for a custom vertical-axis wind turbine with built-in energy storage within a microgrid context. My objective for this research was to establish the design factors that are important in achieving the desired goals of efficiency and compatibility for a custom vertical-axis wind turbine in the context of Cape Town.

A qualitative research approach following a design process was used and primarily focussed on the Delphi technique to facilitate the design project with a focus group of experts in the energy generation field. Using the Delphi method, these experts assisted in determining the design criteria for the vertical-axis wind turbine design and its energy storage system, as well as establishing the microgrid integration.

The design project revealed that effective implementation of vertical-axis wind turbines requires several factors, including the geometry of the blades to capture energy, the variable nature of the wind, and modular energy storage.

Keywords

Biomimetic Design, Design Thinking, Energy Security, Integrated Energy Storage, Magnetic Levitating Bearings, Micro and Macro Grid Systems, Renewable Wind Energy Generation, Vertical-Axis Wind Turbine

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Glossary of Terms

Biomimetic Design:

Biomimetic design refers to “the conscious imitation of biological models to solve today’s technical and ecological challenges,” drawing on evolved strategies from nature to develop innovative and sustainable solutions. This approach conceptualises nature as a template for solving human design problems by abstracting and applying biological functions and structures (Gerola, Robaey & Blok, 2023:1).

Design Thinking:

Design thinking is generally defined as an analytical and creative problem-solving process that engages individuals or teams in opportunities to experiment, create, and prototype models, gather feedback, and iteratively redesign solutions to complex, open-ended problems (Razzouk & Shute, 2012:330).

Energy Security:

Energy security is described by Cherp and Jewell as **“**low vulnerability of vital energy systems”, where vital energy systems encompass energy resources, infrastructure, and uses that support essential societal functions, and vulnerability is framed as a function of exposure to risks and resilience capacities (Cherp & Jewell, 2014, p. 416).

Energy Storage:

Energy storage and the ability to use it later, through battery technologies, is important to aid a consistent and reliable energy supply. Energy storage improves the reliability of the grid and is crucial for the incorporation of renewable energy sources. (Dunn, Kamath, and Tarascon, 2011:928, 934).

Horizontal Axis Wind Turbines (HAWT):

Horizontal-axis wind turbines have three or more-bladed upwind turbines. They typically have variable speed, and their blades have variable-pitched mechanisms. Typically, these turbines are manufactured to have their rotor axis parallel to the ground; this allows them to harness maximum wind energy efficiently. Horizontal-axis wind turbines are widely accepted and used in various applications. They have a well-established design and performance characteristics, making it a popular choice for wind energy generation (Rehman, Mahbub, Alhems, and Mujahid, 2018:3, 7; Jonkman, Butterfield, Musial, and Scott, 2009:vi, 2, 3)

Integrated energy storage:

Mao et al. define integrated energy storage as the inclusion of a power storage system with the intent of controlling power produced by the vertical-axis wind turbines. The system allows storing excess electricity in the form of batteries during periods of high wind speed; the storage system can release the stored power during times of low wind, resulting in a more consistent and reliable power supply (Mao, Chen, Xv, He Shen, Cai, and Lu, 2022:2, 3, 4, 5).

Load-shedding:

South Africa has been subjected to load-shedding since the year 2007, and the term load-shedding is used to reference deliberate rotational energy interruption to control the frequency of energy used in the national grid. This is intended to stabilize the grid to a fixed energy frequency of 50 Hz to avoid a blackout. The South African state-owned energy producer, Eskom, introduced a blackout system that has eight stages aligned to the frequency of electricity outages to specific grids (Roff, Klein, Brand, Renaud, Mgoduso, and Steyn, 2022:1)

Macro-grid system:

A macro-grid, in geographical terms, extends across provincial boundaries or regions. It links power plants, transmission lines, and distribution systems together so that electricity can be supplied to a large population. Macro-grids are not as flexible as micro-grids. If there is a power outage in one part of the macro-grid, it can affect a large area (Amjad, Hamdi, Behnam, and Nikos, 2021:3-4, 5, 6)

Maglev Bearings:

Magnetic levitation bearings employ the power of magnetic fields to hold an object (in this case, parts of a wind turbine) in suspension without physical contact, minimising friction and wear, resulting in greater efficiency and reduced maintenance. It has been demonstrated that permanent magnetic bearings in wind turbines help in reducing maintenance costs, resulting in increased efficiency and less wear and friction (Kriswanto, Naryanto, Prasdiansyah, Al-Janan, Aryadi, Roziqin, Anis, and Sumbodo, 2022:172, 173, 185).

Micro-grid system:

A microgrid acts as a single localized entity interacting with the main electricity power grid. Electricity can be bought from the grid when needed and can transfer the excess power it generates back to the main grid. This system enables the microgrid to be independent and not dependent on the main grid. It is more effective in times of power outage or during periods of maintenance of the main grid (Sharma and Singh, 2023:2).

Renewable Energy:

Sustainability and environmental friendliness are achieved by sources that are naturally renewed and can include sunlight, wind, rain, tides, waves, and geothermal heat. Sustainable

energy landscapes are defined as “a physical environment that can evolve based on locally available renewable energy sources without compromising landscape quality, biodiversity, food production, and other life-supporting ecosystem services” (Picchi, Verzandvoort, Geneletti, Hendriks, and Stremke, 2020:1, 2, 3, 8, 12).

Vertical Axis Wind Turbines (VAWT):

Turbines where the axis of wind rotation is perpendicular to the ground, ensuring that any wind direction can be harnessed. This gives greater flexibility in the placement of turbines and may even be co-located with city infrastructure such as streetlamp posts. Vertical-axis wind turbines could also be an alternative solution to urban areas with turbulent and unstable winds, allowing for the exploitation of the energy effectively (Zhu, Huang, and Shen, 2015:1, 6, 10).

Chapter 1: Introduction

Coal is the main source of electricity in South Africa (more than 90 percent of the electric power in the country is produced by coal). The fact that coal is a combustible fuel causes coal to emit harmful pollutants such as sulphur dioxide, nitrogen oxides, particulates, carbon dioxide, and heavy metals that harm human health (Musango, Amigun, and Brent, 2011:125).

The broad-based energy mix of the world is changing as countries work toward lowering emissions of greenhouse gases and the impacts associated with climate change. A global response to the issues of energy security and reduction of climate change has seen the introduction of wind turbines as a renewable energy source (Moreno-Armendáriz, Duchanoy, Calvo, Ibarra-Ontiveros, Salcedo-Castañeda, Ayala-Canseco, and García, 2018:1).

Cape Town, a city that boasts wind energy resources, is struggling with energy security "due to the increased population growth in South Africa, particularly in urban areas…and so has the demand for energy" (Mabalane, Oboirien, Sadiku, and Masukume, 2020). The focus of the city is to increase the amount of renewable power generation, like solar and wind energy, in Cape Town's power grid. Despite the numerous benefits of renewable energy resources compared to fossil fuels, the use of these sustainable energy resources is complex because of the unpredictable, intermittent characteristics of the resources (Li, 2023:1). This is further exacerbated by an aging municipal energy grid, which has led to load shedding (Joubert & Raji, 2023:3).

1.1 Background to the Research Problem

In South Africa, load shedding has been a reality since 2007 and has affected numerous sectors of business and demonstrated weaknesses in decrepit coal-loaded power plants (Moetlhoa, 2024:6). Load shedding refers to the deliberate shutdown of power in a particular location on a predetermined occasion (Caprotti, 2024:1). Industrial processes require a steady supply of electricity, power interruptions negatively affect production and increase costs (Sewchurran, Davidson, and Ojo, 2016:1).

The unreliability of the South African national grid reveals an urgent need to have a clean and alternative source of energy, like wind power, to ensure the continuity and stability of the electricity supply within the city. The City of Cape Town already has mini-grid solar systems installed in informal regions (Mabunda, Mukonza, and Mudzanani, 2023:1). An example of this is the Zonke Energy project, whereby clean, reliable power is availed through a distributed system using a 1.5 kW solar photovoltaic generator. This system can serve 10-15 households, and each family can supply appliances like televisions, radios, lights, and refrigerators. Such

a solar-based direct current mini-grid is a safer and more cost-effective alternative to the traditional forms of energy, such as paraffin and petrol-powered generators (Zonke Energy Case Study, Energy Catalyst, n.d.).

Despite favourable wind conditions in Cape Town (see Figure 3), there is limited implementation of wind energy generation systems in microgrids suitable for urban applications (Gough, Lotfi, Castro, Madhlopa, Khan, and Catalão, 2019:1). The coastal geography and the unique wind patterns available in the city provide good potential energy sources in the form of wind power. Nevertheless, to achieve this potential, it is necessary to evaluate wind resources and incorporate wind turbines into current electricity systems (Stathopoulos, Alrawashdeh, Al-Quraan, Blocken, Dilimulati, Paraschivoiu, and Pilay, 2018:151).

The utilisation of the horizontal-axis wind turbines is well-known to be efficient regarding changing wind power into electricity, especially when applied in large wind farms (Bardakjian, Mandadakis, and Tingle, 2017:59; Kumar, Agam, Kumar, Dheeraj, and Suri, 2024:1). Horizontal-axis wind turbines, as indicated in Figure 1.1, are required to have a yaw system that positions the rotor and generator in line with the wind direction. Their high towers are meant to grab stronger and higher winds with great altitude, and they are more structurally powerful than the vertical-axis wind turbines. Their cost of production and maintenance is also high, and compared to urban areas, it's space and mechanical needs are also high; thus, alternative and local solutions like vertical-axis wind turbines are required.



Figure 1.1: Horizontal-axis wind turbine (AI-generated, Google Image FX, 2025).

Figure 1.2: Vertical-axis wind turbine (Adapted from Nigam, 2023).

Figure 1.2 illustrates the vertical-axis wind turbine style. These turbines have a rotor shaft and a power generator installed on a tubular steel tower on which the blades rotate circularly as

the wind moves through them. Unlike horizontal-axis wind turbines, a vertical-axis turbine, rotates around a vertical shaft, with the energy generator mounted to the base of the turbine, making them applicable for urban settings as they are small enough for a nominal power output of between 1-3 kW, ideal for a home or in a commercial setup (Castellani, Natili, Astolfi, Hirschl, and Peppoloni, 2022:1). Laveda, Roche, Phadtare, Sauge, Xavier, Bhat, Saxena, Saini, and Verdin (2023:1) point out that small-scale wind turbines seem to be a better solution to maximise wind energy generation as they take "advantage of catching the wind from any direction, thus limiting the need for complex…control systems."

While horizontal-axis wind turbines are highly efficient for large-scale applications, vertical-axis wind turbines lend themselves to urbanised decentralised energy environments, and they can capture the wind in any direction. They are characterized as being more cost-effective for manufacturing, maintenance, and noise reduction (Laveda et al., 2023:1; Li et al., 2022:64; Attia, Saber, and Gamal, 2016:4015). Chong, Gwani, Tan, Muzammil, Poh, and Wong (2017:1) go further to say that the inherent design flaws in vertical-axis wind turbines can be overcome with better design so that wind turbines are able to work in any urban environment. It was therefore deduced that they have a greater applicability to decentralized renewable energy generation in Cape Town.

Cape Town's unique wind characteristics necessitate specialized approaches to wind energy development, including understanding local wind patterns for optimal turbine placement (Qu & Wang, 2011:359; Sota, Ryuichi, and Shimada, 2007:56). Vertical-axis wind turbines are especially beneficial in the turbulent urban wind conditions of Cape Town and could allow for decentralised energy generation and consequently increase energy resilience and sustainable urban development (Zhu et al., 2015:1).

Energy storage systems provide flexibility to accommodate the variable generation of renewable energy sources, contributing to grid stability (Liu, Zuo, Liu, Liu, and Kennedy, 2018:690). Challenges are observed when it comes to attempting to combine energy storage systems with renewable energy systems in limited spaces, such as those in urban environments. The implementation of micro-grids as decentralized systems offers a solution to existing energy challenges through a flexible energy management system Liu et al., 2018:690).

Although there is interest in energy storage and microgrids, the integration of those topics into urban areas, notably in developing countries, is rather limited. This project, therefore, set out to determine the possibilities of energy storage systems and micro-grids within the context of Cape Town's urban energy system.

Bearing systems are important parts of wind turbine technology because they influence the wind turbine's operation, performance, and durability. The nature of loading in urban regions and the cyclic torque of vertical-axis wind turbines make it imperative to use bearings that can endure these working conditions (Brown & Scheurich, 2011: 2512). The vibration, pollution, and limited access for maintenance in urban environments add to the challenge of component selection and maintenance schedules to enhance proper vertical-axis wind turbine performance in city applications (Brown & Scheurich, 2011:2512). Although bearing technology has been improved, designers frequently fail to develop appropriate bearing systems for the vertical-axis wind tunnel in urban areas. In this design project, I contribute to the field by suggesting new bearing designs that may enhance the performance and the life cycle of the vertical-axis turbines in urban settings like Cape Town.

1.2 The Research Problem

Vertical-axis wind turbines are potentially a viable alternative to the traditional commercial horizontal-axis wind turbine design due to their compact nature, omnidirectional wind capture, and their potential use in urbanised contexts. In this design project I explore the design of a custom vertical-axis wind turbine with a built-in energy storage system for a microgrid environment, for the city of Cape Town, South Africa.

1.3 Research Questions

1.3.1 Main research question

What are the critical design parameters for maximizing the efficiency and urban compatibility of vertical-axis wind turbines for microgrid applications?

1.3.2 Sub-Questions:

- What are the primary technical challenges in designing vertical-axis wind turbines with limited space and complex wind patterns?
- How can vertical-axis wind turbine design be optimized for microgrid installations?
- What are the key factors influencing the selection of materials and manufacturing processes for vertical-axis wind turbines?

1.4 Project aim and objectives

This project aimed to design a custom vertical-axis wind turbine with a built-in energy storage system in a microgrid environment.

1.4.1 Research objectives

The objectives of this research are to:

- Identify the key technical challenges of designing vertical-axis wind turbines with limited space and designing vertical-axis wind turbines for complex wind patterns.
- Analyse existing vertical axis systems
- Define a microgrid system within the context of clean energy

Determine the:

- Performance requirements
- Urban environmental factors
- Aerodynamics
- Geometric feasibility
- Determine the:
- Performance requirements
- Urban environmental factors
- Aerodynamics
- Geometric feasibility
- Sustainability factors
- Explain specifications that create efficient vertical-axis wind turbines that match the context of Cape Town urban micro-grids.

In Table 1.1 below, I have mapped these objectives according to the research questions and the methods used to achieve these objectives:

Table 1.1: Research questions, objectives, and methods used (Author's own, 2024).

• Research Questions	• Objectives	Method
What are the primary technical challenges in designing vertical-axis wind turbines with limited space and complex wind patterns?	Identify the key technical challenges of a) designing vertical-axis wind turbines with limited space. b) designing vertical-axis wind turbines for complex wind patterns.	Literature review Precedent analysis Questionnaires

How can a custom vertical-axis wind turbine design be optimised for microgrid installations?	A) Analyse existing vertical axis systems B) Define a microgrid system within the context of clean energy	Literature Precedent analysis Questionnaires
What are the key factors influencing the selection of materials and manufacturing processes for vertical-axis wind turbines?	• Determine the: o Performance requirements o Urban environmental factors o Aerodynamics o Geometric feasibility o Sustainability factors • explain specifications that create efficient vertical-axis wind turbines that match the context of Cape Town's urban microgrids.	Literature (industry-specific journal references)

1.5 Research design and method

The research design was informed by the Double Diamond design process (Design Council, 2007:5). I gathered both qualitative and quantitative data, and in sections 3,4,5, and 6 of this report, I describe how the Delphi method assisted in the collection of expert opinions and how thematic analysis aided in the design process. The concepts were then improved with Computer-Aided modelling and simulation. In this report, I present the process for informing design decisions.

1.6 Delimitations and Limitations

This study was limited to a small and manageable sample. The problem definition was also limited by the following factors:

1.6.1 Delimitations

- **Geographic focus:** The analysis is limited to the City of Cape Town, its peculiarities in meteorology and infrastructure. The results cannot be generalized to other regions and are only particular to Cape Town.
- **Technology focus:** The project is based on the design of a vertical-axis wind turbine and does not cover horizontal-axis turbines, solar, hydro, or other renewable energy.
- **System scale:** The project focuses on the special requirements of a decentralised energy solution within a microgrid, and not large utility generation.

1.6.2 Limitations

These are some of the limitations that can affect the generalizability and scope of the design:

- **Time and Resource Constraints:** The project was based on a limited time frame, affecting the scope for rapid prototyping, which constitutes an opportunity for further research.
- **Sample Size:** Due to the specialised nature of the research, the data gathered for this design project was guided by the Delphi method, which requires a minimum of three expert participants. A larger pool may have resulted in a different outcome.
- **Prototyping** and Testing: Physical prototyping was not a realistic and functional task due to time and financial limitations, as well as the academic nature of a 60-credit master's design project. The final design was developed and validated through a process of Computer-Aided modelling and simulation; however, it was not physically prototyped and evaluated in a real-world environment. This implies that the findings are a demonstration of theory, and they might not be completely representative of the real-life factors.

1.7 Significance of the project

This project is important as it goes beyond generic renewable energy proposals to create a context-specific design custom vertical-axis wind turbine with a built-in energy storage system in a microgrid environment. This research has directly responded to the call for a focus on urban compatibility (Taleai, Sharifi, Sliuzas, and Mesgari, 2007:262), technical viability (Ferreira et al., 2024:9), material choice (Trivkovi´c, Svorcan, Balti´c, Zori´, and Pekovic, 2022:39), and microgrid integration (Shahgholian, 2021:1).

1.8 Contribution to Knowledge

This design project offers parameters that could inform future projects for the implementation of custom vertical-axis wind turbines with integrated energy storage, and covers related aspects such as:

- Material Selection Rationale
- Compliance with Cape Town Building Regulations and Codes
- Preliminary Structural and Load Analysis
- Manufacturability and Assembly Considerations
- Blade Upright Supports
- Mounting Brackets and Urban Integration
- Performance Estimation and System Sizing Analysis
- Vertical-Axis Wind Turbine Power Generation Potential
- Generator Performance with N52 Neodymium Magnets
- Battery Storage Capacity
- Inverter Charger Specification and System Analysis

1.9 Ethical considerations

To safeguard the research process and ensure the rights of participants, I gained permission from the university's ethics committee to commence with the data collection. The following measures were put in place:

- **Informed Consent:** Written, voluntary, and informed consent was obtained from all participants in the expert questionnaires of the Delphi study.
- **Confidentiality and data privacy:** All responses received from experts were treated as confidential. Data was stored on my CPUT OneDrive account, anonymised and encoded. All data will be kept and managed as required by the university under the provisions set by the Protection of Personal Information Act No. 4 of 2013.
- **Anonymity and Confidentiality:** Every precaution was taken to make sure that all responses were entirely anonymous. In the case of the Delphi expert panel, the responses and opinions were kept secret. Notably, all responses were anonymized and subsequently aggregated and provided to the panel across rounds, in such a way that the statements and opinions of individuals could not be attributed to a particular individual. Any data, regardless of its type, was stored in encrypted and password-protected files on the university servers, and only I could access such data.
- **Data Minimisation and Security:** The data was only collected based on data that had a direct and verifiable answer to the research questions and objectives. Data security measures were taken at each level (acquisition, storage, processing, and analysis),

including the conceptual design stage, where information is captured in SolidWorks CAD models; this helps in protecting the intellectual property of the design.

- **Conflict of interest:** Experts were asked to declare a conflict of interest, which may affect their answer (Shapira, 2023:8; Moyal and Ritov, 2020:4). In addition, participants were asked to sign non-disclosure agreements for the design, which will remain the property of CPUT.
- **Expert compensation:** The expert respondents were not remunerated for their contribution to this research.
- **Research Integrity and Transparency:** The study was conducted with the highest academic integrity, including sincere and precise reporting of all methodological choices, impartial demonstration of all gathered information, detailed analytical findings, and a reasonable statement of its constraints.
- **Benefit and Risk:** The primary objective of the practice-based study was to have a positive impact on sustainable urban development and energy resilience in the city of Cape Town. During the process of designing, I was very attentive to the possible environmental, social, and visual changes due to the proposed custom vertical-axis wind turbine system. I also made sure that all the design considerations were made based on the principle of not causing harm.

The adherence to these ethical principles ensured that the research conformed to the academic ethical standards set out by the university. This report is a comprehensive, written description of the entire design process I followed. Through the application of the Double Diamond design process and a triangulated mixed method strategy, I was able to arrive at an evidence-based scaffolding to inform the design of a custom vertical-axis wind turbine.

1.10 Ai Declaration

This design report, in part, incorporates information developed and edited with the help of artificial intelligence (AI), namely Grammarly, Scite, Gemini, and Claude.ai.

AI was employed to enhance intelligibility, organisation, and technical accuracy in the following ways:

- Scite.ai was used as a tool to find academic journals that were relevant to the topic.
- I used Claude.ai to assist me in formulating the flow of my writing process so that it could identify where improvement was needed or where gaps were in terms of things that needed to be clarified. This aided me in revising my scholarly writing style to be clearer and more concise. I further used Gemini to organise the data that was collected during the first and second rounds of the Delphi method to assist me in identifying key

statements. Following the thematic analysis process, I asked Gemini to highlight specified codes in the text to see where the areas of consensus were.

- To supplement and explain the qualitative data analysis and interpretation, Claude.ai was used to aid with the early mathematical calculations, including the addition of numbers and solving equations (Johnson, Singh, Gupta, Sankar, Gill, Shalini, and Mohan, 2024:187; Bolgova, Ganguly, and Mavrych, 2025:718).
- Grammarly and Microsoft Word 365 were used to highlight correct English (UK style) grammar.

AI-generated content was used as a software tool, verified and edited to achieve academic rigor and originality, and to comply with institutional standards. No AI software generated data, falsified information, or evaded the ethics of research. I remain completely accountable for the accuracy, originality, and scholarly value of the work submitted.

1.11 Non-Disclosure and Intellectual Property Protection

To safeguard the confidentiality of the expert feedback to the Delphi questionnaires as well as protect the originality of the design and components thereof, non-disclosure agreements were explained and signed by all the participants in the research beforehand. The participants were informed that their observations would be anonymized and would not be disclosed to any other party other than being utilized in this design project in an academic context. The intellectual property (IP) behind the custom vertical-axis wind turbine design, with its combination of energy storage and magnetic levitating bearings and all the constituent components thereof, remains the property of the Cape Peninsula University of Technology (CPUT) and has been disclosed to the Technology Transfer Office (TTO) of CPUT to manage the legal protection options for the design or parts thereof.

Chapter 2: Literature review

For this review, an online search using Scite was conducted to source articles, and Claude.ai was used to understand complex systems and terms. The prompts used included searching for articles on Vertical-Axis Wind Turbines, energy storage systems, and frictionless bearing systems. The sourcing process was started by developing a search strategy with key terms being “Vertical-Axis Wind Turbines,” “Urban Wind Energy,” “Integrated Energy Storage,” “Micro or Macro Grid Systems,” and “Urban Integration.” Meteoblue.com (a meteorological website) was consulted to assess Cape Town’s climate conditions. I then browsed the South African government-managed energy producer’s website, Eskom.co.za, to view the generating capacity and breakdown frequency. I sourced a total of 58 articles; after a preliminary reading, 6 were excluded, and 52 were included. The criteria used for inclusion were only recent articles within the past 10 years. The articles were then sorted according to context and themes. Older journal articles and foundational readings were included if there was no other, equally thorough and authoritative work on the subject in the more recent five-year window. The literature review is arranged into 4 themes.

- Context: Regional climate
- Environment: Urban areas
- Infrastructure: "Micro or Macro Grid Systems" was chosen, and the search string contained these two terms to make sure that the review included literature on both small-scale and large-scale segmented power distribution models.
- Technology: "Vertical Axis Wind Turbines" and its larger concept, "Urban Wind Energy," were considered necessary to document literature on the essential energy generation device and its application to the built environment.

2.1 Context

The Western Cape government in Cape Town can adopt wind power as its primary renewable energy strategy because it offers essential opportunities for sustainable development while addressing its dual energy adequacy problems and climate change requirements. The information in the following infographic, Figure 2.1, indicates the frequency and direction of wind within the city of Cape Town during 2024.

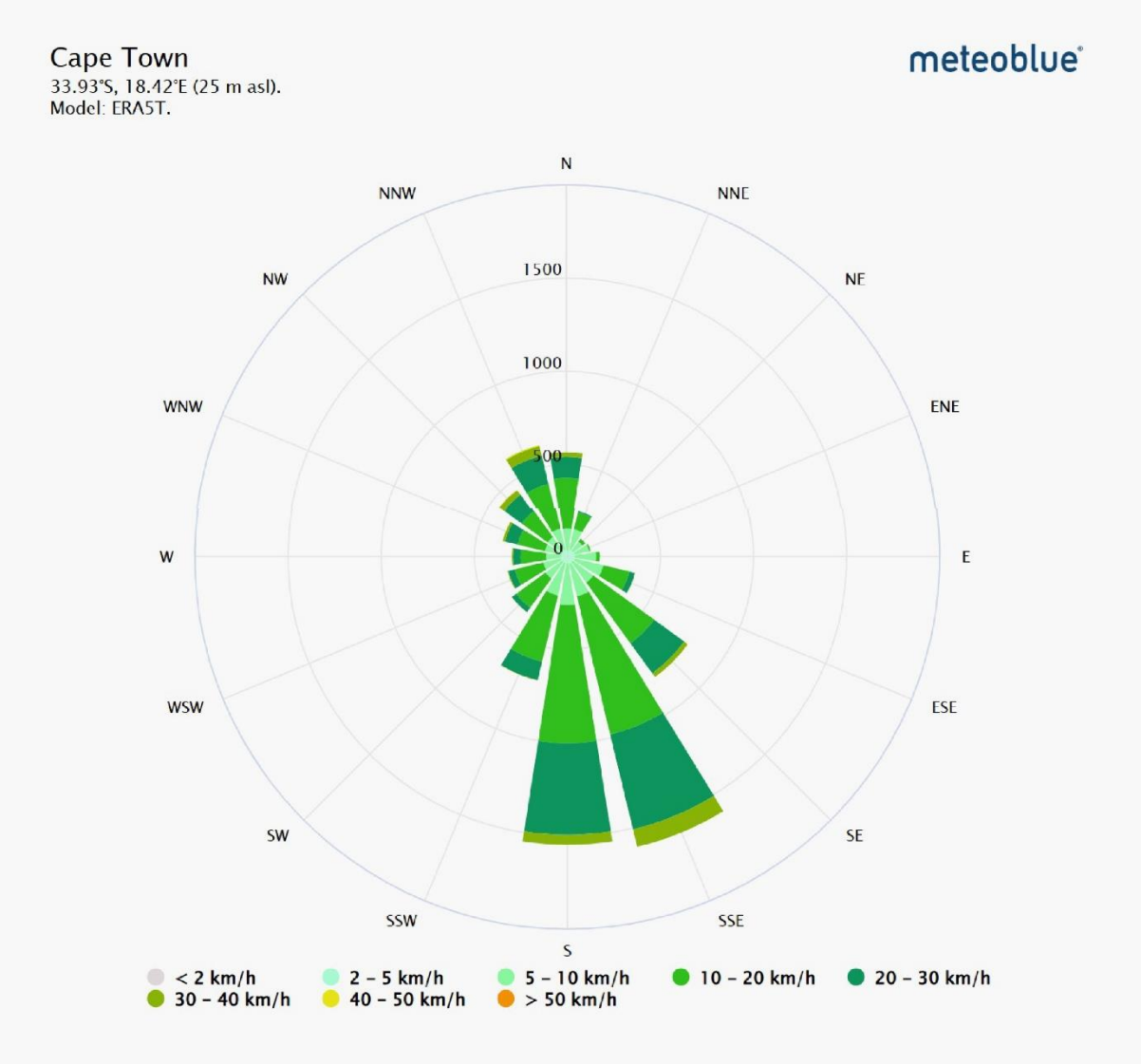


Figure 2.1: Simulated wind direction and speed for Cape Town, 2024 (Meteoblue, 2024).

Figure 2.2 below shows a geographical map representation of the wind pattern at a height of 20 m above ground on a single day, 16 September 2025. On this colour-coded map, one can see that the coastline of Cape Town experiences an almost jet stream type of wind circulation passing the coast. Other colour-coded sections on the map indicate the inland areas of the Western Cape; it clearly illustrates the potential for wind turbine installations in the province.

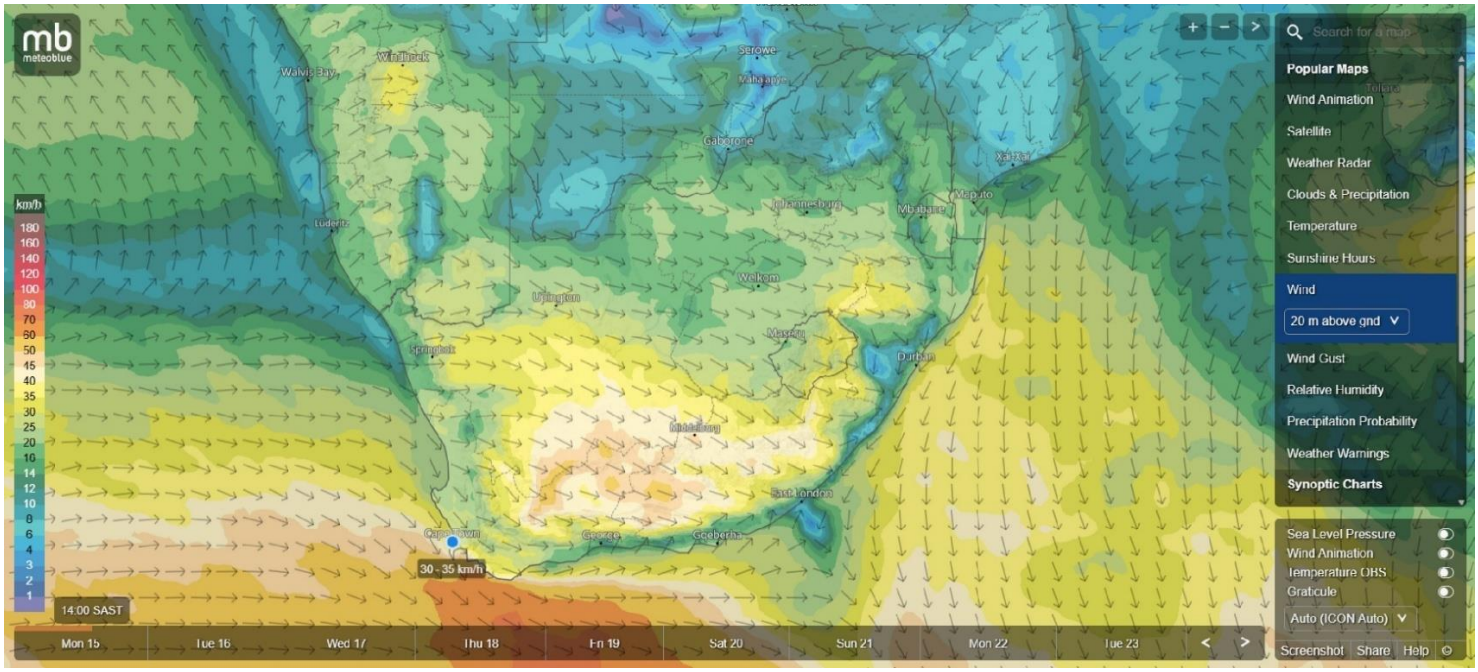


Figure 2.2: Wind direction 20 m above ground (Meteoblue, 2024).

The recorded wind speed was recorded at 30 to 35 km/h, which is strong enough to power a wind turbine, and this was experienced at a height of only twenty metres above sea level.

Urban wind turbines serve to create localized power production, minimize emissions, facilitate sustainable development, and operate as independent power supply units (Strasszer & Xydis, 2020:1, 2). Multiple research investigations show that small wind turbines can successfully deliver decentralized renewable energy production for urban areas. Renewable technology adoption receives substantial backing from governments worldwide because these policies focus on cutting greenhouse gas emissions through renewable energy reliance (Otero, Martius, Allen, Bloomfield, and Schaefli, 2022:1).

From 2007 to date, South Africa has been facing an array of energy-generating challenges due to loadshedding. Load-shedding refers to the planned interruption of electric energy to a specific region at a particular time (Caprotti, 2024:2).

The wind speed diagram presented in Figure 2.3 shows detailed information about prevalent wind velocities in Cape Town during the twelve months from January to December 2024. The chart demonstrates a complete picture of wind direction spread.

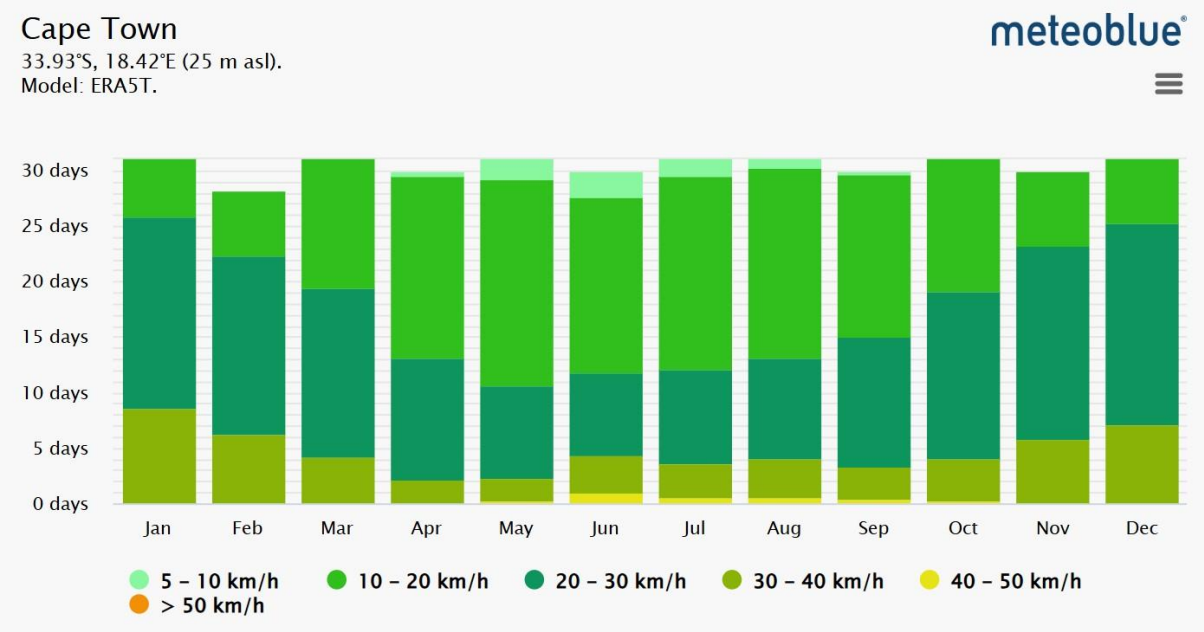


Figure 2.3: Wind speed direction over twelve months in Cape Town (Meteoblue, 2024).

The regional assessment for renewable energy projects demands this kind of data, especially for the Maglev wind turbine design evaluation. Such wind direction information serves to clarify wind power source consistency and variability, thus supporting strategic sustainable energy project choices within Cape Town.

Small Darrieus styled custom vertical-axis wind turbines generally require a cut-in speed of at least 2.1 m/s of wind velocity as per electricity generation standards, although this requirement depends on the model and structural aspects of the turbine design (Yan, Li, Gao, Lian and Wu, 2023:1). The data demonstrates that Cape Town suffered no deficiency in wind speed or direction and never failed to reach 10 km/h throughout 2024. This information confirmed that Cape Town is highly suitable for wind energy generation, which could be a sustainable source of energy production.

The extraction of wind power produced by Cape Town's regular south-easterly wind creates an advantage for the city to use the resource for maximum energy production during the energy crisis. Decentralized renewable energy generation in urban areas can succeed through the installation of small wind turbines on urban infrastructure.

Research from several studies confirms that this technique successfully delivers energy requirements by combating residential energy poverty while decreasing environmental emissions and enhancing sustainable energy practices (Chong et al., 2017:2; Salvadori et al., 2021:1, 2; Takahashi et al., 2009:26; Strasszer & Xydis, 2020:1, 2, 3). This confirms that wind turbines installed on rooftops function effectively to generate decentralized renewable power

for residential buildings with small structures and low heights (Salvadori, Bernardino, Querzoli, and Ferrari, 2021:2). Small wind turbines placed in highly populated urban areas enable consumers access to renewable power sources in the management of constant load-shedding and in an environment that has implications for various industries according to Takahashi, Yasuda, Ohmoto, and Hara (2009:26).

2.2 Environment

One of the fundamental contributing factors for this study is that coal and other fossil fuels have globally been the dominant sources of energy for centuries due to their abundance as well as their low cost. The negative impact of their use on the environment and human health cannot be ignored. Reports prepared by the Intergovernmental Panel on Climate Change (IPCC) have highlighted that carbon dioxide emissions due to the burning of fossil fuels and through industrial activities have been a major contributor to the rise in emissions of greenhouse gases. (Yang, Duan, Tang, Cai, and Sun, 2018:1110). This results in rising global temperatures, extreme weather events, and rising sea levels that threaten coastal cities and ecosystems such as Cape Town. Coal has long been a primary resource for energy production, but the extraction processes and the transportation of it have led to a serious negative environmental impact. The consequences of this are vast and include an increase in climatic temperature, which is accompanied by unpredictable weather conditions. Rising sea levels have devastating consequences and have the potential to wipe out coastal cities and their ecosystems.

The views of Hendryx and Ahern (2009:541, 547) indicate that conventional coal energy production near urban areas has a range of negative health risks to communities around such facilities. These communities are affected by air and water pollution, which could further complicate pre-existing health issues within the community.

The research on wind energy and its effect on biodiversity has shown that the interaction of the sometimes-sensitive ecological systems with energy facilities could impact the surrounding area negatively. Subsequent effects could encompass regional soil erosion as well as habitat modification, which leads to the disruption of wildlife habitats. These effects are all potential side effects of the development of structures like the custom vertical-axis wind turbine.

Before conventional and renewable energy production is considered in an environment, careful consideration needs to be given to the environmental effects of site selection, as well as the possible impacts of generating energy in the chosen settings. In my research, the authors, Evans et al., reviewed the impact of surface coal mining activities in Appalachia, results indicated serious changes in the ecosystem (Evans, Zipper, Hester, and Schoenholtz,

2015:1436, 1437). In 2019, the World Health Organization (WHO) assessed outdoor air pollution as being responsible for 4.2 million premature deaths throughout the world (Pérez, 2024:1). Mitigation strategies may be used to curb the effects of wind turbine arrangement as well, to make sure that ecological balance is preserved.

The call for renewable energy is caused by the need for such energy resulting from the pressing consequences of climate change and depletion of finite resources. While these alternative energy sources have environmental benefits, their supply also mitigates the hazards caused by climate change (Kyriakopoulos, Arabatzis, Tsialis, and Ioannou, 2019:2).

Wind energy is promising as a clean, renewable, and accessible energy source. Quartey (2020:2, 3) stresses that with the gradual change of the environment due to climate change and global warming, renewable energy has become a very viable option in promoting global warming and climate change.

Mitigating the detrimental effects of fossil fuels and their overconsumption needs to be addressed to combat the numerous challenges of climate change; this necessitates a critical transition to renewable energy sources (Kyei, Boateng, and Frimpong, 2025:190). It is also important for energy security and reducing the fuel oil and gas import dependence. Wind is plentiful in South Africa and especially in the Western Cape, with the regular strong south-easterly wind patterns, making it very suitable for the exploration and expansion of a micro-to-macro grid of energy systems that could be an important regional face for the energy mix of Cape Town (Mukonza & Nhamo, 2018:21, 22).

Since 2007, Eskom, the state-owned parastatal, has continuously utilizes its coal reserves due to a lack of good quality stockpiles, thereby creating an energy crisis in South Africa due to frequent power outages because of infrastructure breakdowns (Eberhard, 2005:5309). This results in temporary emergency area-specific blackouts called loadshedding. Loadshedding intervention helps stabilize the national grid to maintain the 50 Hz electricity frequency. The electricity demand stems from population expansion in the major cities around the country, combined with industrial growth.

The energy crisis has had an impact on the economy, with businesses and households experiencing regular power cuts that disrupt productivity and daily life. Eskom shows its continuous energy generation difficulties through regular data infographics about its “Monthly Eskom generation capacity breakdown for 2024” (Figure 2.4) and “Monthly Eskom generation unavailability for 2024” (Figure 2.5). The major difference between these two figures is what they tell us about the total installed generation capacity. Figure 6 indicates the distribution of the total capacity of the fleet by every category of energy generation. It shows the fraction of available capacity and all forms of unavailability, providing an overall picture of the capacity

situation. Figure 6 is concerned only with the loss of capacity. It shows the percentage of the entire fleet that is unable to produce electricity during a particular month, as the sum of all unavailability. These measuring points capture losses that propel the performance dilemmas.

The data represented in these two figures demonstrate the energy problems experienced by Eskom throughout sixteen months when it lost an average of 58.1% of its power-producing capacity. This statistic indicates how the country has been adversely affected by the loss of energy production. There is, therefore, a necessity to find renewable green power solutions that can replace coal energy production facilities. The statistical evidence reveals only a fraction of the ongoing energy-generating difficulties that consumers face numerous times daily. The extended period of unstable energy supply has deformed everyday life while affecting business operations and national economic development, alongside the national economic interests of the country.

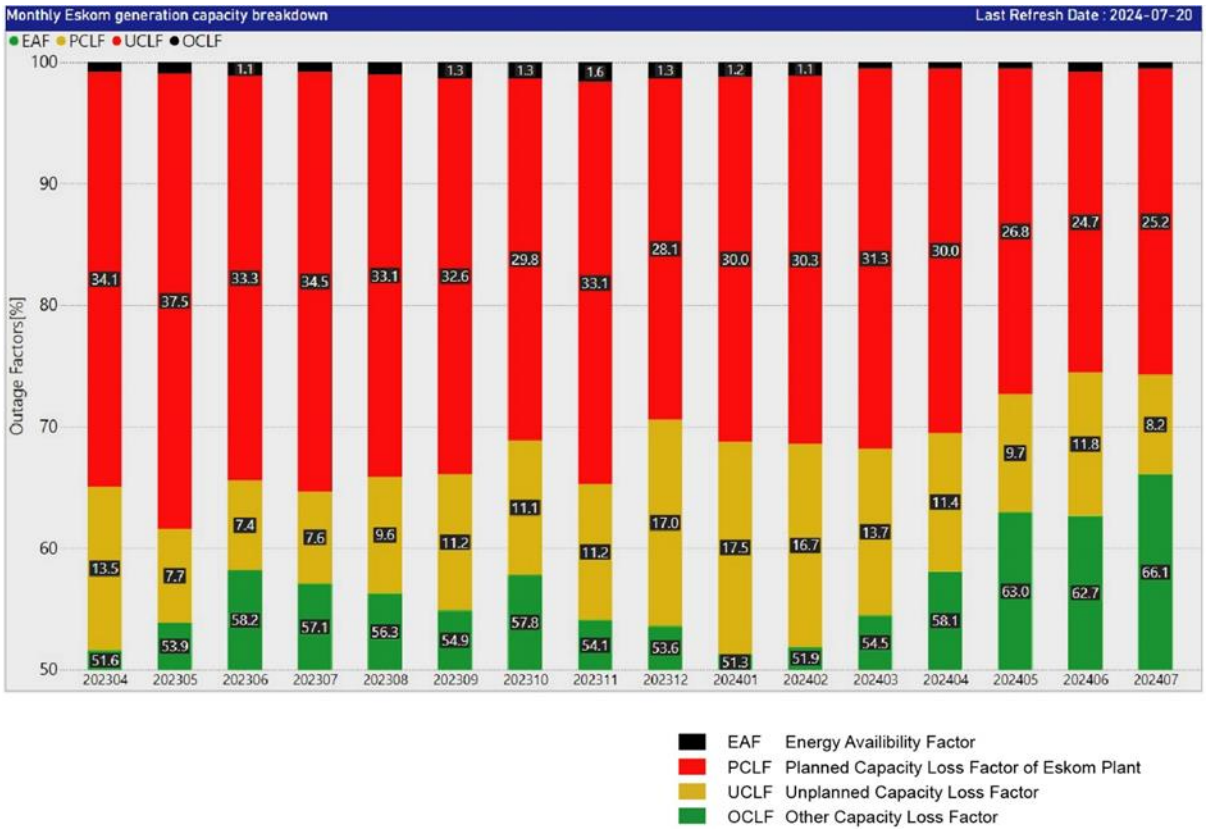


Figure 2.4: Monthly Eskom generation capacity breakdown, 2024 (Eskom, 2024).

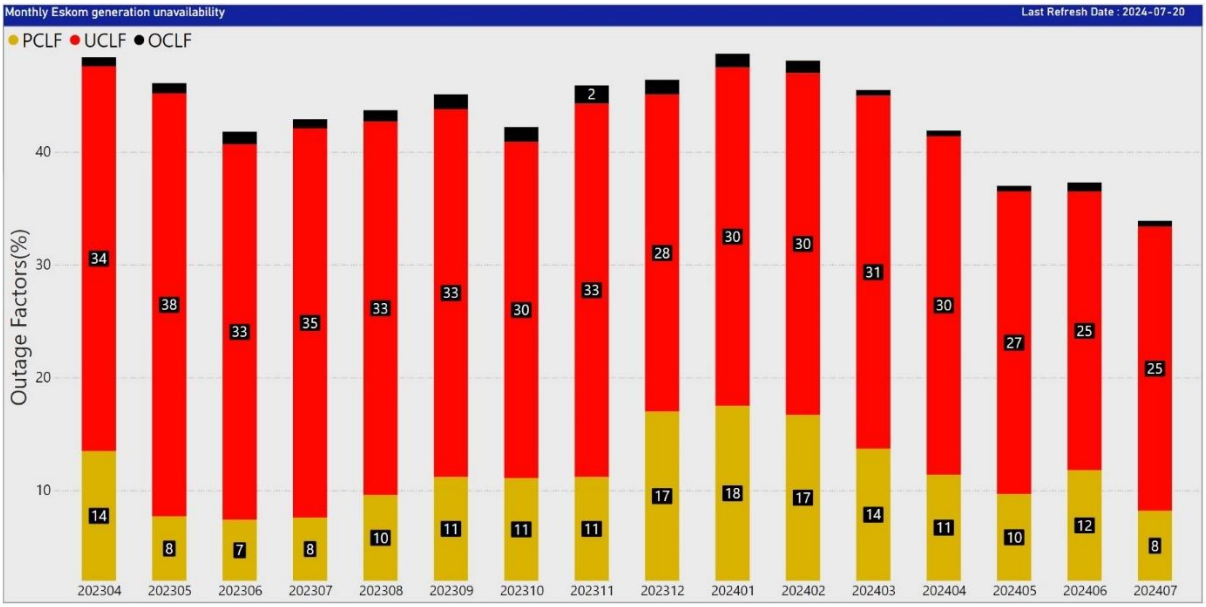


Figure 2.5: Monthly Eskom generation unavailability, 2024 (Eskom, 2024).

Strategic research combined with specific initiatives should be targeted at addressing the current challenges that exist when urban areas merge with renewable power solutions, including wind power. The Western Cape Government should both resolve the energy crisis and assist in climate change prevention by optimizing its local wind power generation capacity.

There is now a transformation in the international energy system, and the use of renewable energy is increasing due to climate change impacts and the security of supply (Güneş et al., 2023:3). Wind as a natural resource is looking promising as a feasible clean energy source.

In the last few years, the knowledge base on wind energy in urban environments such as Cape Town, South Africa, has gained traction. The city has had to face electricity cutouts due to load shedding and air pollution (Gough et al., 2019:1). The city has plenty of regular coastal winds, which predominantly come from the southeast; the city is subsequently subjected to continuous wind patterns. This makes it possible to use the southeasterly wind to generate energy.

The application of wind power attached to buildings and lampposts, as examples, has its challenges, which need to be addressed to obtain optimal results. The key pain points that need to be looked at are wind assessments for energy generation and an analysis of site selection. Factors such as wind turbine installation and linking it to the electricity grid are vital to incorporate wind energy systems across the city's urban environment (Stathopoulos et al.,

2018:150, 153). These key pain points are valid and need to be addressed, especially in the context of Cape Town, as the city experiences the effects of loadshedding and air pollution, to produce sustainable energy solutions (Sato et al., 2007:56).

Climate change needs to be addressed as well as a goal to improve energy security for the city; these should be driving forces to address transformation and the adoption of renewable energy sources (Xu, Goswami, Gulledge, Wullschleger, and Thornton, 2016:50; Cronin, Anandarajah, and Dessens, 2018:1, 2). Renewable energy sources like wind energy have become essential in the war to manage climate change as well as its outcomes. Severe weather patterns greatly affect the continuously changing electricity requirements for cities (Otero et al., 2022:1, 2; Cronin et al., 2018:1, 2). Moreno-Armendáriz et al. say that due to climate change, society is concerned about its consequences, and therefore, there is a need for consistent, secure energy as the demand for energy increases (Moreno-Armendáriz, 2018:1).

Wind technology is ever evolving, indicating potentially effortless implementation within urban spaces where wind patterns are consistent, as is the case in Cape Town. Gough et al. (2019:2) agree that due to local energy problems, urban wind energy research should be prioritised.

(Eitan, 2021:1–3). The beneficial geographical setting of Cape Town, in combination with its climatic characteristics, is ideal for the exploitation of supplementary energy generation (Xu et al., 2016:2, 4; Otero et al., 2022:6, 11).

Wind energy integration projects could pose varying challenges for urban area implementation. Evaluations need to be conducted to determine where and how to position wind turbines in the urban setting to sustain strong energy grid linkages of production. Millward-Hopkins et al. say consideration of resource evaluations with specific turbine positioning has to receive emphasis as these factors aid in enhancing efficiency and reliability (Millward-Hopkins, Tomlin, Ma, Ingham, and Pourkashanian, 2011:225, 241). Factors such as these need to remain as essential contributions as they are relevant for urban areas that have a high dependence on the state-owned parastatal to generate sufficient energy. They need to be innovative, sustainable energy solutions, and all the while deal with air quality and energy supply problems (Eitan, 2021:9).

The national government's restrictive energy policies further hamper the deployment of wind energy, requiring further improvement in urban situations, and are joined by previously built-up architectural structures. This leads to numerous challenges for both resource assessment as well as actual wind power collection that can be exploited (Gonzalez Aparicio et al., 2020:1, 2, 14, 15). Modelling urban wind patterns has encountered a multitude of challenges due to

various zoned land uses and building architectural designs, all leading to difficulties in installing wind turbines, as mentioned by Liu and Wang (2020:1, 2, 3, 16).

Practical innovative solutions are required for wind energy systems as they have presented enormous potential in the fight against climate change and urban energy reliability. (Cronin et al., 2018:1, 5, 12; Perera, Nik, Chen, Scartezzini, and Hong, 2020:1, 9).

2.3 Infrastructure

Cape Town's energy vulnerability problem has even led to informal areas where mini-grid solar systems have already been deployed to achieve energy security (Caprotti, 2024:3, 8). The regional energy shortfall in Cape Town requires that new energy generation capabilities be explored because of the consequences of the national electricity grid's struggle to maintain its systems. The continuous disruptions of energy generation require innovative, well research-driven solutions.

When loadshedding started, Eskom devised a systematic plan to divide the national grid into clustered areas to form distribution blocks to distribute energy. The power network operates through rotating blocks of areas, so Eskom can disconnect electricity in each sector temporarily to stabilize the grid and avoid a complete blackout. The classification system exists for evaluating the level of electricity shortage. Various stages of load-shedding require specific power cuts from the electricity grid and are as follows:

- **Stage 1** marks the least severe level of power depletion. The electrical power reduction remains minimal during this period, which in turn produces brief consumer disruptions.
- **Stage 2** is the requirement to shed additional electricity, which raises power outages to become more frequent and time-consuming.
- **Stages 3, 4, and beyond** are when the quantity of electricity reduction in successive stages leads to enhanced frequency and intensity of power outages.
- **Critical events** affecting the national grid can push the stages of electricity shutdown to exceed Stage 8.

The implementation of load-shedding stages corresponds with the extent of power capacity reduction that leads to specific durations and frequencies of power outages for consumers. Research shows that power outages have become both more common and severe, while the loss of generating capacity continues to rise over the years. Rolling blackouts in South Africa have attracted the attention of power managers managing the congestion of old coal-based power plants in the country. The failure to embrace the new technologies, coupled with an inability to effectively harness the available resources, has made it a challenge for institutions

in the sector that heavily rely on a stable electricity supply to adapt and innovate (Moetlhoa, 2023:8, 9).

The electricity sector in South Africa has been facing hardships such as under-frequency load-shedding, increasing electric power prices, postponing construction of new power stations, and the implementation of environmental regulations, which in total have plunged the country into one of its huge electricity problems (Sewchurran et al., 2016:1, 2, 3).

Vertically oriented wind turbine systems with built-in storage elements and frictionless bearing systems present an encouraging solution for developing sustainable power grids.

2.4 Technology

Urban areas hold promise for custom vertical-axis wind turbine deployment, except that Cape Town lacks proper studies on effective integration strategies. This research aims to explore custom vertical-axis wind turbines in the context of Cape Town in South Africa. Despite the considerable number of studies on horizontal-axis wind turbines and their absorption into urban structures, the study of custom vertical-axis wind turbines in such an environment is rarer. The research aims to enhance the existing theoretical guideline, which further illustrates the benefits of custom vertical-axis wind turbines by determining their suitability for the climatic and urban context of Cape Town.

The primary technique of wind power production within the energy sector is the horizontal-axis turbines that tend to be employed in offshore or rural areas. Custom vertical-axis wind turbines offer the possibility for Cape Town and other cities that experience turbulent winds to overcome the shortcomings of horizontal-axis wind turbines, which are commonly experienced in laying down such generators in cities, as Zhu, Huang, and Shen (2015:1-2) put it. Custom vertical-axis wind turbines have become important instruments capable of helping Cape Town get over the energy crisis and develop sustainable urban spaces with the use of the weather patterns of urban areas of the city through the impact minimisation that horizontal-axis wind turbines usually carry out.

Vertical-axis wind turbines have also been considered popular in generating wind energy in cities since they can be installed in any direction and can be integrated into buildings, to fulfil the requirements of different urban environments (Zhu, Huang, and Shen, 2015:1, 2). The technology of these turbines can work under all wind conditions because they can be oriented in all directions, which can utilise them effectively in regions that have buildings that create changing wind patterns. The fact that they can operate with the wind at any rate makes custom vertical-axis wind turbines better options compared to the traditional horizontal-axis wind turbines in the harsh settings (Stathopoulos et al., 2018:150, 151; Chang, Tsai and Chen, 2021:2). The scientific data indicates that the custom vertical-axis wind turbines are very

effective in tapping the urban wind energy even when the turbines operate under normal wind turbulences experienced in congested places.

The buildings and other infrastructure integration has clearly resulted in the opportunities of decentralized energy generation and has shown the future of achieving localized production of power in the urban landscapes (Zhu et al., 2015:1). Given the decentralized nature of the custom vertical-axis wind turbines, they allow communities to produce their power at or close to their consumption point (Stathopoulos et al., 2018:146; Carcangiu and Montisci, 2012:1006). This is a city energy solution in Cape Town, which, among other places, has considered the concept of custom vertical-axis wind turbines as a solution within reach to help solve the long-standing energy shortage predicaments. Their ability to be fitted easily within architectural constructions creates a conducive nature of custom vertical-axis wind turbines towards the local power generation system at the decentralized locations of energy production.

These benefits could potentially assist the city in considering new energy security strategies that may improve energy resilience, decrease air pollution emissions, and aid in advanced sustainable urbanism. The long-term motivation toward energy self-sufficiency in the city conforms to the city planning and policy-maker efforts in Cape Town to establish superior energy systems (Ochieng and Gideon, 2024:2970, 2971, 2981, 2984; Kumar et al., 2024:11814 -11815; Stathopoulos et al., 2018: 151-152). The erection of custom vertical-axis wind turbines is useful in reducing greenhouse gas emissions, as well as reducing energy requirements in cities. The model illustrates its sustainability movement and urban resilience practices by showing the increased energy reliability and mitigation of the climate problems (Suri, 2019:4; Stathopoulos et al., 2018:151). Wang claims that the wind energy solutions of urban landscapes need particular consideration, and attention should be given to the critical importance of custom vertical-axis wind turbines to convert wind energy in urban areas (Wang, Feng, and Guo, 2022:1, 4).

The characteristics include a better aerodynamic design, which makes custom vertical-axis wind turbines an appropriate solution to urban areas since they produce fewer aesthetic effects and demonstrate a higher level of harmony with the environment compared to those of their horizontal counterparts (Kumar et al., 2024:11809; Carcangiu and Montisci, 2012:1001, 1006; Cronin et al., 2018:6, 10). Vertical axis wind turbines placement and installation in rows and in the roadways eliminate land incident conflicts and improve the utilisation of urban space. The meticulous and careful examination of urban components within sites of installed wind turbines is used to maximize the power generation output and address the turbulence of wind (Wang, 2020:4; Stathopoulos et al., 2018:153; Chang et al., 2021:1).

2.4.1 Energy storage systems and micro-grids

Cape Town may strengthen the power infrastructure in the city by the use of energy storage technology. Local city energy trends, along with technology appropriateness, can develop innovative solutions that address the issue of urban energy use and promote sustainability and power system resilience with the changes in energy systems. The purpose of this research is thus to add to the truth that it aims at examining the potential of the energy storage systems and micro-grids in the urban energy system of Cape Town.

One of the renewable energy sources is wind energy, which is typified by varying generation patterns of certain forms of wind generation necessitating proper storage facilities to store the energy (Qu & Qiao, 2011:359). This also implies that there must be the appropriate energy storage in existence since the wind power is only produced when the wind is blowing, meaning that the energy produced should be constant. Wind energy is one of the necessary components in renewable energy systems because the power output profile of wind energy is unpredictable and therefore, needs a capacity to provide dependable energy storage to maintain a constant presence of the electricity supply. The literature reviewed by Qu and Wang emphasizes the fact that the necessity of storage facilities is predetermined by the intermittent character of wind power due to the establishment of fixed power grids by Cape Town to meet the high demand for its power in the city (Kumar et al., 2024:11808, 11814, 11815).

The circumstances in urban cities like Cape Town are even worse in the sense that in those cities, the energy demand is quite high, and grid stability is also of significance; this implies that battery storage is more pertinent when coupled with wind energy (Qu & Qiao, 2011:359). In terms of integrating wind energy, one can employ energy storage mechanisms such as supercapacitors and hydrogen storage systems, in particular, in urban areas (Qu & Qiao 2011:359; Wang, Feng, and Guo, 2022:1, 3, 18). According to Stathopoulos et al. (2018:153), the introduction of new high-level storage tools can promote the integration of wind energy in the city, such as supercapacitors and hydrogen storage. Hydrogen storage has become one of the effective methods to ensure renewable energy stability and increase energy consumption (Wang, 2020:2).

These storage systems help in the collection and use of excess wind energy at times when the wind power density is high and the release of it during times of low wind density. Power storage systems allow the collection of surplus wind energy in high production periods while providing energy delivery during moments of reduced power generation, which increases the reliability of the power network. It means that through the proper methods of managing variability of wind power with the help of energy storage, cities like Cape Town can increase the renewable energy share in the total amount of energy consumed, decreasing the traditional energy import, and increasing the energy resilience (Qu & Qiao, 2011:359; Wang et al., 2022:4, 18). The function benefits Cape Town specifically because it helps increase

renewable energy usage as well as lower carbon emissions (Kumar et al., 2024:11809, 11812; Stathopoulos et al., 2018:146, 147, 153).

Energy storage systems bring flexibility to varying generations of renewable energy sources and, in this way, help maintain the stability of the grid. Energy storage systems are an enabler for the stable operation of fluctuating renewable energy outputs because they provide greater operational flexibility. The implementation of energy storage systems with renewable energy generation enables cities to build a more robust energy structure that reduces fossil fuel consumption and makes utility systems more secure. Energy storage needs an immediate solution because cities require it to decrease their dependence on imported traditional power and boost their power reliability.

Specifically, challenges are observed when it comes to attempting to combine energy storage systems with renewable energy systems in limited spaces, such as those in urban environments, like Cape Town. The implementation of micro-grids as decentralised systems offers a solution to existing energy challenges through a flexible energy management system Liu et al., 2018:689-690, 691). Liu et al. suggest the deployment of microgrids as regional grid management systems that address energy-related problems in urban settings effectively, according to Chang et al. (2021:1). Microgrid systems allow communities to independently produce and use energy, which in turn allows them to utilise sustainable resources while enhancing their efficiency and sustainability. Although there is a rapidly increasing interest in energy storage and microgrids, the integration of those topics into urban areas, notably in developing countries, is rather limited. The growing interest in these systems demonstrates insufficient research about their use in developing urban settings (Chang et al., 2021:1, 13).

The transition toward a sustainable custom vertical-axis wind turbine with a built-in energy storage system in a microgrid environment needs economic optimisation of storage systems as a critical factor for success. The integration of energy storage systems through this method is supportive of deep decarbonisation objectives in the electricity sector; hence, they enable renewable source penetration, increase, and maintain grid stability (Ochieng and Gideon, 2024:10).

2.4.2 Bearing Systems

Production of energy close to the source assists in minimising the main problem of periodic power failure that occurs with large-scale energy production. The performance maximisation requires a set of rules describing how the custom vertical-axis wind turbines are going to work together with the energy storage and micro-grids, thus creating a harmonious picture of how

the system will operate as a whole, to capture the energy needs of Cape Town. These details are necessary to reduce the power quality concerns and improve the reliability and efficiency of wind energy systems in urban environments because this will help engineers to adjust the design to local requirements (Kashem, Chowdhury, Ahmed, Ashraf, and Shabrin, 2020:559, 566; Chirapongsananurak and Santosa, 2015:1, 5).

Reflective integration of bearing systems in designs cannot be achieved without well-structured planning where performance requirements are weighed against the maintenance requirements, in addition to the elements of reliability, to minimise disruptions to operations. Predictive maintenance, driven by real-time data analysis, can allow organisations to increase the lifespan of vertical-axis wind turbines, including Baserba, Sedlak, Barnosell, Molinos-Senante, Schraa, Rosso, Verdaguer, and Poch (2023:2, 3) and Suri (2019:2, 4) report. Predictive analyses are complemented by condition monitoring methods to improve bearing quality, which would result in the greater strength of vertical-axis wind turbine functionality, as described by Mollerstrata, Ottermo, Goude, Eriksson, Hylander, and Bernhoff et al. (2016:1, 6, 10).

Bearing systems are important parts of wind turbine technology because they influence the wind turbine's operation, performance, and durability. The nature of loading in urban regions and the cyclic torque of vertical-axis wind turbines make it imperative to apply specific bearings that can endure these specific working conditions (Peng, Zhang, Fan, Shangguan, and Yang, 2022:1, 2). Increasing the performance of vertical-axis wind turbines within city applications becomes more difficult due to vibration combined with air pollution and restricted maintenance needs (Peng et al., 2022:2, 3, 25).

Studies about horizontal-axis wind turbine bearing systems outweigh the available literature on vertical-axis wind turbines. Vertical-axis wind turbine operations pose a problem because these wind turbines face operational challenges while located in windy Cape Town settings with complicated urban environments (Kumar et al., 2024:11808, 11811, 11814; Stathopoulos et al., 2018:151, 153). Vertical-axis wind turbines must have appropriate bearing designs that support their operation under cyclic torque and load dynamics. The study by Chang et al. (2021:1, 13) explains that selecting appropriate bearings for vertical-axis wind turbines becomes difficult due to complex operational challenges that result from urban districts and their combined vibration effects and pollution.

Under the conditions of limited maintenance access as well as urban environmental pollutants, traditional bearings cannot survive because of vibration effects (Wang, 2020:29, 32, 37). The successful operation of vertical-axis wind turbines needs special urban-optimised bearing

systems (Kumar et al., 2024:11808, 11810, 11811, 11812, 11814). Certain urban areas have highly unpredictable, turbulent wind patterns within cities, and this creates adverse conditions that compromise the stability of operations, in addition to decreasing operational efficiency in wind turbine systems. According to Möllerström, Ottermo, Goude, Eriksson, Hylander, and Bernhoff et al. (2016:1, 6, 10), bearings behave as an important system connector under such circumstances where high turbulence levels have a significant impact on the mechanics of turbine components.

Modern systems are produced based on superior materials and designs; they are supposed to perform beyond minimum requirements, and minimal maintenance is needed to produce the most energy-efficient levels (Chang et al., 2021:1, 13). The working conditions that surround the operation of the vertical-axis wind turbine necessitate a strong bearing system since environmental factors that cause difficult working conditions that require careful design planning of the structures (Stathopoulos et al., 2018:151, 153, 155; Chang et al., 2021:13). The development of innovative bearings technologies created to operate in urban areas and developed in terms of vertical-axis wind turbines, must incorporate methods based upon the industrial design principles. The functional enhancement process requires the analysis of space limitations and economic boundary measurement (Chang et al., 2021:1, 2, 4; Wang, 2020:5, 16, 21, 32, 33, 37).

To illustrate a comprehensive development strategy of new bearing designs, scholars should incorporate material and optimisation, including bio-inspired designs, that must operate under different loading conditions (Ochieng and Gideon, 2024:2976, 2977, 2975). “Aeroelastic structures… bend, oscillate, or twist under a wind load… capture wind energy even at very weak wind speeds… continuously modifies and shapes its behaviour… integrated into balconies or rooftops… carbon fibre composites and shape-memory alloys… withstand high stresses while remaining flexible.” (Ochieng and Gideon, 2024:2981).

2.5 Innovation Parameters

The development of a custom vertical-axis wind turbine with a built-in energy storage system in a microgrid environment must consider aerodynamic factors as well as direct structural design and upkeep, and adopt human-friendly and flexible methods of increasing its social acceptance. Collective efforts by industrial design and engineering practitioners will be critically important in the development of technically operational, socially acceptable, and aesthetically pleasing vertical-axis wind turbines in urban centres like Cape Town, with the contribution of environmental science. The teamwork between industrial designers, engineers, and environmental scientists is essential to create aesthetically appealing and technically

efficient systems, meeting the unique demands of the urban environments (Ahmad et al., 2022).

Previous research admits that vertical-axis wind turbines will work best in urban areas due to their specific structural features and the ability to be embedded into the urban environment which in turn could lead to community acceptance (Hezaveh, Bou-Zeid, Lohry, and Martinelli, 2016:1, 2, 16; Huang, Wang, Li, and Shi, 2024:617, 623, 630; Feng, Zhao, Qu, Bai, Zhang, and Li, 2018:1).

Therefore, it can be deduced that for seamless integration for urban suitability and community acceptance, "slender rotors are therefore preferable…strong deficits directly behind the turbines do not necessarily imply longer wakes…a stronger initial deficit most likely will dissipate faster because of higher shear and turbulence generation…" (Hezaveh et al., 2016:16). Yongzhe, Dongxiang, and Yong (2012) build on this by stating that "…vertical axis wind turbine…is recognised as a clean and convenient power generator in urban and rural areas… How to choose design parameters and optimise the structure remains a problem in small-scale VAWT design" (Yongzhe et al., 2012:334).

The aerodynamic performance of vertical-axis wind turbines can be optimised through careful selection of blade designs and airfoil configurations, which significantly affect their overall efficiency in turbulent urban conditions (Yongzhe et al., 2012:334, 337). "Vertical axis wind turbine has become popular research topic in recent years because it has better aerodynamic performance than the horizontal axis wind turbine under the complicated wind environment and therefore has tremendous potential applications at the urban environment, where the wind is very turbulent and unsteady" (Zhu et al., 2015:1). This has made vertical-axis wind turbines an attractive alternative source of distributed or urban renewable energy generation due to its flexibility to the turbulent airflow environment where it can be utilised to increase energy reliability and help in sustainable city planning (Zhu et al., 2015:6, 10).

Research shows that custom airfoils for wind turbines boost performance and durability, specifically in unpredictable atmospheric patterns of urban wind zones (Tian, Yang, Zhang, Wang, Li, Ma, and Cong, 2017:1, 4–5, 6, 9; Boumehani, Noura, Kerfah, Khelladi, and Dobrev, 2020:388, 400; Kim, Al-Abadi, and Delgado, 2018:85, 86, 98). Unique airfoil configurations are a key component that combines noise reduction with energy enhancement capability, which would lead to more public support and operational reliability in urban wind power projects.

Cape Town can use vertical-axis wind turbines placed in urban areas to solve the energy needs of municipalities while establishing paths for sustainable urban development. Most research omitted investigation of the design and operational demands of these turbines for

real-time environments that need well-defined operational principles. Current scientific knowledge remains deficient because authorities need to establish the parameters that optimise the performance of vertical-axis wind turbine infrastructure within urban settings. The previous sections in this paper have discussed some of the major challenges and opportunities in the context of proper integration of vertical-axis wind turbines into urban settings, with a special reference to Cape Town only.

To date, research on vertical-axis wind turbines, energy storage, and micro-grids is still progressing, and therefore, there is a need to achieve a system-level understanding of how the elements interrelate, especially from the aspects of mitigating the current urban challenges. Recognising the above-discussed challenges, a major research gap emerges relating to the absence of design parameters ideal for urban vertical-axis wind turbine systems. Industrial design, with its optimisation approach focused on meeting the user requirements, can fill this void. Through the integration of engineering fundamentals with style and use criteria, industrial design can encourage the increase of vertical-axis wind turbine systems that are technically effective, stylistically impressive, and socially admissible in the urban scape.

According to Kumar et al., Rafiei et al., and Boumehani et al., designers must develop the right design of vertical-axis wind turbines that are employed in urban areas and can maximise their potential to harness turbulent wind energy without causing too much noise and maintain urban aesthetics, according to Kumar et al. (2024:11808, 11810, 11811), Rafiei, Gharali, and Soltani (2023:3701, 3716), and Boumehani et al. (2020:388, 400). When applied together with functional designs, the principles of industrial design enable the designers to come up with certain bearing systems that will enhance the performance of the vertical-axis wind turbines, which will contribute to the improvement of their working life. The surrounding environment of the city, comprising turbulence, vibration, and pollution, demands ingenious bearing solutions to tackle these difficulties. Investigations by Zhu et al. (2015:1, 2, 6) showed good results of vertical-axis wind turbines under turbulent wind conditions that are common in cities.

One of the things that is needed critically is the development of aerodynamic components that are already designed with structural integrity; this is necessary in the vertical-axis wind turbine design operations. At their optimal performance capacities, lift-type vertical-axis wind turbines are found to be more effective in transforming wind energy, as per the research results that allow them to address the performance shortcomings typical under urban wind conditions. The performance of these turbines will be enhanced by greater awareness of the parameters involved in the design of blades and the design of air foils in cities.

The integration of a built-in battery system will enable the possibility of storing surplus energy and offer a steadier power supply. To achieve efficiency, magnetic levitating bearings should

be used to minimise friction. Optimisation of the vertical-axis wind turbine design in terms of the maximum aerodynamic efficiency, structural integrity, and power generation capacity.

Even though the existing research on vertical-axis wind turbines, energy storage, and microgrid systems is available, they are fragmented and tend to focus on a single technical aspect. It was clearly needed to explore how these factors interact, especially in curbing the energy challenges faced by Cape Town, such as space, aesthetics, and evolving wind patterns.

The literature review addresses theoretical perspectives of the following design approaches (e.g., parametric design, biomimicry), urban planning (placemaking, smart cities, urban metabolism), and energy system engineering (resilience, distributed generation, grid stability). Authors have identified the lack as encompassing long-term validity, technology-readiness, low-speed performance, self-starting optimisation, site-specific performance prediction, location principles, structural durability design, unified optimal design, practical tools, and cost reduction principles. The insufficiency of detailed design principles and application forms the starting point for this design project.

Chapter 3: Discover

In the following sections, I describe the process followed for this design project. The Design Council's Double Diamond design process informed the research design (Design Council, 2007:5), as can be seen in Figure 3.1. The chapter is organized in such a way that it introduces:

1. Summarising of academic literature, which determines the state of the available knowledge.
2. Mood boarding and precedent analysis.
3. Inspiration Biomimetic inspiration inspired by nature, like the Barn Owl or Manta Ray.
4. Delphi round one to confirm preliminary design directions by experts.

Four stages are associated with the Double Diamond framework: discover, define, develop, and deliver. These phases are used as headings for the following sections of this report.

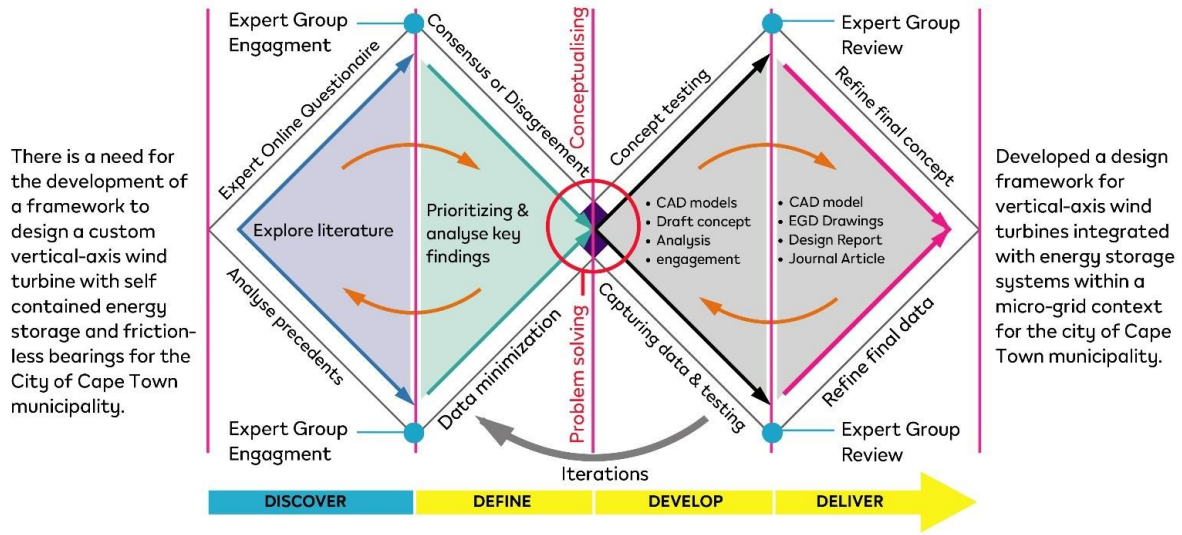


Figure 3.1: Double diamond process for the design project (Adapted from Design Council, 2007).

The preliminary phases of this design project were based on the first diamond, which is used to investigate the problem.

The first divergent stage enabled wide-ranging research of the multi-dimensional problem of urban micro grids and the adoption of vertical-axis wind turbines in the city of Cape Town. This included the study of a broad scope of variables, such as technical and meteorological data regarding the wind-patterning, but also social and aesthetic factors like noise and aesthetic pollution.

At the conclusion of this chapter, the design issue will be clear enough to begin the focused definition stage (Chapter 4). The resultant multi-source evidence base provided is rich and informative of design parameters, but not prescriptive.

3.1 Literature review

Literature, including academic articles, industry reports, and policies, to offer a theoretical, technical, and contextual background to the design project. The following were included in the review process:

Systematic Database Searches: I used academic databases (Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar) to carry out the searches, assisted by Scite Ai. I searched using keywords that represented vertical-axis wind turbine aerodynamics, technologies of advanced energy storage (lithium-ion batteries, flow batteries, supercapacitors, and integration strategies), various sources of urban wind energy, assessment tools, and sustainable urban development principles. This strategy resulted in a thorough coverage of the existing scientific knowledge and trends.

3.2 Industry Reports

This stage was fundamental in determining the technical and environmental confines of the study. The data contained the local wind speed, direction, and seasonality of the Cape Town region. I gathered quantitative information on available vertical-axis wind turbines and on scholarly repositories related to energy production, efficiency, and material properties. This information helped to determine the technical feasibility of the design.

Other quantitative data were collected in the form of engineering specifications of available vertical-axis wind turbines, and in academic databases of energy production, efficiency, and material characteristics.

I was also able to review reports of agencies, including the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). I then continued to analyse government documents, both national and local, such as the Department of Energy South Africa, the Department of Energy, Cape Town, and key technology providers. This provided me with insights into the existing energy policies, market forces, technology, and the practical implementation thereof, particularly in South Africa and Cape Town.

In the discovery phase, I ensured that I was up to date with the latest research. In that manner, my work reflected the existing state of the field. I wanted to contribute to knowledge in the deployment of large-scale energy storage in microgrid connections. The sphere is developing rapidly; therefore, my results matched current reality, as opposed to outdated assumptions.

3.3 Visual Context and Conceptual Foundation

The boards below are visual summaries of the major technical elements that have been identified in the Discover phase, and act as visual representations of Cape Town's urban environment. My thought was to have a visual of the urban setting of Cape Town, Figure 3.2, where the custom vertical-axis wind turbine needs to be seamlessly integrated into municipal structures. The idea is to be able to attach these vertical-axis wind turbines to private buildings as well, where no adequate municipal structures are available.

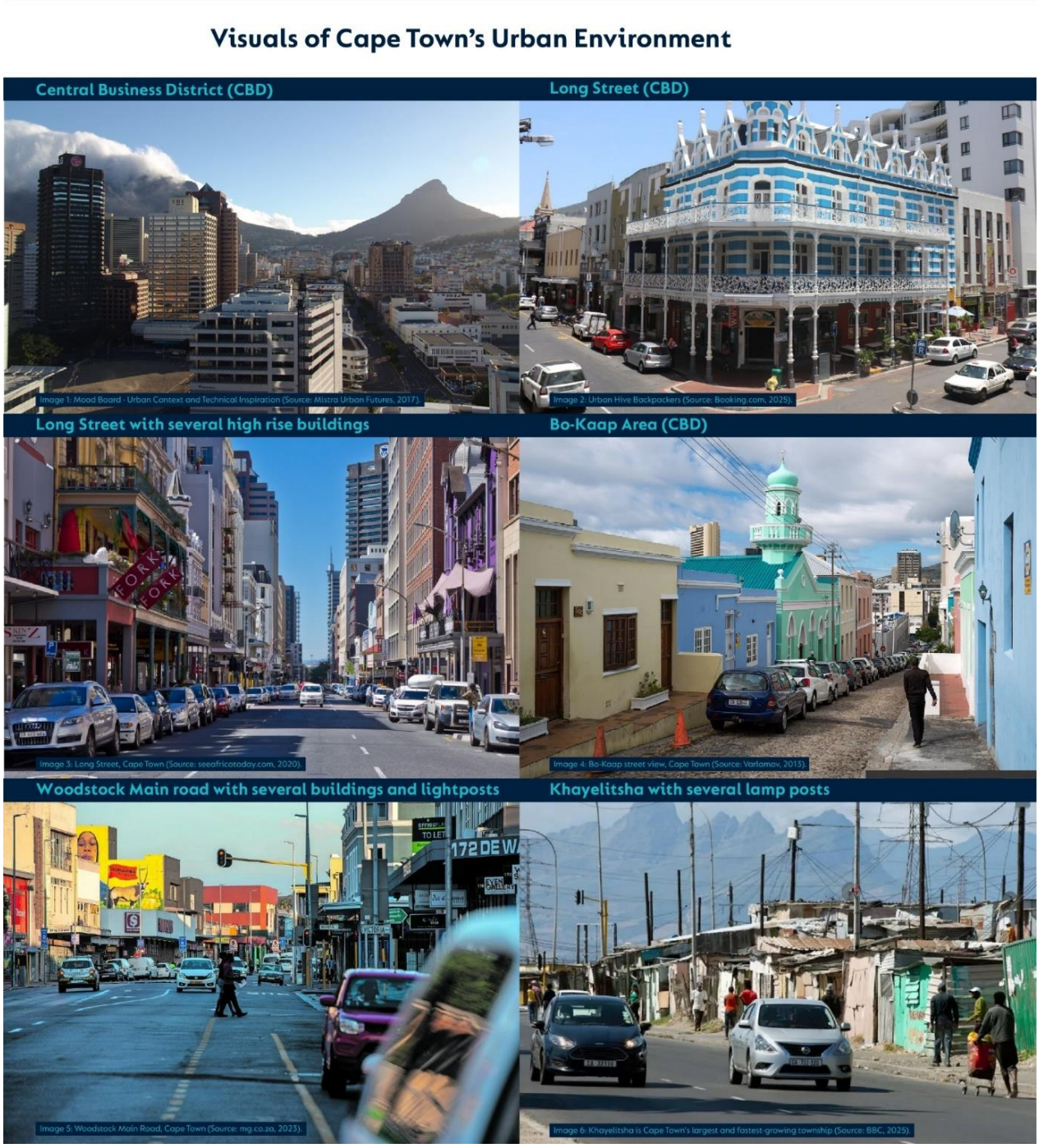


Figure 3.2: Mood board (Author developed, 2025)

Image 1: Mood Board - Urban Context and Technical Inspiration (Source: Mistra Urban Futures, 2017).

Image 2: Urban Hive Backpackers (Source: Booking.com, 2025).

Image 3: Long Street, Cape Town (Source: seeafricatoday.com, 2020).

Image 4: Bo-Kaap Street view, Cape Town (Source: Varlamov, 2013).

Image 5: Woodstock Main Road, Cape Town (Source: mg.co.za, 2023).

Image 6: Khayelitsha is Cape Town's largest and fastest-growing township (Source: BBC, 2025).

3.4 Precedent Analysis

Precedent analysis included analysing existing vertical-axis wind turbine systems and integrated urban energy systems across the world. This review assisted me in gaining knowledge of what has already been put in place, what design solutions are effective, what issues and challenges are being experienced, and how the technical performance varies in various urban settings. This resulted in a discussion that offered an empirical basis for further design development. The analysis of the precedent results was captured in the images (Figures 3.3 and 3.4), which were then followed by an interpretation of their direct contribution to the conceptualisation of the design and its parameters.

To determine the best possible solutions, I decided to collate a series of existing wind turbines (Figure 3.3) to establish their advantages and disadvantages. This guided me to ask the right questions in terms of the most suitable wind turbine system, namely horizontal or vertical wind turbine, as well as the current airfoil blades and energy generators used. This was important to understand the basic principles of wind turbines and suitable materials based on the various environments in which these turbines were placed. I chose the vertical-axis system as it is the most suitable for turbulent urban environments like Cape Town due to its ability to capture omnidirectional wind.



Figure 3.3: Existing vertical and horizontal-axis wind turbine systems board (Author developed, images from various sources).

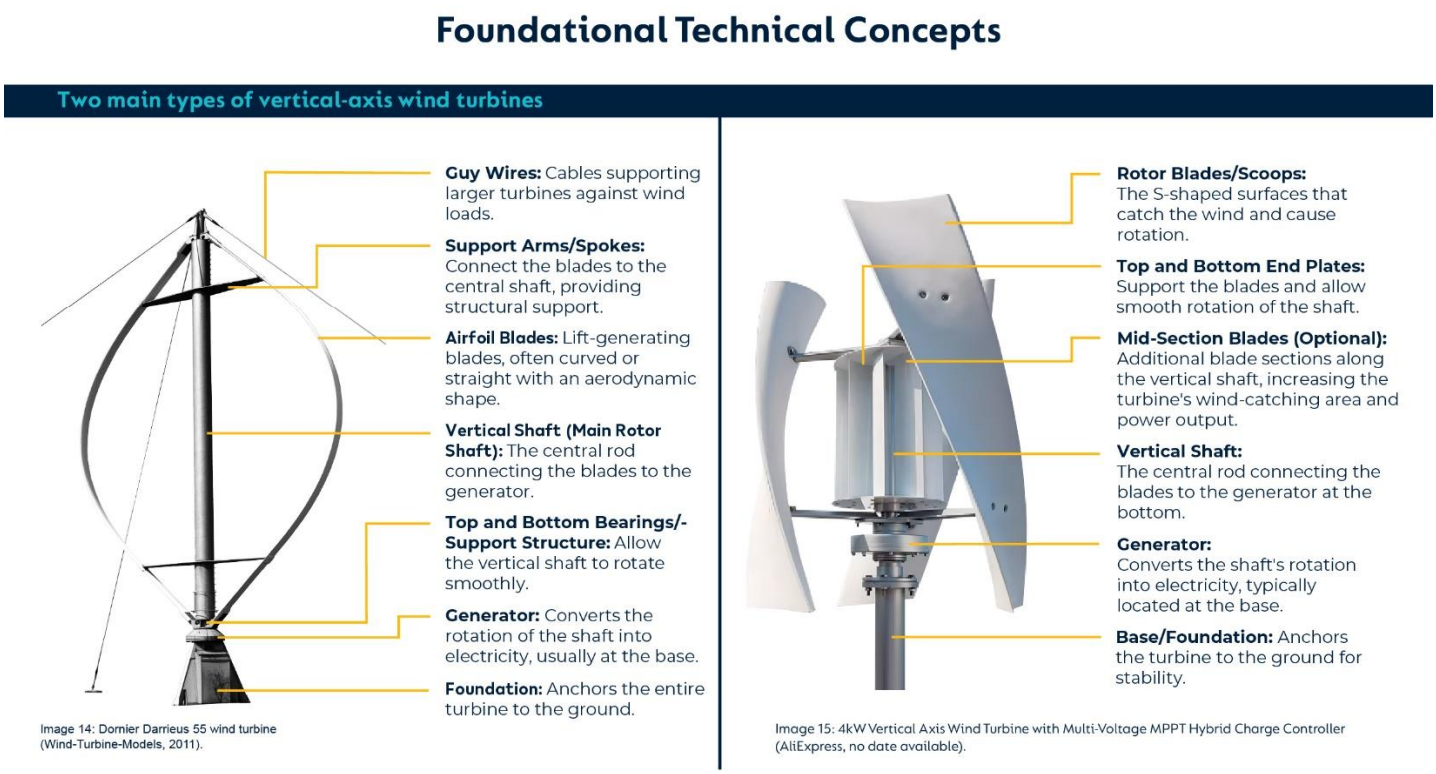


Figure 3.4: Existing vertical and horizontal-axis wind turbine systems analysis board (Author developed, images from various sources).

I set out to find the available bearings (Figure 3.5) that are used in wind turbines. The thought was to understand how they work and why they are designed the way they are. My findings were that they mostly used ‘two-ringed’ metal rings that house a cluster of steel bearings; the steel balls were then encased in industrial-grade grease in an attempt to reduce structural fatigue. Even with these attempts, bearings eventually need to be replaced due to the various forces acting on them during their lifecycle.

Cape Town’s wind patterns, as illustrated in Figures 2.1, 2.2, and 2.3, have shown that rooftop wind turbine systems were a viable option due to the consistent wind speed within the city's urban environment.

I also searched for existing rooftop vertical-axis wind turbines (Figure 3.5) that were perfectly suited for rooftop integration, which then guided me to analyse their beneficial features. I found that a manageable structural size was necessary for ease of installation and that most parts needed to be modular. These key features were later taken into consideration when I developed the custom vertical-axis wind turbine with built-in energy storage.



Figure 3.5: Existing bearing systems and rooftop examples (Author developed, images from various sources).

One of the fundamental things of this design project was to establish the available energy storage solutions that are currently available in the market and to analyse their evolution or non-evolution. I found that the battery banks are standardised, as can be seen in Figure 3.6, hence making it very difficult to build them into a wind turbine solution, as they are bulky and, for the most part, are bulky. This is problematic as it does not yield itself very well to the shape of standard wind turbines, as most support structures are cylindrical in shape.

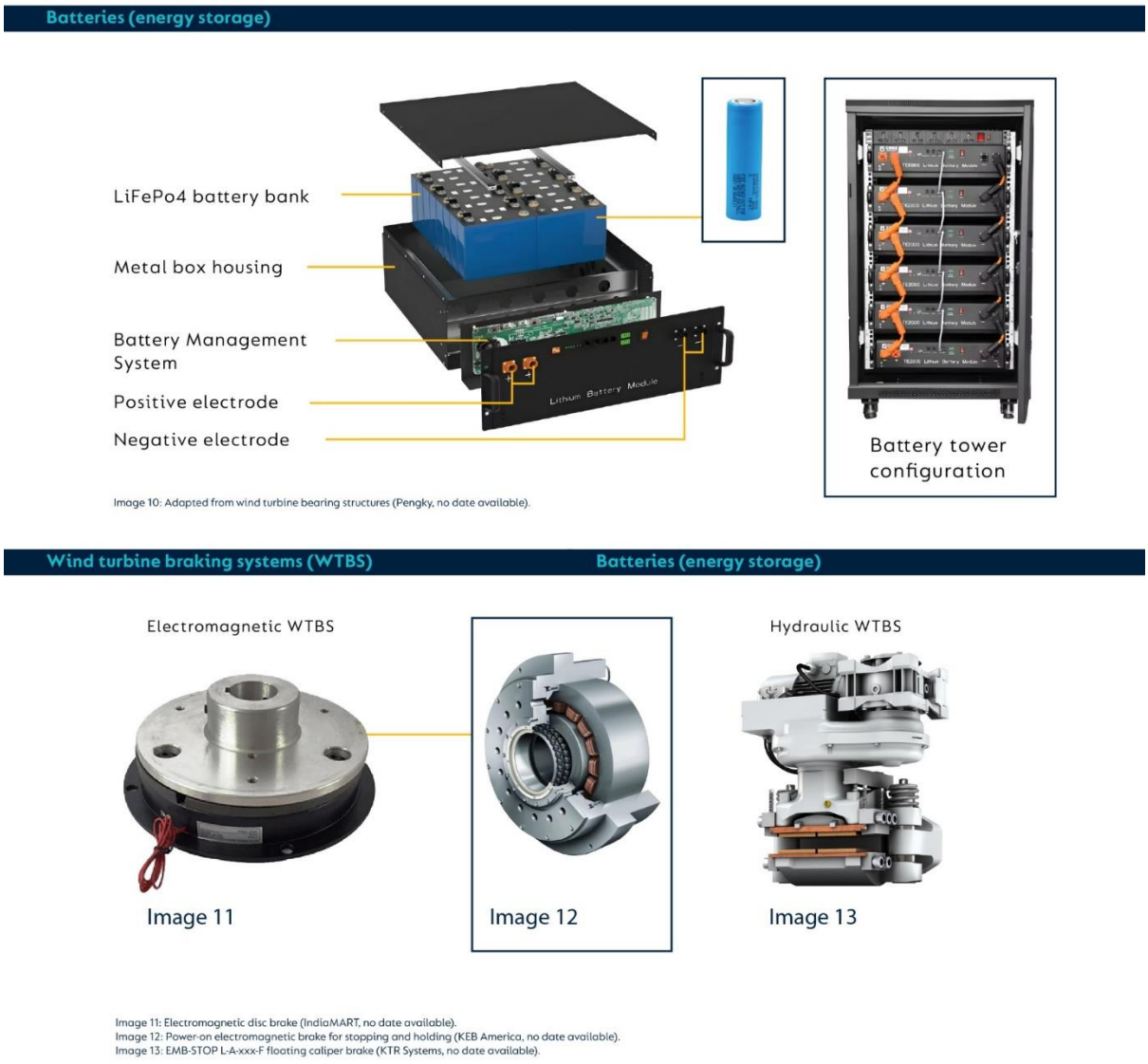


Figure 3.6: Existing battery bank and energy storage systems (Author developed, images from various sources).

Figure 3.6 also illustrates a collection of braking systems. This was important to understand what is available to slow down wind turbines. I found that some wind turbines have smart systems with electromagnetic braking systems, and other versions have mechanical systems. This research, although identifying the available systems, does not investigate this part of a wind turbine, but rather leaves room for further research.

Once I gathered all the relevant information, I then set out to familiarise myself with what was already in existence. I started to explore the precedents and did a few initial concept sketches based on the shapes and functionalities of the existing vertical-axis wind turbines, all the while continuously following the industrial principle of “form follows function” as stated by Louis Sullivan, a famous architect. These sketches were pivotal in understanding the various

aspects and allowed me to explore other options through an iterative design process, shown in Figures 3.7 and 3.8.

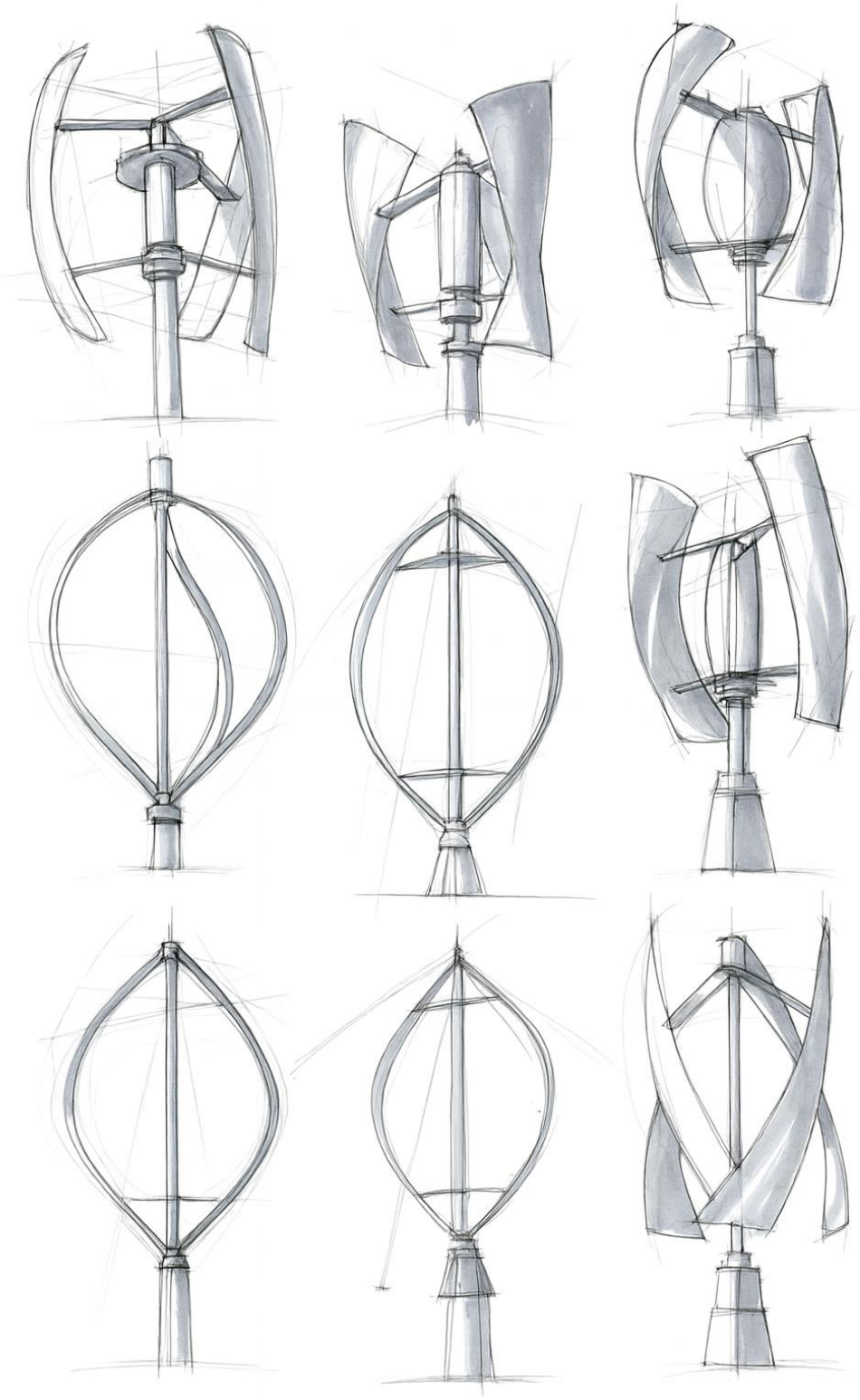


Figure 3.7: Sketches from Precedent Analysis (Author's own, 2025).

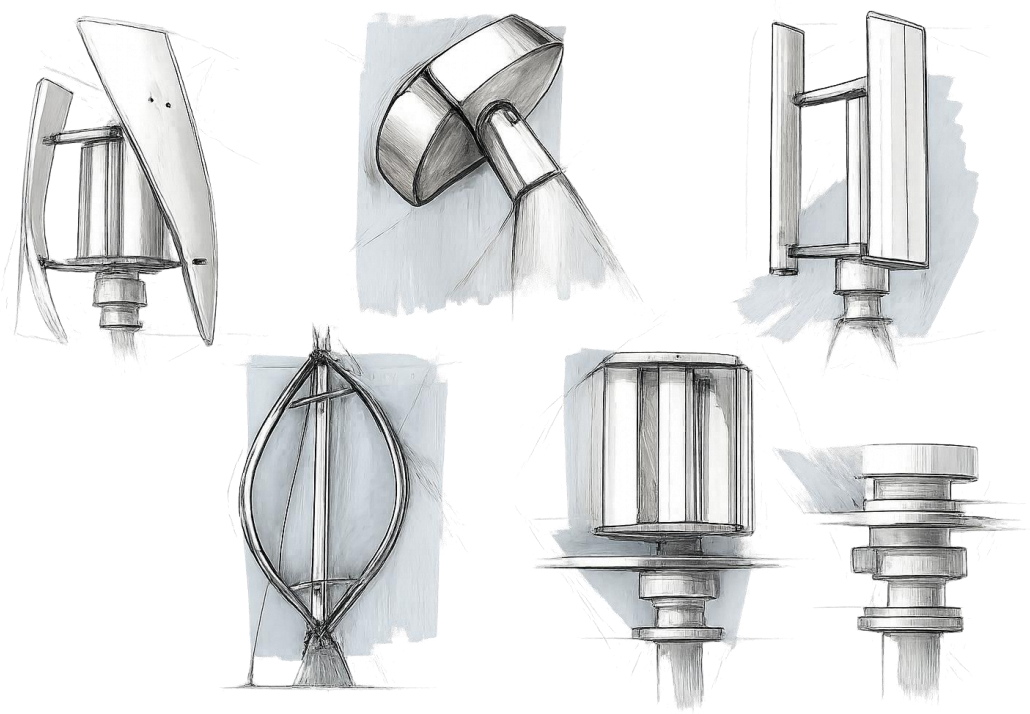


Figure 3.8: Sketches from Precedent Analysis (Author's own, 2025).

3.5 Biomimicry: Nature-Inspired Design Solutions

This step in the discovery phase embraced biomimicry to solve the unique problems of wind energy in the city and go beyond traditional engineering. I sought a long-term solution by following nature-tested techniques and approaches. Through analysing the anatomical forms and functionality of the Barn Owl (Figure 3.9) as well as the Manta Ray (Figures 3.10 and 3.11), the objective was to create new design principles for the vertical-axis wind turbine blade airfoils. The idea stemmed from developing a quieter vertical-axis wind turbine for greater community acceptance and more efficient kinetic energy generation. The concept needed to harness more of the energy in the turbulent, multi-directional winds, which typify urban areas.

3.5.1 Barn Owl: Acoustic Optimisation



Figure 3.9: Barn Owl biomimicry inspiration (Adapted from Earth.com, 2024).

Barn Owls (Tyto Alba) have massive possibilities of minimising atmospheric noise. They serve as an important biomimetic model of what can be called quieter vertical-axis wind turbine systems. To render their flying effective and silent, these animals have three features: a serrated leading edge composed of soft primary flight feathers; a velvety dorsal surface; and a flexible, serrated trailing edge. This combination aids in noise reduction caused by common aerodynamic flaws as it interrupts a turbulent airflow and therefore diffuses pressure oscillations. The noise-absorbing structures of wind turbines are based on the serrated leading edge of the owl, which is designed to improve the flow of air around the turbine. The design has the effect of minimising and controlling acoustic pollution in the congested city centres.

3.5.2 Manta Ray - Kinetic Efficiency



Figure 3.10: Manta Ray, side view (Adapted from Wallpaper.com, n.d.).

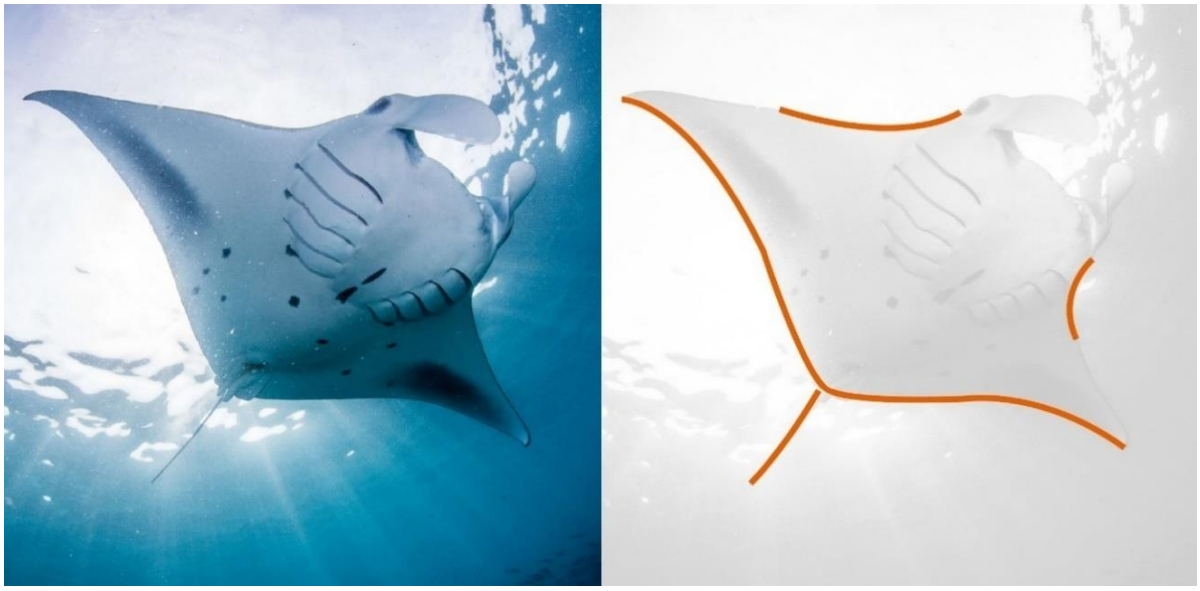


Figure 3.11: Manta ray, bottom view (Adapted from Modern Megapolis Guide, 2023).

The Manta Ray (Mobula birostris) offers an example of how biomimicry can be used to enhance the kinetic efficiency of a drag vertical-axis wind turbine blade. It has a kind of hydrodynamic pectoral fins, particularly the wing shape and wing tips, which provide effective control of the airflow. These characteristics make the wings efficient in generating propulsion and lift with a minimum of energy.

To come up with a vertical-axis wind turbine blade, I used the anatomical shapes of the Manta Ray, including its delicate lines, surface ornamentation, texture, and chord variations evident in the body of the fin. Using this biomimetic design should create a bigger torque with decreased wind speeds. The objectives are a high flow attachment, fewer moving parts, which involves reduced drag resistance, and finally, an increased total power coefficient of the micro-grid wind turbine system.

3.5.3 Anatomical Translation to Engineering

The translation of the anatomical structure was the first to develop the biomimetic-inspired wind turbine blades, the critical structures of the Manta Ray that would confer efficient hydrodynamics. This has a black-and-white schematic superimposed on a full-colour reference, which indicates the leading edge and primary chord length of the fin. At this point, the abstraction of the shape of the fin was considered as part of the airfoil. The resulting conceptual blade (Figure 3.12) is in the triangular shape of the Manta Ray that has substantial surface area, which is intended to maximise the drag component of a Savonius rotor. The initial design was based on the curvature derived from the Manta Ray wingspan. Such versions were crude, and this is why I was still searching for a better and efficient approach

that could generate high production to drive generators.

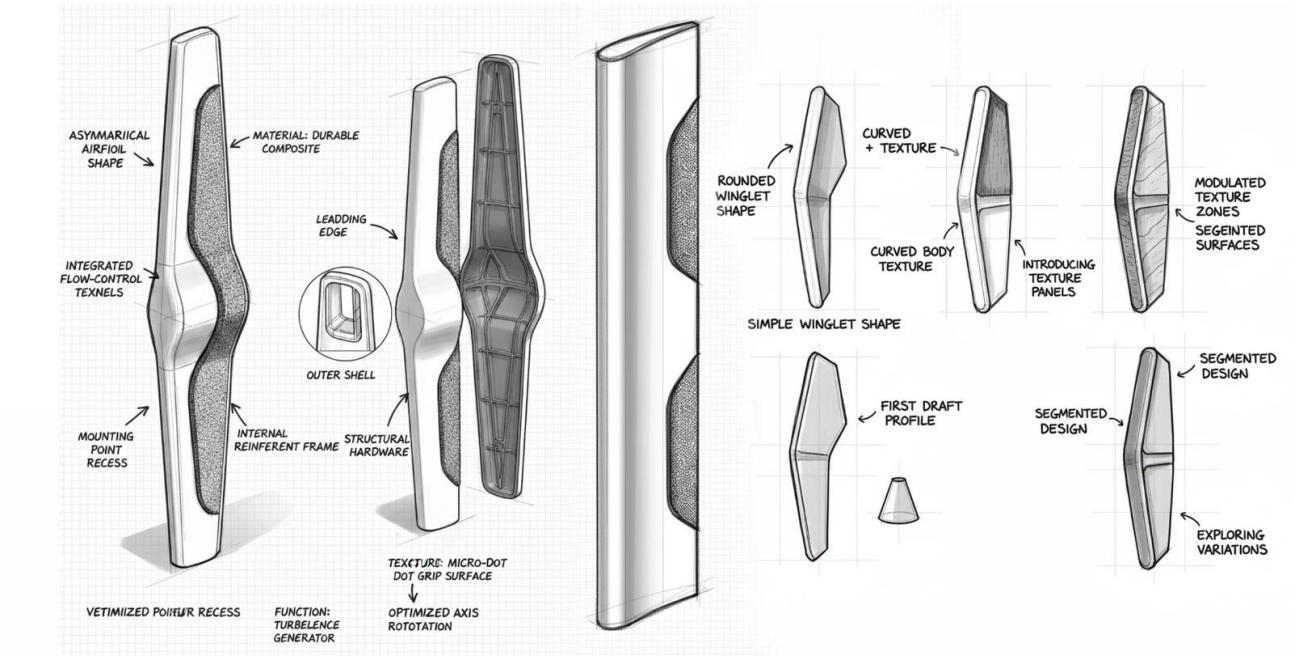


Figure 3.12: Manta Ray pectoral fin anatomy sketches (Author's own, 2025).

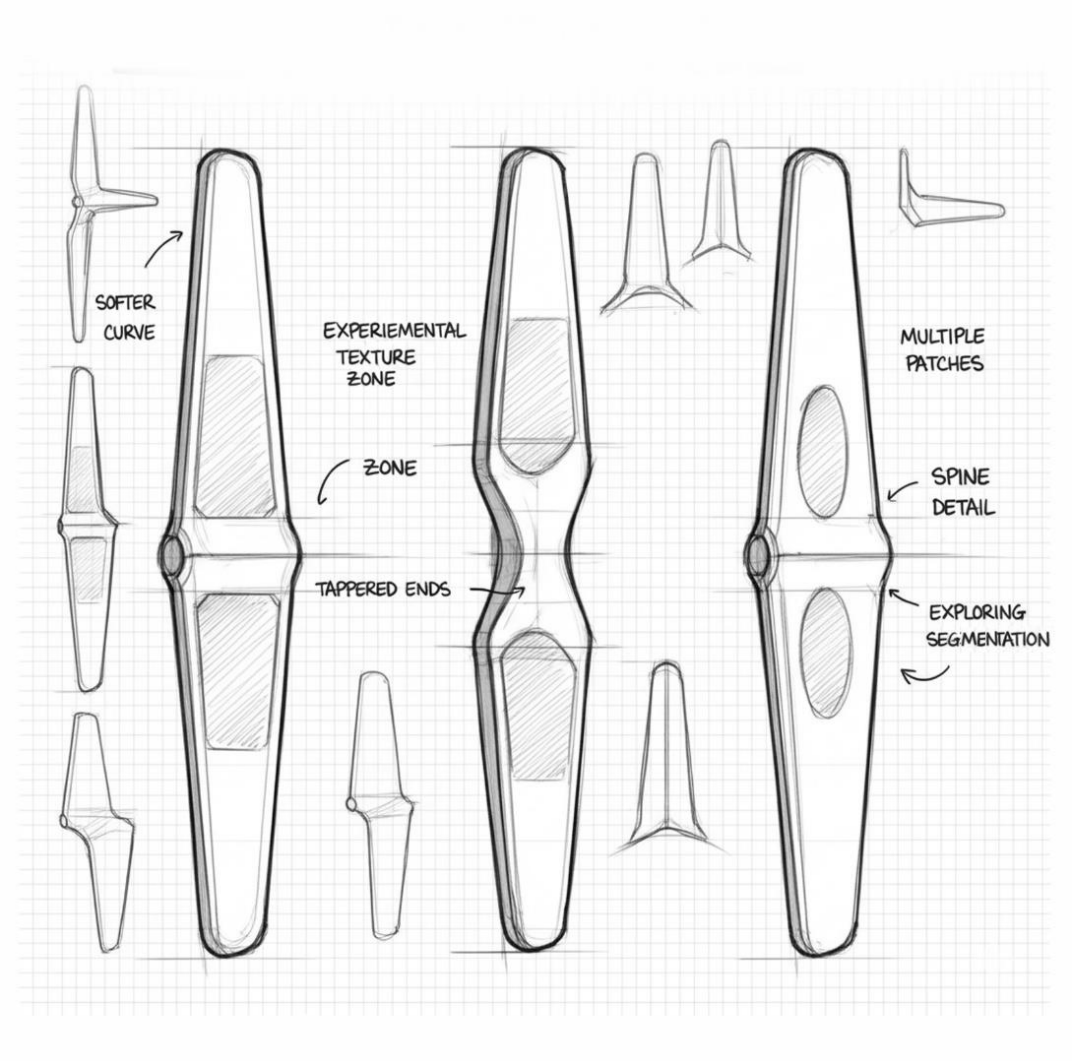


Figure 3.13: Manta Ray physiological contours and flow features (Author's own, 2025).

In Figure 3.12, I illustrate the secondary anatomical structures that regulate flow efficiency. This process was an attempt to find a blueprint that describes the flexibility of the trailing edge and the shapes of the leading edge. To maintain a smooth movement and prevent stalling, the Manta Ray uses these characteristics over a big area. This can be seen in the sketches of the blade shape (Figure 3.13), where I investigated a stronger controlled curvature at the trailing end. This was aimed at reducing the aerodynamic noise, as well as enhancing lift at lower angular velocities. This was a break with an essentially drag-based idea to a lift and drag design.

3.6 Expert Engagement and Data Collection

The discovery phase culminated with an engagement with experts in the field. This information was crucial in informing the technical feasibility of the design.

The physical observation (qualitative data) of the city and the available infrastructure used on the site aided in determining the location where the installation was possible and showed some design limitations. The interviews with experts provided important insights concerning the way in which people understand renewable energy, visual aesthetics, and noise.

3.7.2 Expert Engagement via Delphi Method (Round 1)

I used the Delphi method to collect professionally informed data. This is a common practice in the energy sector, as the narrow scope of information is extracted by subject matter experts, and the process is systematic and achieves consensus. According to Boulkedid et al., the Delphi method is a type of communication strategy that aims to achieve consensus but without the social adversaries that are experienced with group discussions. It can be applied in a variety of situations, both forecasting and non-forecasting tasks in management and technology tests (Boulkedid, Abdoul, Loustau, Sibony, and Alberti 2011:1). Kisvari et al. indicate that this method is cost-effective and applicable to the determination of clear targets and goals (Kisvari, Lin, and Liu 2021:25).

The strength of the Delphi method is its dynamics because it allows the participants to obtain a more vivid impression of common opinions due to the cumulative feedback from several rounds. According to Castillo et al., this technique provides dependable results, which are shown in a low dropout rate and strong results (Castillo, Joodi, Williams, Pezeshk, and Chhabra 2021:121,122). Repeated aggregation of collective views of experts is pulled towards a more sophisticated decision, which enhances decision-making (Jünger, Payne, Brine, Radbruch, and Brearley 2017:2).

3.8 Participant Selection and Justification

Each of the three members of the Delphi panel was selected and invited professional and had a provable and relevant experience in disciplines that were directly related to the dissertation and had a recognised authority. This composition proved to be the best solution to master's-level research, which guarantees a wide range of opinions about the limitations of a small group of participants in projects over a long period, their longitudinal engagement, and the management of information (Da Silva et al., 2023:5, 6, 11).

The panel of experts comprised an academic and two industry professionals, which was the most appropriate number of respondents according to the Delphi method. They were all qualified professionals with skills that matched the scope of the study. The survey has been designed with the help of Google Forms; each participant has been sent a link with the help of which it is possible to obtain feedback on the questions that are proposed. The initial Delphi questionnaire is presented in the addendum, referred to as 8.1 Delphi First Round Questionnaire.

In line with the instructions of the Delphi method, I ensured the anonymity of the respondents. I have designed the questionnaire and posted it in Google Forms, sharing it with the professionals. The findings of the research were influenced by their feedback. The first feedback was thematically analysed to develop a standardised operating program that guarantees data homogeneity and generates qualitative information about the design potential, the operational issues, and policy suggestions.

Thereafter, I created computational models and conducted numerical simulations to determine the overall aerodynamic performance and energy conversion efficiency, and structural integrity of the selected design. The experimental, Computer-Aided models are justified with these empirical studies, and these studies determine the effect of the different design parameters on the overall performance of the system.

In this qualitative research, I present the challenges of vertical-axis wind turbine integration based on the literature, interviews with the experts, and Computer-Aided Design algorithms (Wijayanto, Kono, and Kiwata, 2020:1). A triangulated methodological approach was employed to determine the feasibility of the vertical-axis wind turbine design. (Sciberras and Dingli, 2023:31).

3.9 Delphi Round 1 Objectives

Delphi Round 1 aimed at achieving consensus on technical issues, design issues, and urban integration requirements. The Define phase of the research was informed by feedback from the experts to identify all the important parameters to be met by the vertical-axis wind turbine. This included the blade geometry, energy storage, and compatibility with a microgrid.

This Expert-Informed Design Journey Map in Figure 3.14, included below, was developed to illustrate, at a glance, the iterative process in which the input of the experts through the Delphi rounds guided all the phases of the Double Diamond model, which starts with the initial discovery and ends with the final delivery.

3.9 Summary

The Discover phase created an all-inclusive base of the custom design VAWT with:

1. Literature Review: Established the viability of Cape Town wind resource (Figures 3-4), reported load-shedding effects, and established that the Vertical-Axis Wind Turbine was the most desirable in turbulent urban winds, as opposed to the Horizontal-Axis Wind Turbine.

2. Precedent Analysis: The various components of Vertical-Axis Wind Turbine systems were analysed, as well as their bearing technologies and battery configurations, to see the optimal practice and frequent failure modes.

3. Biomimetic Research: Based on the anatomy of the Barn Owl feathers, derivation of the principle of acoustic-optimization, and based on the anatomy of a Manta Ray pectoral fin, derivation of the principle of kinetic-efficiency.

4. Expert Evaluation (Delphi Round 1): During the data gathering process, three experts in the field of renewable energy endorsed that magnetic-levitation bearings and embedded storage. They further endorsed that Savonius blade geometry would be a suitable solution in Cape Town's urban environment.

The main findings that go to the Define phase:

- Blades of the Savonius drag type can be used despite their efficiency restrictions.
- Magnetic bearings are feasible in the elimination of friction and maintenance.
- Intermittency management requires in-built storage.
- Care must be taken regarding noise, aesthetics, and the load of construction in urban installations.

The given findings allow the targeted convergence and synthesis of the design recorded in Chapter 4.

Expert-Informed Design Journey Map



Scenario

In reaction to continued load-shedding and constraints of centralized energy infrastructure, a design team of a mechanical engineer, an electrical engineer and an energy professional were gathered to developed a vertical-axis wind turbine system suited to the urban environment of Cape Town. I used the expert feedback to select major aerodynamic efficiencies, structural limitations, and regulatory implications that are vital in designing a vertical-axis wind turbine system in the urban setting of Cape Town through the Delphi round, and thematic analysis. Their knowledge informs a small, quiet, modular turbine with internal energy storage, with an optimum design to fit building frontages and street utility.

Goal

This expert-driven design process aimed to come up with a vertical-axis type of the wind turbine system that is technically viable, contextually incorporated and regulation-based to meet the urban microgrid infrastructure of Cape Town.

The process is informed by the input of three domain experts, the input of which was organized into a thematic analysis from the data captured during the Delphi questionnaire interaction.

Stages	Discovery	Define	Develop	Deliver
Expert Input Theme	Urban energy instability, load-shedding, need for microgrid resilience	Technical feasibility, aerodynamic efficiency, material selection	CAD feedback, magnetic bearing integration, battery bank sizing	Decentralized energy generation, load-shedding mitigation
Design Implication	Explore Vertical-Axis wind turbine integration with energy storage and microgrid systems	Prioritize Savonius blades, magnetic bearings, and compact design	Refine blade geometry, generator configuration, and battery layout	Frictionless operation, low-noise design, urban resilience
Challenge	Grid unreliability, space constraints, public skepticism	Noise concerns, aesthetic integration, structural integrity	Maintenance access, component alignment, cost constraints	Modular assembly, expert-informed optimization
Opportunity	Decentralized energy generation, load-shedding mitigation	Ensure regulatory compliance and urban adaptability	Installation logistics, visual impact, inverter oversizing	Scalable deployment, stakeholder alignment, policy support
Researcher actions	**Objective:** Scout the problem area and assemble background knowledge. **Researcher Actions:** 1. Carried out a sizeable review of literature on the issue of energy in urban settings and the viability of VAWT. 2. Delphi Round 1 administered to obtain expert views on technical, environmental and regulatory factors. 3. Gathered weather information and city structures that are unique to Cape Town. 4. Thematic analysis (e.g., noise, aesthetics, grid instability) was used to define the most important themes.	**Task:** Summarise the results in a concise design brief and problem statement. **Researcher Actions:** 1. Evaluated professional feedback and theme-based patterns to rank design parameters. 2. Developed a design brief, specific to context, of a VAWT system coupled with microgrids. 3. Reduced technical issues (e.g. aerodynamic efficiency, structural integrity). 4. Earmarked regulatory and aesthetic restrictions to urban use.	**Goal:** Generate and refine design solutions. **Researcher Actions:** 1. Created iterative CAD models of the vertical-axis wind turbine system using SolidWorks. 2. Integrated expert feedback from Delphi Round 2 into design refinements. 3. Simulated performance metrics (e.g., swept area, RPM, power output). 4. Designed components: Savonius blades, magnetic bearings, dual generators, battery banks. 5. Evaluated manufacturability, structural load paths, and urban mounting options.	**Goal:** Finalize and document the design solution. **Researcher Actions:** 1. Produced detailed engineering drawings and exploded views of the final design. 2. Conducted performance estimation and system sizing analysis. 3. Validated compliance with Cape Town building codes and national standards. 4. Documented the full design process and outcomes in the dissertation. 5. Proposed future research directions and real-world prototyping considerations.

Figure 3.14: Expert-informed design journey map (Author's own, 2024).

Chapter 4 – Define

In this chapter, the initial convergent phase of the Double Diamond process takes place. It embodies in Chapter 3 the broad findings and translates them into explicit design parameters and specifications. The primary approach in this case is thematic analysis of expert responses as part of Delphi Round 1. It is supported by scribbling of concepts and the scrambling of initial CAD.

The chapter covers:

- Coding and theming of responses to expert questionnaires.
- Biomimetic principles to engineering specifications.
- Preparation of first concept drawings of important sub-systems (blades, bearings, storage, mounting)
- Making technical justifications on component choices.

At the conclusion of the chapter, the design problem changes its focus from the general investigation of the urban VAWTs to a specific set of specifications. These features necessitate a 2.38m by 1.0m Savonius turbine, with magnetic bearings and 2.4kWh of inbuilt storage, which would fit well in Cape Town structures.

The define phase determines the specification based on which Chapter 5 iteration work will be conducted.

4.1 Thematic Analysis One

To investigate performance and efficiency in the energy operations, I performed a qualitative review of the survey with the energy experts as suggested by the authors (Zaabi, Antony, Garza-Reyes, Tortorella, Sony, and Jayaraman, 2024:8, 11, 12). This discussion was based on thematic procedures. Then, I analysed the data which was collected from the Delphi questionnaire to find the key statements which were then coded into key findings. These fully adhered to the six steps that were summarised by Zaabi et al. (2024:11,12, 15, 37):

- **Data Familiarisation:** I have performed a qualitative review of the whole qualitative data, reading and re-reading through the feedback of the experts. This enabled me to get the general content, form first thoughts, find patterns, and make notes of specific areas of special interest.
- **Code Generation:** I coded parts of data, such as phrases, sentences, and paragraphs, with tags, labels, and short descriptions. The process of coding is in a loop, combining both inductive and deductive tactics. The data itself gave rise to codes with no preconceived ideas being used other than the research questions, literature review,

and theoretical frameworks, including wind-turbine aesthetics and noise issues in urban areas.

- **Theme Searching:** I was searching by Themes and grouped and re-grouped the first codes into umbrella themes. This entailed repeated comparison, observation of similarities, relations, and conceptual differences. An example is codes associated with visual intrusion, noise pollution, building integration, and public acceptance might be lumped together under a broader theme e.g., Urban Integration Problems and Socio-Aesthetic Acceptability.
- **Review of Themes:** To identify the errors, incoherence, and inconsistencies, I cross-linked the initial themes with the whole raw data. Such a process of back and forward entailed combining codes into themes, disaggregation of themes into codes, revision of the themes, or deleting those that could not be subject to further inclusion. The final product was a list of themes that well captured the subtleties of the participants.
- **Defining and Naming Themes:** I defined each theme specifically herein, stating the main meaning, scope, and content of that theme. This gave a clear picture of the conceptual framework, so that there was a coherent analysis. A sample of representative data was chosen to represent each of the themes, making the analysis based on the voice of the participant, and to give empirical support to the themes' conclusions.
- **Report creation:** Lastly, I was able to create an analytical narrative that connected the discovered themes with research questions and came up with the final report, as can be seen in Figures 4.1 and 4.2.

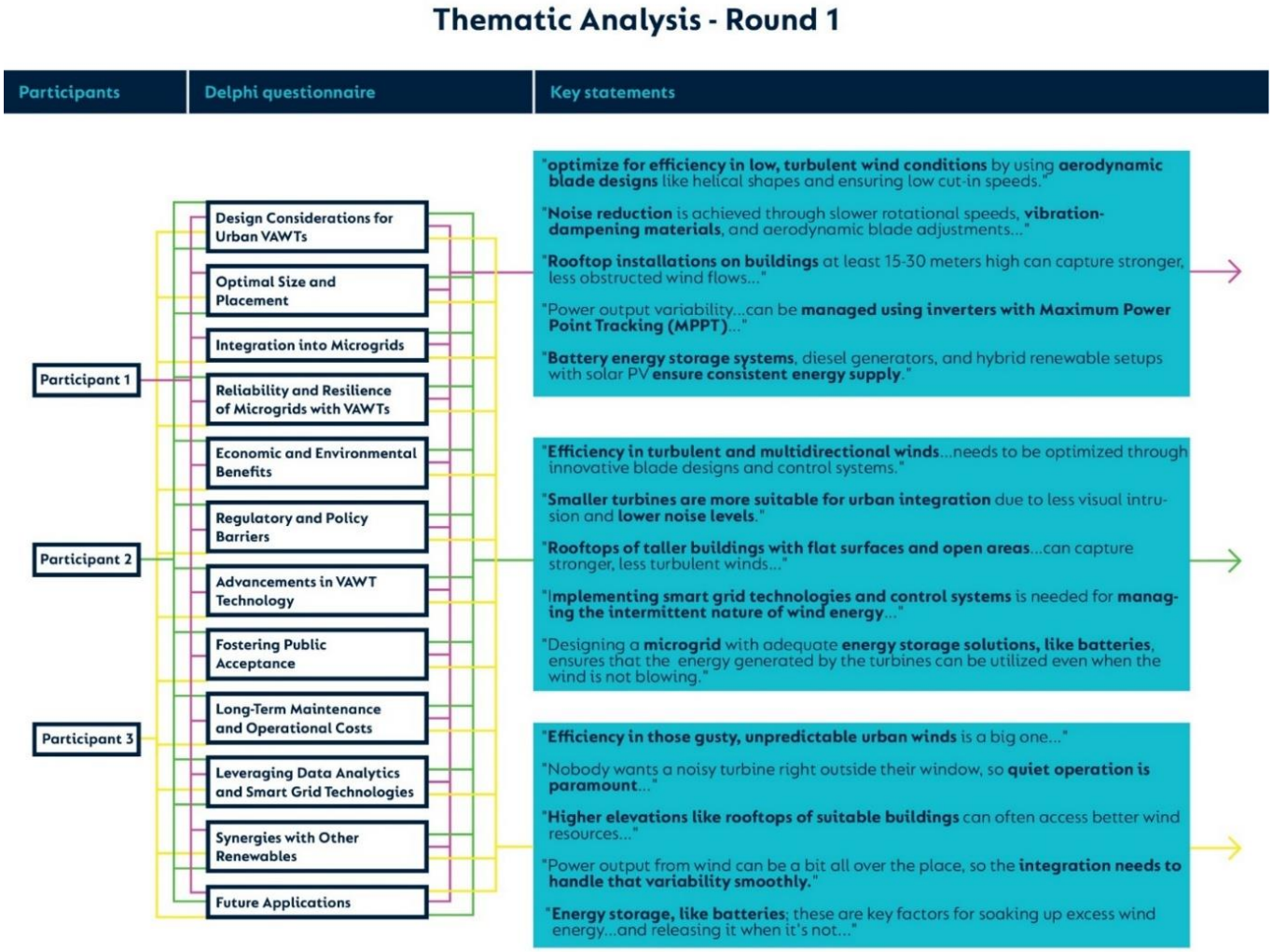


Figure 4.1: Thematic analysis of Delphi responses 1 (Author's own, 2024).

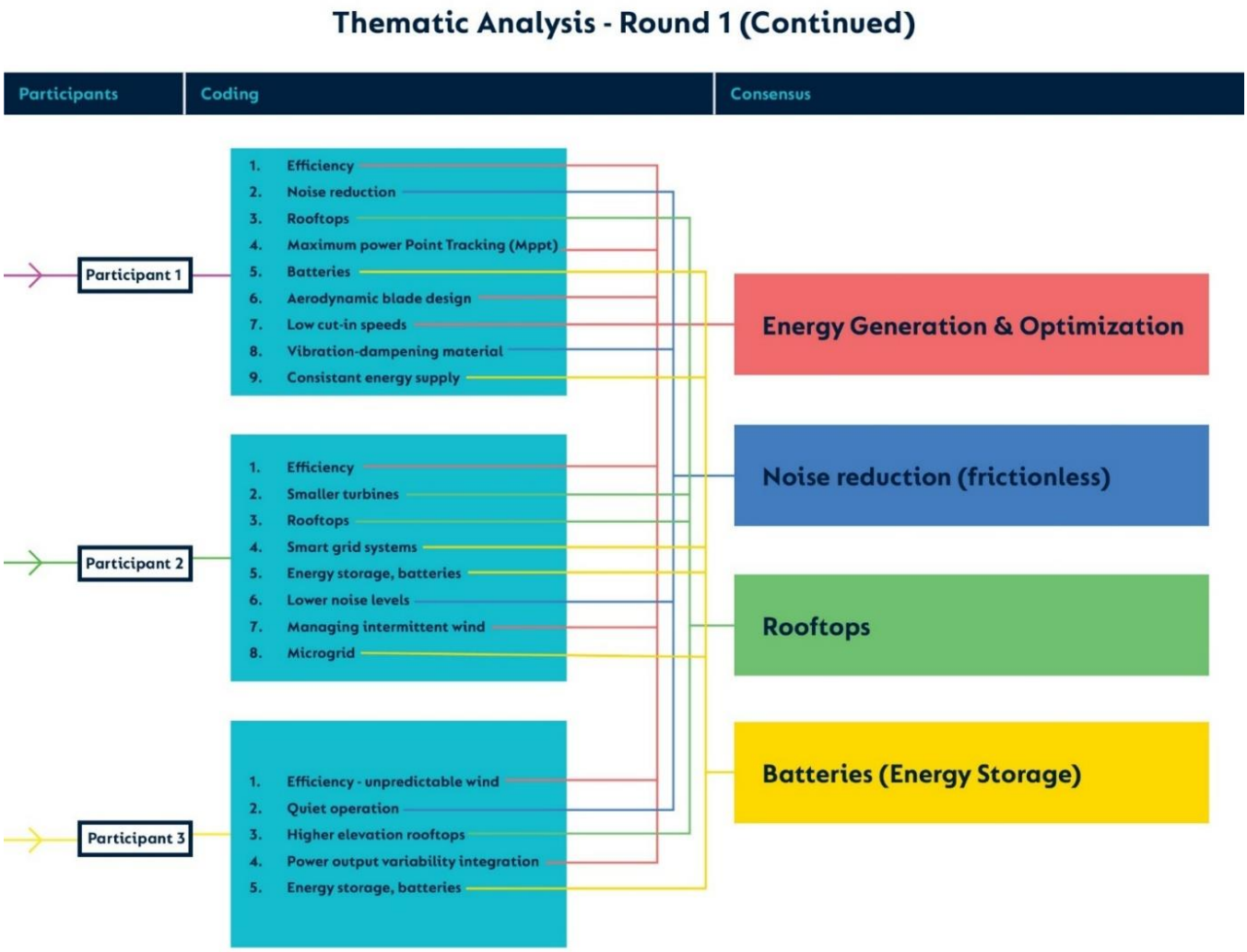


Figure 4.2: Thematic analysis of Delphi responses 2 (Author's own, 2024).

4.2 Concept Development: Sketches and Iterations

This section presents the concept sketches that were used to develop the vertical-axis wind turbine system. It is these visual explorations that provide the initial phase of ideation, where abstract concepts and situational analysis are transformed into the actual design possibilities. The section highlights sketching as a generative tool in research by documenting these early sketches. It shows that visual thinking contributes to the framing of the problems, the creation of solutions, and the optimisation of the main aspects, which are the blade geometry, magnetic bearing systems, and energy-storage integration. Along with guiding the technical course of the project, these sketches are also useful in ensuring the final design satisfies urban energy requirements as well as the expectations of the stakeholders.

Material choice, laws of aerodynamics, and structural component building are the critical issues that are explored during the sketches before the commencement of the CAD modeling. Every drawing is a stage in the design thinking process, such as reviewing a professional and

verifying natural resource requirements, and whether a structure fits into the city infrastructure, and there are also records of the development of an idea to a prototype through photographs. These concept sketches were used as the basis of the stage of CAD models, in which abstract concepts are converted into specific technical objects. The original design development concept was the translation of biomimetic concepts into a useful blade evolution. Figure 4.3 illustrates that I sketched the profiles of the blades, chords, and surface patterns iteratively as a result of the Manta Ray pectoral fin. These drawings consisted of the patterns and curvature of the animal to decrease drag. Later on in the process, I eventually went to CAD modeling.

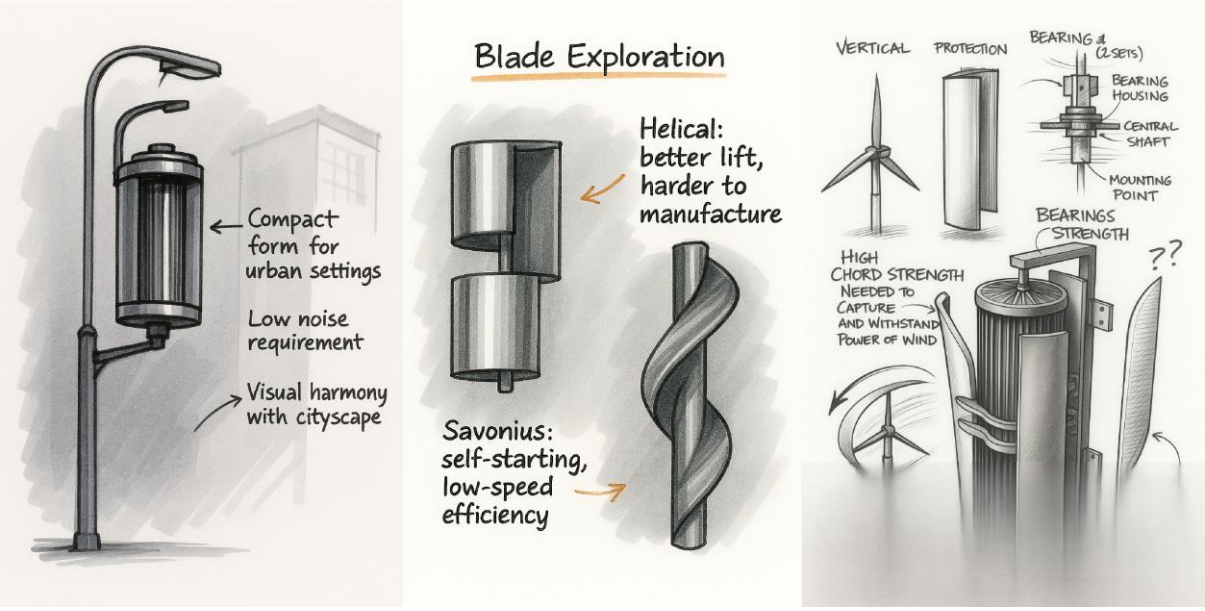


Figure 4.3: Turbine blade design exploration (Author's own, 2025).

In Figure 4.4, I once applied design thinking principles to develop the functional element of the inner workings of the custom vertical-axis wind turbine. This allowed me to clearly plan and ideate where certain parts need to be incorporated to make the most practical sense in terms of functionality as well as manufacturability.

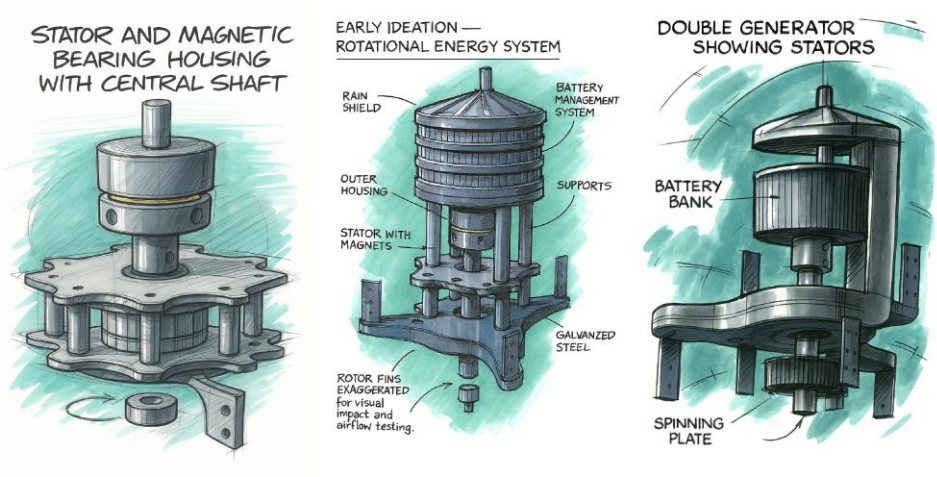
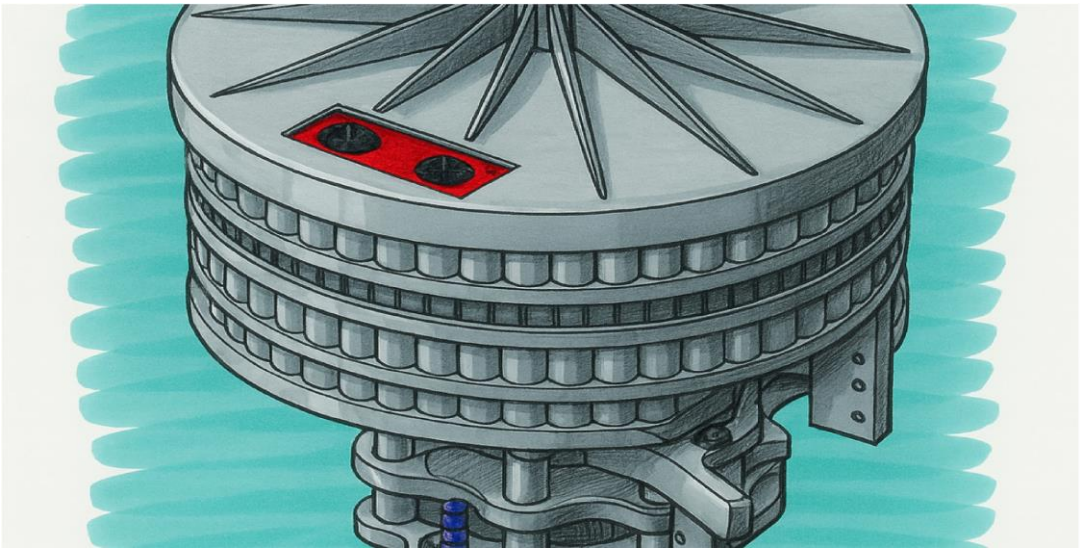


Figure 4.4: Wind turbine inner workings (Author's own, 2025).

As set out in the aims and objectives, built-in energy storage was a crucial factor. Below is a concept sketch (Figure 4.5) that later became a key point in understanding that the configuration of the Panasonic 26650 Li-ion (NMC/NCA Chemistry) batteries used in battery banks could be adjusted to meet the needs of this new wind turbine by taking advantage of the cylindrical shape and placing them around the axis. This advantage aided the aerodynamics when the outside cover was installed on the CAD model.



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Once the battery concept was developed, I continued to conceptualise the inner workings, such as the bearing system, blade placement, and so forth. These sketches are illustrated below in Figure 4.6.

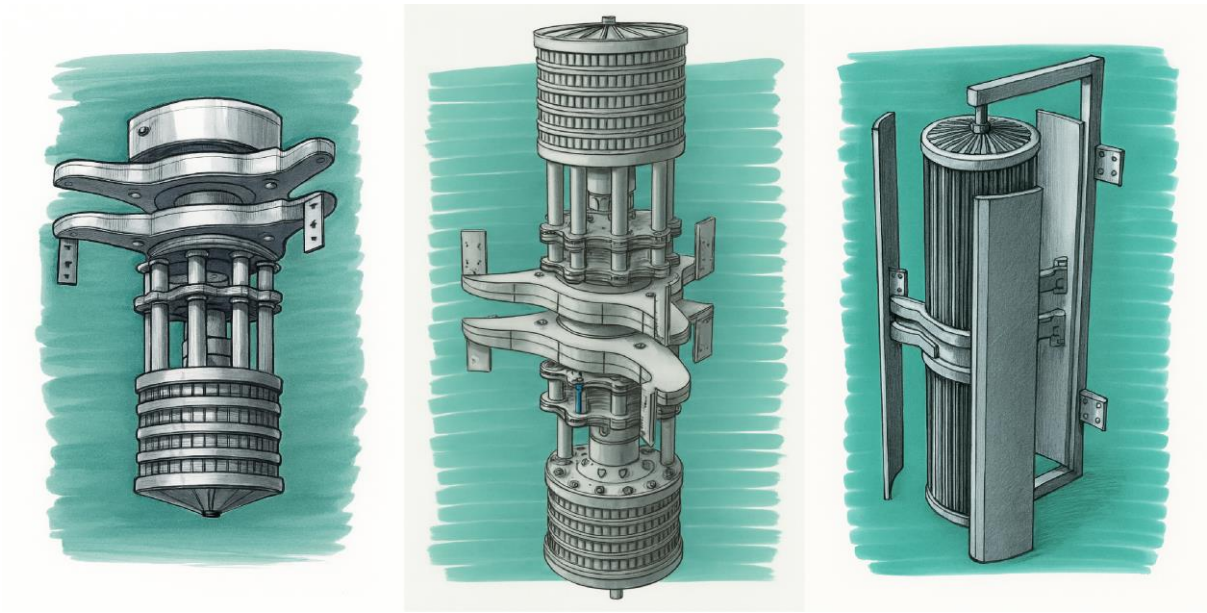


Figure 4.6: Concept sketch of the inner working of the wind turbine and final concept (Author's own, 2025).

4.3 Key Design Components and Technical Justification

Once I have defined the technical design of each subsystem, I then assessed the theoretical performance of the integrated system. Such an assessment included power output, storage, and scaling simulations as baseline considerations. The section moves out of the general process to the more specific design, through CAD work and research, to explain all in detail.

4.4 Generator System

The generator in the turbine is a two-axial-flux permanent magnet generator. I started sketching a concept idea, keeping in mind the industrial design principle of form follows function, as can be seen in Figures 4.7 and 4.8. It was developed to be highly efficient with low speed and high torque, which goes with the wind profile of Cape Town urban regions. This generator has four stators; each stator accommodates fourteen windings, each having 100 turns using 0.6mm copper wire windings in a delta system. It has an approximate electromechanical efficiency of 80%.

The design is stable at the ideal speed of 80 RPM and corresponds to the amount of wind data used in Chapter 2 (Figures 3 and 4) as well as the CAD models in this dissertation.

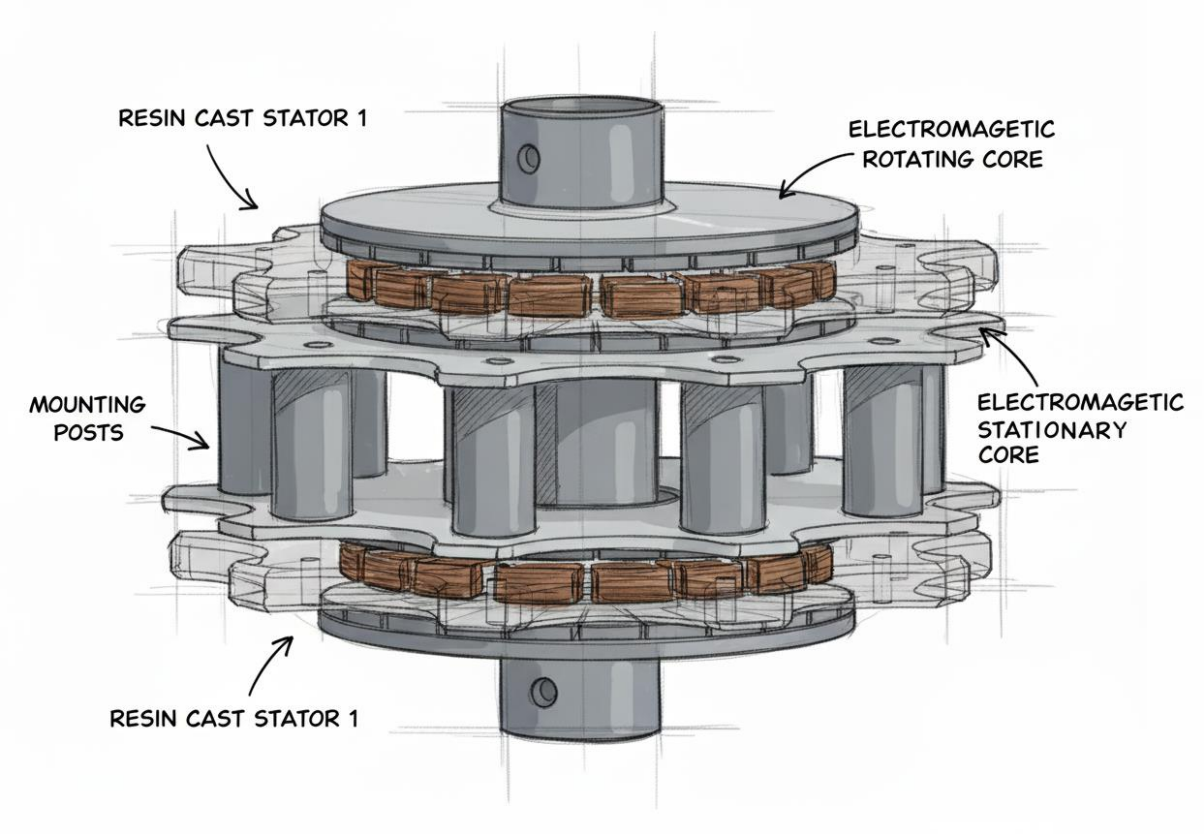


Figure 4.7: Concept sketch of two-axial-flux permanent magnet generator (Author's own, 2025).

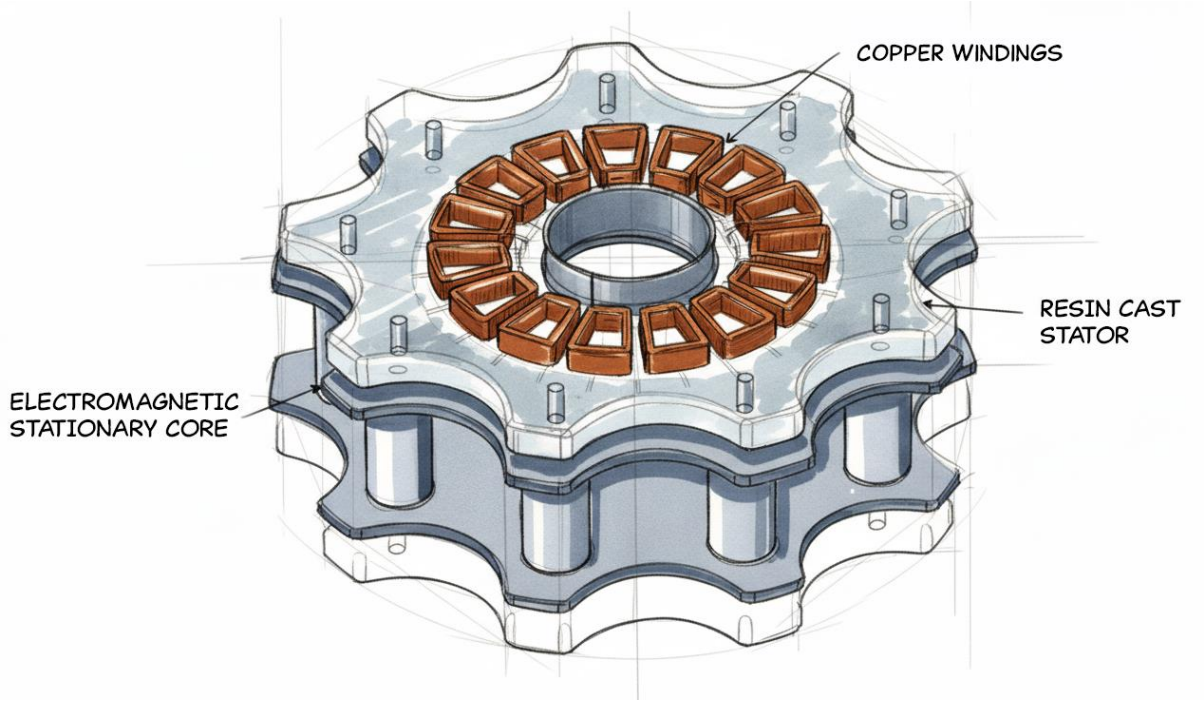


Figure 4.8: Concept sketch of stator (Author's own, 2025).

4.5 Levitating Bearing System

Figure 4.9 shows the concept sketch of the levitating bearing system. To give you a better understanding, I have included a sectioned view (Figure 4.10) that illustrates the placement and shape of the magnetic bearing system with N52 neodymium magnets inside its casing. This image also shows the gap of 10mm to ensure the control of vibration. This frictionless design requires no lubricants, and wear is minimised due to the opposing magnetic poles of the magnets. The system works quietly, and this is a very important feature that is required in residential applications. The Delphi feedback showed that there may be some balance between cost and performance in hybrid bearing options, which may help make the final selection.

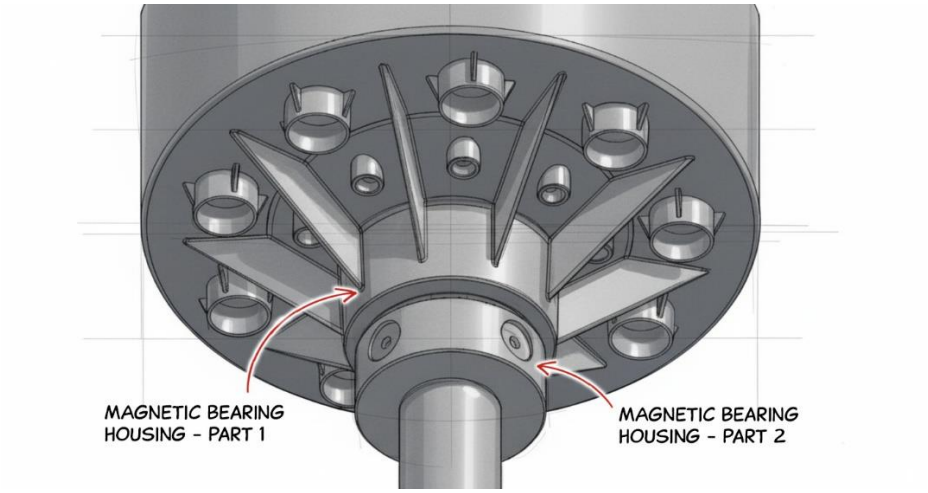


Figure 4.9: Concept sketch of Levitating Bearing System (Author's own, 2025).

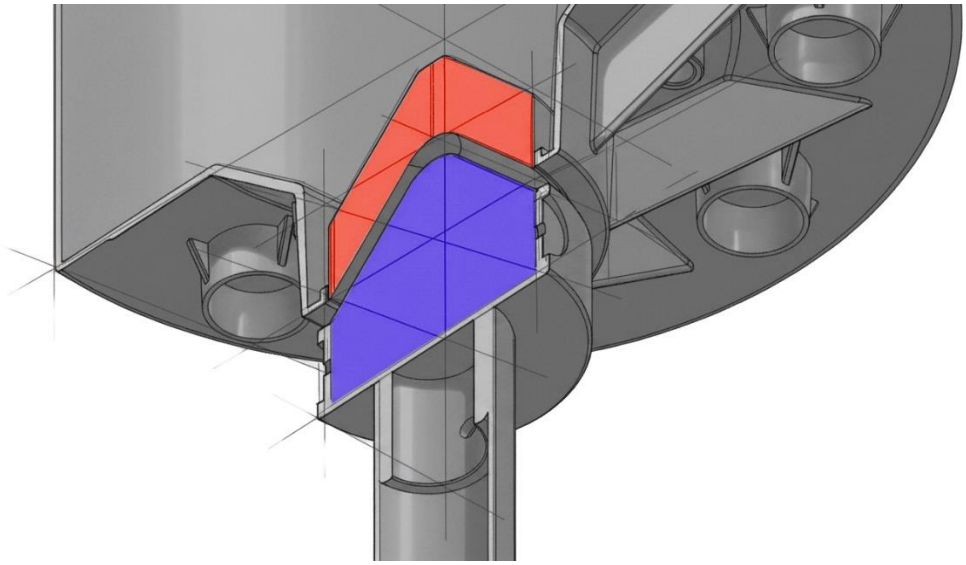


Figure 4.10: Concept sketch of Levitating Bearing System Sectioned view (Author's own, 2025).

4.6 Blade Design

The turbine features a three-bladed Savonius drag design (Figure 4.11). It can be initiated naturally, and it works well in turbulent city wind. The height of the blades is 2.38 m, and they are 1 m in diameter, occupying a total area of 2.38 m²2. The symmetrical airfoil, as can be seen in Figure 4.12, will reduce turbulence, noise and provide technical and aesthetic requirements in the city.



Figure 4.11: Concept sketch of the Blade Design (Author's own, 2025).

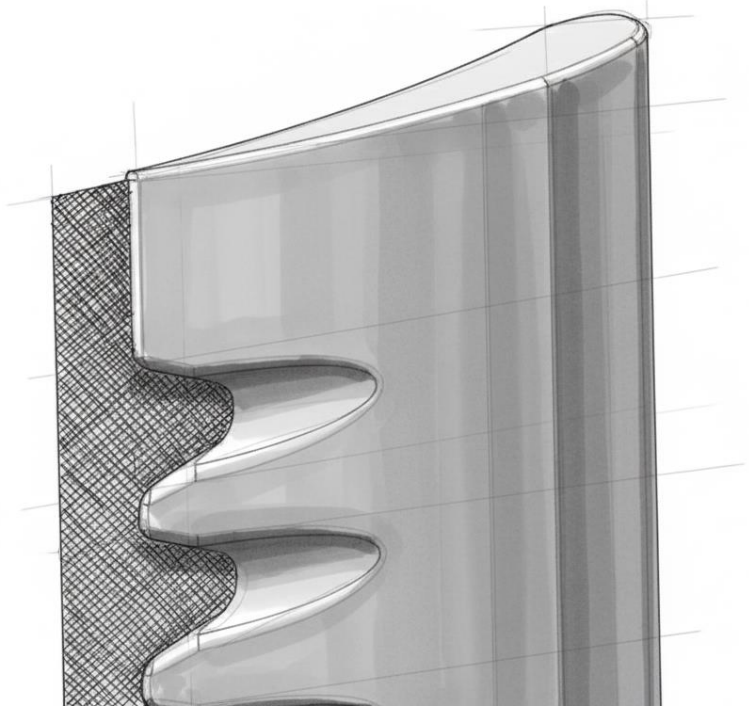


Figure 4.12: Concept sketch of the Blade Design – Close Up (Author's own, 2025).

4.7 Energy Storage and Management

To reduce the intermittency of the wind energy, the system includes 2240 x Panasonic 26650 Li-ion (NMC/NCA Chemistry) cells at 5000 mAh and 3.7 V, as can be seen in Figure 4.15. This provides a total energy storage capacity of 41.44 kWh for the vertical-axis wind turbines. A Dual Battery Management System (BMS), the red part in Figures 4.13 and 4.14, offers safety and efficiency, and power delivery is achieved with three directly connected external Victron Quattro 48/15000 inverters with a three-phase configuration totalling 45kW. This is a hybrid system that needs a step-up transformer to be employed to achieve 11kV from a standard 230V supply. For compliance purposes, a National Rationalised Specification (NRS 097) relay is needed. For approval, a separate protection device is required to ensure the system is compliant with the national grid's safety rules. The expert review indicated the non-correlation between the shift output and the inverter capacity, leading to a recommendation of a smaller inverter to optimise cost-performance.

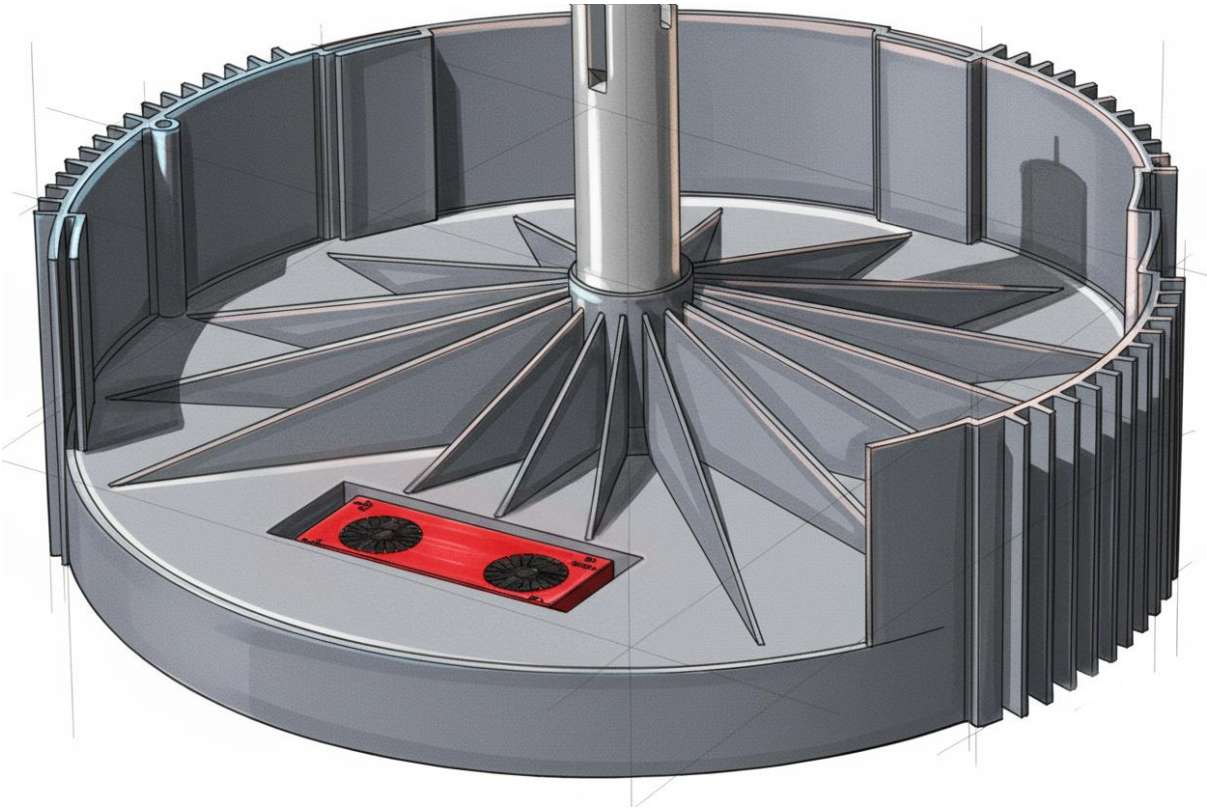


Figure 4.13: Concept sketch of Battery Management System (Author's own, 2025).

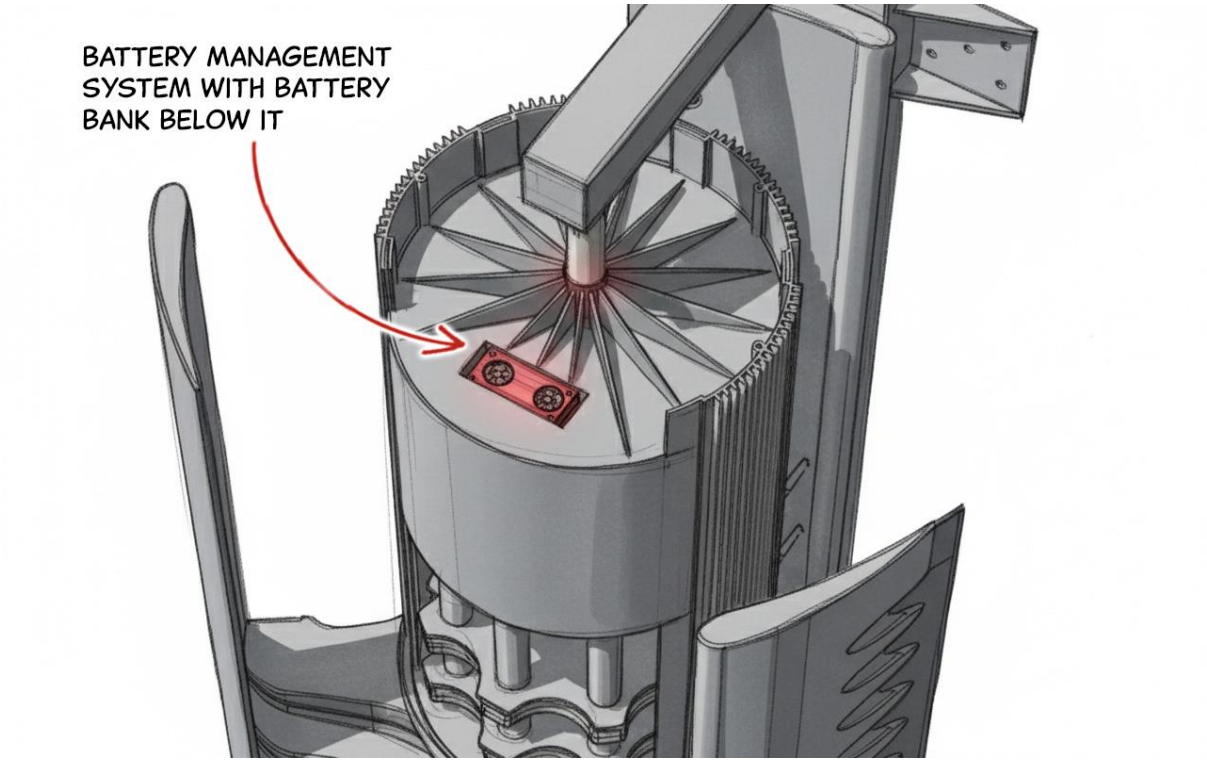


Figure 4.14: Concept sketch of Battery Management System and Battery Bank (Author's own, 2025).

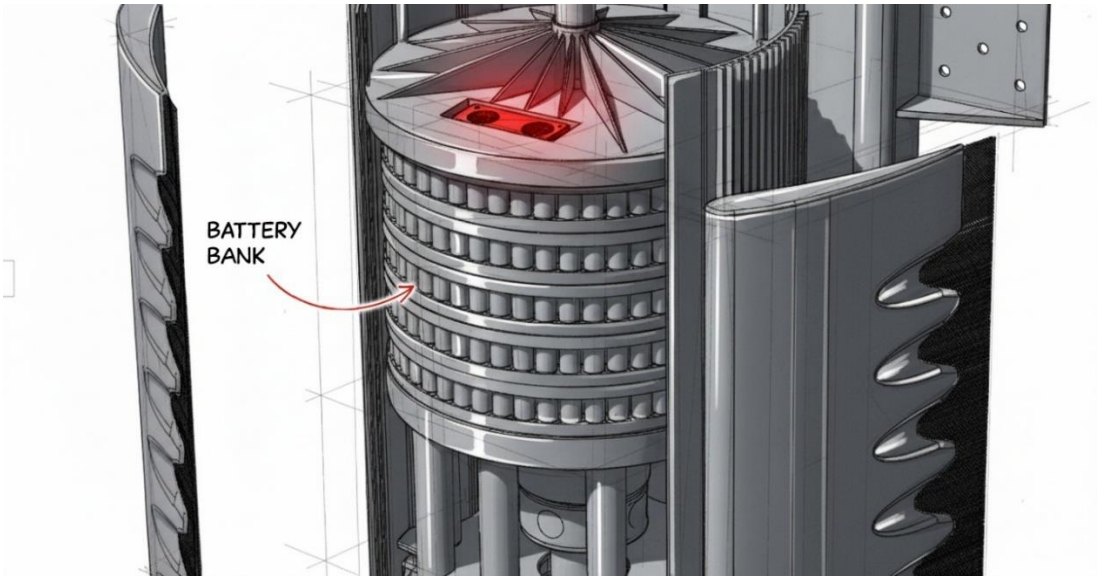


Figure 4.15: Concept sketch focussing on the Battery Bank (Author's own, 2025).

4.8 The Mounting Bracket

The mounting bracket in Figure 4.16 has good structural integrity and resistance against corrosion because of galvanised steel brackets. The modular bracket design is versatile, and it can be mounted on top and on the side of various municipal and private structures all over the city. The system also complies with the SANS 10400 and the bylaws of the Cape Town municipal, which give the requirements that the deployment system should meet in a given urban area.

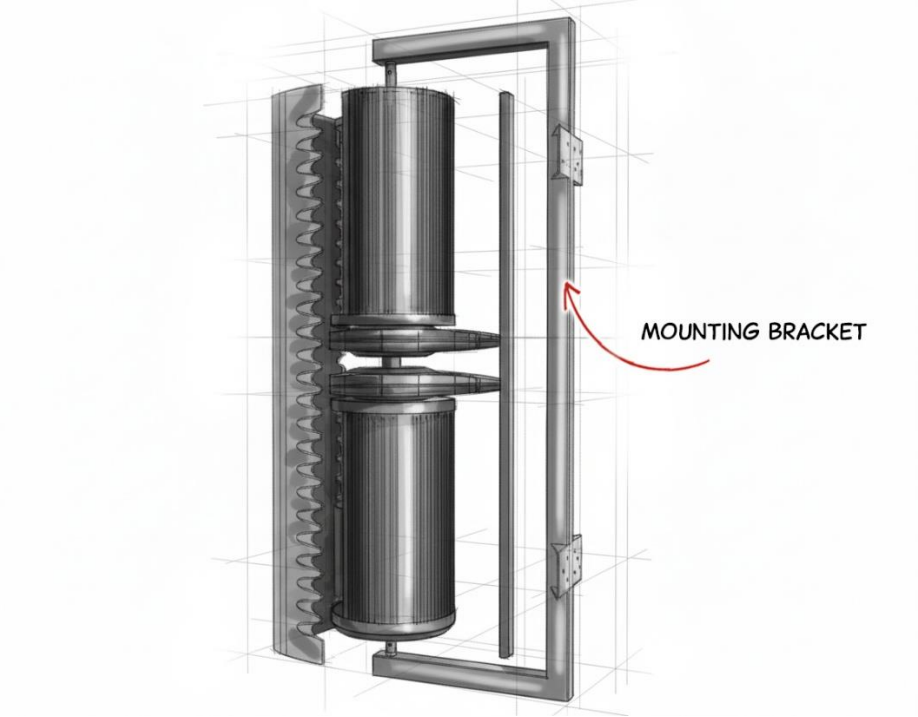


Figure 4.16: Concept sketch of the Mounting Bracket (Author's own, 2025).

4.9 Critical Evaluation of Blade Type Selection

Blade type selection is also a critical issue that needs to be critically evaluated.

4.9.1 Savonius Configuration Rationalisation Even with Efficiency Constraints

The Savonius drag-type rotor is an intentional design trade-off whereby urban compatibility is more important than power extraction. In Table 4.1, we critically consider that decision in relation to other options of Vertical-Axis Wind Turbine.

Table 4.1: Comparison Vertical-Axis Performance (Author's own, 2026).

Turbine Type	Power Coefficient	Self-Starting	Noise Level	Structural complexity
Savonius (drag)	0.15-0.25	Excellent	Low	Low
Darrieus (lift)	0.35-0.45	Poor	Moderate	High

Hybrid Savonius–Darrieus	0.25-0.35	Good	Moderate	Very High
Helical Darrieus	0.30-0.40	Fair	Low	Very High

The reason why Savonius was selected, even with a 40-60% efficiency reduction including the following reasons:

1. Self-Starting Capability

The urban wind of Cape Town differs between 2 and 20km/h. Darrieus turbines require external starting or a steady speed of wind of 5-6m/s. Savonius turbines start rotating at 2.1m/s which is necessary in intermittent urban wind.

2. Omnidirectional Operation

No yaw mechanism is required. The wind changes in the Cape Town city canyons is rapid (see Figure 4). Darrieus turbines become unproductive by 10-15 per cent when the wind is off-axis.

3. Low Noise Profile

Savonius tip-speed ratios (TSR 0.9 -1.0) are 3-4x smaller than Darrieus (TSR 3.0 -4.0) with less than 45 dB(A) versus 55-65 dB(A) of lift-type machines. This is vital in the case of residential sites.

4. Structural Simplicity

Drag blades receive compressive loads mainly. Lift type blades are expensive with composite lay-ups or airfoil extrusion complicated, increasing the cost of manufacture by 300-400 percent and making them hard to maintain.

5. Manufacturing Feasibility

Blades made of HDPE/PVC can be locally, either thermo-formed or rotationally molded in South Africa. Darrieus airfoils must either be CNC machined, or made up of composite, which the local capability cannot sustain.

Acknowledged Trade-offs

- **Energy Yield:** A Darrieus of the same size would yield 1.82.2 times the amount of annual energy (100165 kWh/year vs. 5575 kWh/year).
- **Economic Payback:** The reduced output results in an elongation of payback period, which is around 15 years to 25-30 years with a tariff of R1.50/kWh.
- **Scalability Issue:** To make any meaningful contribution to energy larger arrays are necessary.

The reasons why a hybrid design was not sought

More efficient (Cp 0.25 -0.35) hybrid Savonius-Darrieus designs, with drag cups and lift airfoils, have been demonstrated to maintain a reasonable self-start. However:

- They add complexity and fragility to the structure (Delphi Round 2 comments).
- The combination of drag compression and lift bending and torsion forces will require over-designed supports.
- Production expenses are close to 250 percent of an untouched Savonius design.
- The noise becomes unbearable to the residential areas.

Design Philosophy

This project focuses on deployment, community acceptance and technical strength rather than on the theoretical optimum efficiency. An actually constructed Savonius turbine that is reliable, obtains popular approval is more valuable than a higher efficiency model that is impossible to install, which is either too expensive, noisy or difficult to assemble.

Future versions may seek:

- Twisted Savonius blades (587 efficiency gain at less complexity).
- Deflector plate augmented designs (potential 1520% increase).
- Cape town specific wind profile optimised aspect ratio (height/diameter).

The present design is viable and can be enhanced over time instead of trying to obtain an optimal-but-undeployable solution.

4.10 Summary

The Define phase was effective in transforming the general research in Chapter 3 into specifications of a design:

Defined System Architecture:

- Blade Design: The turbine consists of a three-bladed Savonius rotor, which is 2.38m high and has a circumference of 1.0m, with biomimetic ribs set after manta-ray hull flow.
- Bearing System: N52 neodymium magnetic levitation with an air gap of 10mm - frictionless, low-maintenance bearing.
- Generator: Dual axial -flux permanent-magnet-generator, with 4 stators, each with 14 copper windings (100 turns of 0.6 mm of wire). Optimized for 80 RPM.
- Energy Storage: 2.4 -kWh battery bank 480 Panasonic 26650 cells 80S6P, dual BMS.
- Power Conversion: The capacity of the generator is 500 VA inverter.
- Mounting: The universal bracket system is used to support building facades, lamp posts, and roofs.

Design Decisions Identified:

1. Self-starting and low noise designed savagely, although Cp = 0.15-0.25.
2. High flux magnets used in a miniature generator are N52.
3. The size of the battery guarantees 1015 days of reserve at normal production.
4. The materials are suitable for the coastal climate of Cape Town: sea-resistant steel, HDPE, and ASA plastic.

Outcomes of Thematic Analysis: The plan was verified, yet it was noted by the experts that the plan requires:

- Heat control in the generator's whereabouts.
- Prefabricated building to reduce maintenance.
- Wind-load structural test SANS 10160.

These parameters give the basis of the iterative development of CAD discussed in Chapter 5.

Chapter 5 – Develop

In the Develop phase, the second divergent phase of the design process, the specifications defined in Chapter 4 are explored through iterative CAD modeling, simulation, and expert validation. I changed between abstract and representational thoughts, made elemental sketches, and scaffolded the ideas. Through having this divergent phase of thought, I reviewed numerous configurations of vertical-axis wind turbines, generator topologies, and energy-storage strategies. Initial ideas were motivated by the need to pursue both concurrent advantages in effectiveness in the urban wind patterns, generally turbulent and unpredictable, and in aesthetic assimilation.

I subsequently used SolidWorks as the main tool of digital prototyping, which was complemented by the creative techniques (SCAMPER, benefit mapping) and the second set of expert Delphi feedback. The arrangement of the chapter is based on the evolution of:

- SCAMPER and benefit mapping are all creative ideation tools.
- Primary CAD modelling and fit analysis.
- Material choice and penalty tests.
- Structural and load analysis preliminary.
- Blade design was developed after numerous models.
- Expert Delphi and thematic analysis.

This Develop phase, as compared to the earlier convergent Define phase, deliberately examines design variations, evaluates options, and polishes subsystem assembly. The aim is not the direct optimization but an extensive search in the space of design solutions.

At the end of this chapter, a validated CAD model emerges, which has been informed by stakeholder needs, expert technical guidance, and regulatory constraints. This model forms the foundation for the final Deliver phase (Chapter 6).

Considerations of importance at this stage were:

- **Exploration of Blade Geometry:** The exploratory ideas concerned peculiarities of the vertical-axis wind turbine designs. Savonius drag blades were shifted to priority, due to being the easiest to manufacture, and they are self-initiating in low turbulence conditions like those found in the urban environment. I made the most out of the cross-sectional and surface area drag to work with the required volume of material without compromising on structural integrity.
- **Generator Location and Type:** I then examined the top-mount and bottom-mount generator locations. Although direct drive is more optimal with a top-mounted system, an iterative evaluation (relying on accessibility and stability of the structure during

maintenance) preferred a base-mounted system. This resulted in minimised maintenance, a decreased centre of gravity, and stability on a facade or street pole. The choice eventually led to an axial-flux permanent-magnet generator due to the level of efficiency and size.

- **Energy Storage Integration Strategies:** I scrutinised and examined storage strategies based on modular battery banks located out of the turbine, or in its base, or next to the side of the turbine. Illustrations of the final solution for the battery bank can be seen in Figure 49. Developments focused on a more streamlined solution that minimises the amount of cable reels, both external and visual cable trunks, as well as improves the aesthetic quality of the critical energy storage elements and security.
- **Geometric Fit Analysis and Spatial Fit Analysis:** This meant paying close attention to the sizes of components, having enough clearance between the parts being assembled, and ensuring that the moving parts could move without touching each other, such as a blade turning freely in its container or a enough clearance between stages of the generator. It also presupposed an analysis of the visual balance and whole aesthetics of proportion of the surrounding urban landscape. Such a strict test was to make sure that the design was physically doable and, ergonomically, feasible.
- **Mass Properties Analysis:** With SolidWorks, I then checked the critical mass parameters of each part and the system of the vertical-axis wind turbine, with the centre of gravity and the moments of inertia. Such data were used in the initial design layout, static and dynamic stability, and in assisting in the determination of handling and installation requirements. In the case of urban installations, structural integrity, safety, and efficiency of logistics are non-negotiable; hence, the correct mass properties were of priority.
- **Interference Detection:** The software has highly advanced interference detection tools that regularly detect and prevent any form of possible conflict or undesirable contacts on parts. This digital screening helped to avoid design pitfalls that could affect manufacturability, operational efficiency, or integrity of the structure, hence maximising the manufacturability of the product.

5.1 SCAMPER Method

In Figure 5.1, I employed the SCAMPER method as a creative thinking tool to rationally examine design alternatives and modifications. The method facilitated ideation and the process of answering a set of structured questions on how to replace, blend, modify, adapt, put to another use, remove, and reverse/rearrange a design component.

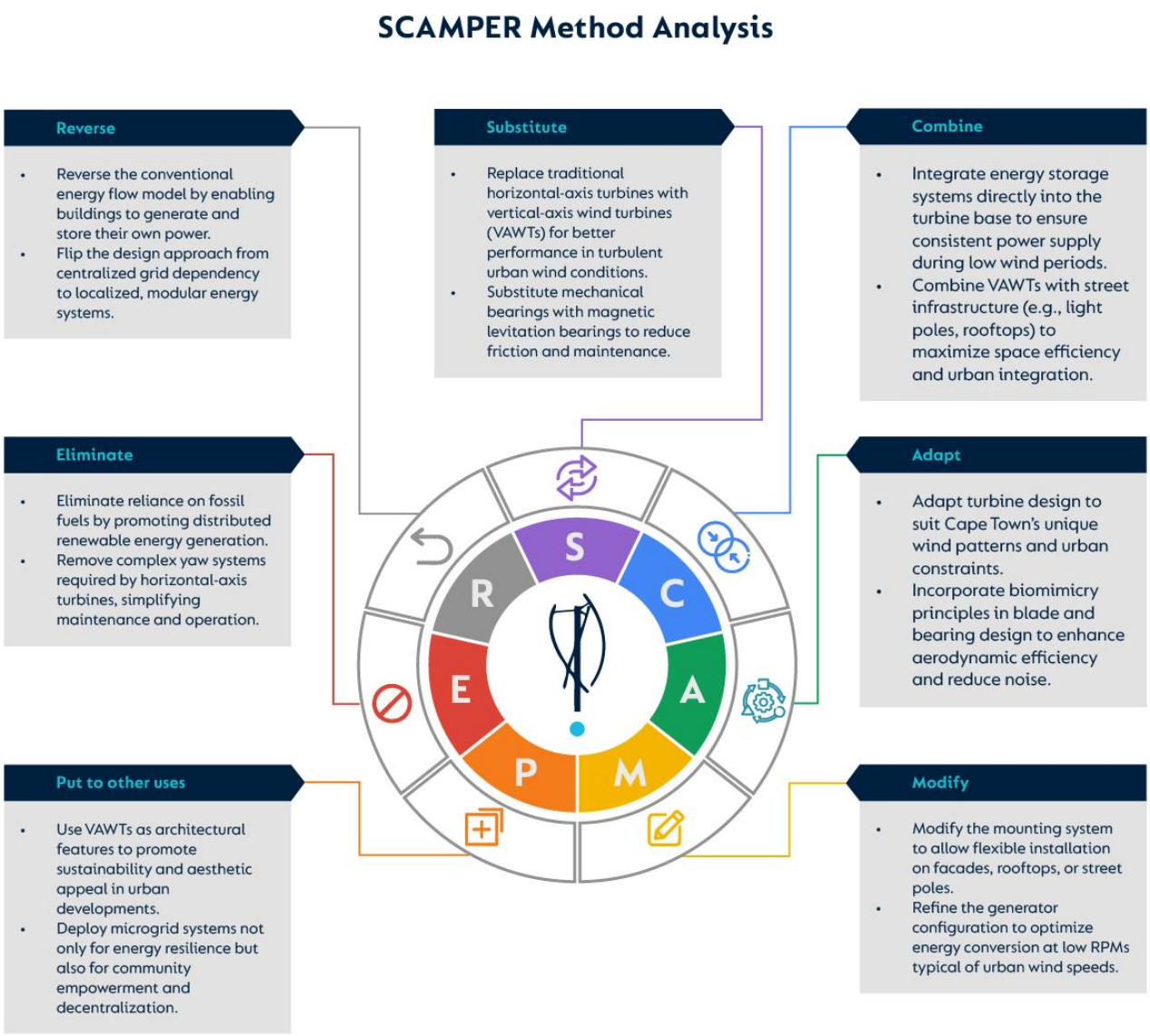
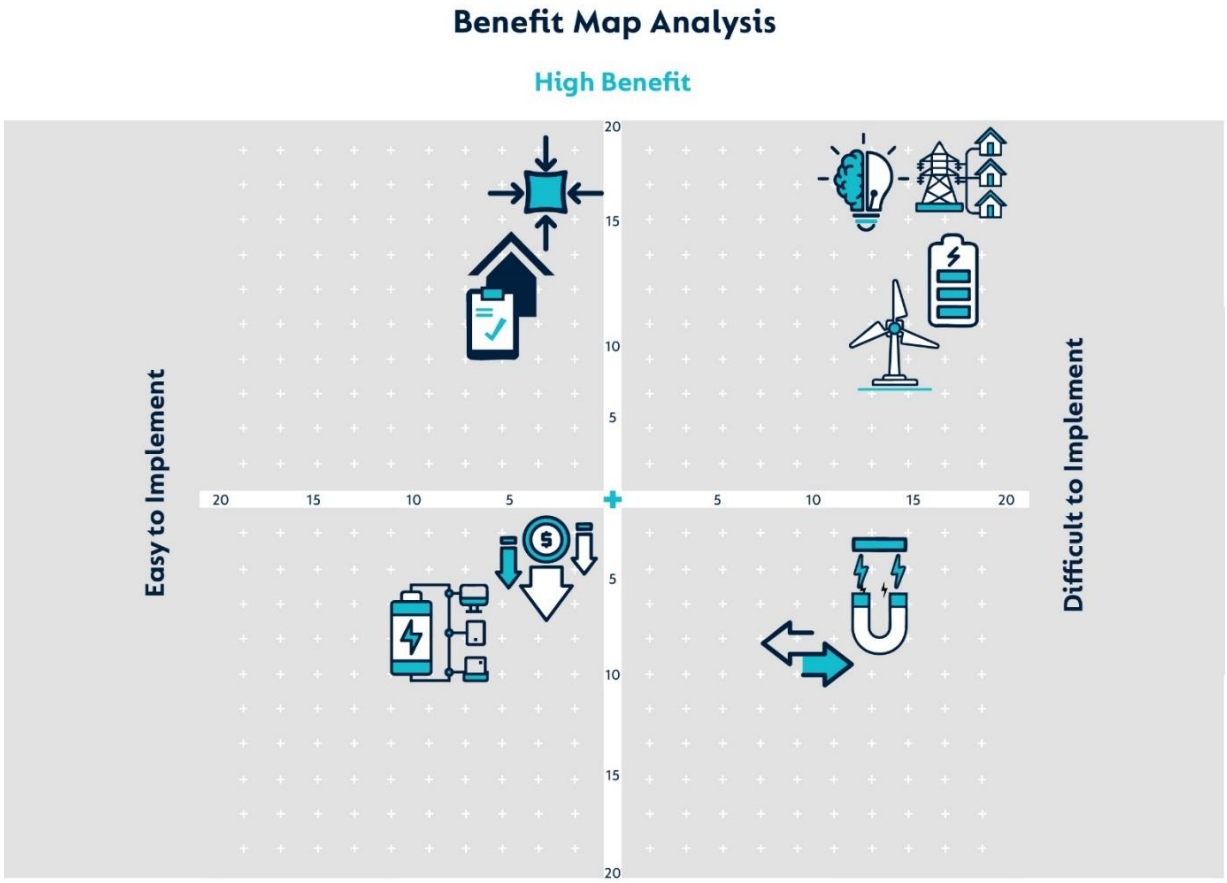


Figure 5.1: SCAMPER method for turbine design development (Author's own, 2024).

5.2 Benefit Mapping for Stakeholder Value Alignment

A Benefit map (Figure 5.2) was developed to make sure that the design solution would consider the needs of multiple stakeholders at the same time and ensure that the technical decisions made were aligned with user needs. This is a visual analysis tool that demonstrates the relationship between design elements, functional abilities, and stakeholder value in the technical, social, environmental, and economic aspects. The benefit map was an important assessment tool at the Develop stage, as it would enable the purposeful evaluation of the capacity of all design features to achieve the objectives of urban integration, energy resilience, and sustainability. It also provided an organised means towards ranking design features according to their general worth to various stakeholder groups, such as the residents, city

planners, providers of energy, and the maintenance staff. This mapping exercise directly informed the iterative refinement process and helped justify design trade-offs when expert feedback revealed competing priorities.



	Design Feature	Benefit	Stakeholders Impacted
	Vertical Axis Wind Turbine (VAWT)	Operates efficiently in turbulent urban wind; captures wind from any direction	Urban planners, Municipal energy departments, Residents
	Integrated Energy Storage System	Ensures consistent power supply during low wind periods; supports load-shifting	Households, Businesses, Grid operators
	Magnetic Levitation Bearings	Reduces friction and maintenance; increases turbine lifespan	Maintenance teams, Municipal budget planners
	Modular Microgrid Integration	Enables decentralized energy generation; improves energy resilience	Local government, Informal settlements, SMEs
	Compact Urban-Friendly Design	Fits on rooftops, street poles, and facades; low noise and visual impact	Architects, City planners, Residents
	Built-in Battery Management System (BMS)	Enhances safety and efficiency of energy storage	Electrical engineers, Safety regulators
	Dual Generator System	Increases energy capture and redundancy	Increases energy capture and redundancy
	SCAMPER-Inspired Innovation	Encourages adaptability, substitution of out-dated systems, and elimination of inefficiencies	Policy makers, Sustainability advocates
	Compliance with Cape Town Building Codes	Facilitates legal deployment and public acceptance	Municipal authorities, Developers
	Low Manufacturing and Maintenance Costs	Makes the system economically viable for municipalities and communities	Investors, Local manufacturers, NGOs

Figure 5.2: Benefit map analysis (Author's own, 2024).

5.3 Digital Prototype

The Prototype phase consisted of converting the conceptual ideas into a three-dimensional computer-based model using SolidWorks. Here, I virtually tested the concept in the form of prototyping the ideas, virtual testing the assembly, and determining the initial performance under real-world circumstances. Every design choice was evaluated against the design brief, the literature, and the expert participants' advice from the Delphi rounds.

5.4 Design Decisions and Analysis

The SolidWorks digital environment facilitated analysis of all the parts and, more importantly, the engineering of parts within the large system. Simulation of performance was carried out to determine energy production, efficiency, and structural integrity, as well as to compare the cost-effectiveness with current technological standards. Findings by Wijayanto et al. are used to support the analysis and address emerging issue threats, and which methods can help mitigate them (Wijayanto, 2020:8, 13). These are elaborated on below:

5.4.1 Material Selection

The choice of materials became one of the focus points and one of the choices. The team considered strength-to-weight ratio, long-term roles within the local coastal environment of Cape Town, such as corrosion resistance, UV damage, and salt spray, manufacturability, and cost-effectiveness to the local industry. This loop-based design method explored material selections with the understanding that it applies through qualitative simulation of performance, opinion of experts regarding environmental stressors, and life-cycle financial analyses. For instance:

- **Blades:** Since it will be a Savonius drag blade, the end material selection will give preference to high-rigidity components, high-impact-strength components, and simpler geometries that would be easy to manufacture. Probably, reinforced plastics, e.g., high-density polyethylene (HDPE) or PVC, or lightweight alluminium alloys. This multi-level sieving of materials indicates a high demand on the performance of structures in turbulent urban winds, and a simple cost and production process of materials contrasts with the thin-layered helical-blade composite processes, which are complicated.
- **Supports and Mounting Bracket:** The important structural components and MPH multipurpose mounting bracket were designed sequentially with high-strength, non-corrosive steel alloys (hot-dip galvanised structural steel or marine-grade stainless steel). They were designed due to the rigorous initial load analysis, which was sustained as per SANS 10160 about wind loads, the necessity to withstand high

dynamic wind loads, long-term integrity under a corrosive sea condition, and a strict interpretation of structural engineering principles (SANS 10400-B).

- **Generator Housing:** Thermal management, weight reduction, and environmental resilience were repeatedly checked, and from this it is determined that lightweight materials of alloys of aluminium, like high-performance engineered polymers, are chosen. These materials are good for the heat dissipation of electrical components, low mounting weight in the urban environment, and offer ingress resistance to dust and moisture.

5.4.2 Compliance with Cape Town Building Regulations and Codes

The compliance factors included the overall size, the components chosen, and the overall implementation of the vertical-axis wind turbine system, environmental and legal considerations pertaining to Cape Town. Notably, the design development by means of iteration ensured that building regulations, municipal by-laws, and national standards available in the City of Cape Town were met. The significant alterations and learnings included:

5.4.3 National Building Regulations and Building Standards Act, 103 of 1977 (SANS 10400)

Part B: The Structural Design provides a solid load-bearing system for the whole turbine and mounting station. This plays an important role in resisting the high wind loads associated with Cape Town, as stated in SANS 10160 (structural design actions of buildings). The standards consider the wind pressure and vibration so that they are safely attached according to Part A (General Principles and Requirements) and Part D (Public Safety). As a result, the multi-purpose hanging suspension was optimised to ensure adherence and avoid falling and hurting people or not being fastened.

5.4.4 City of Cape Town Municipal Planning By-Law, 2015

The limited size of the turbine, low tonal noise signature, can be attributed to Savonius-based drag rotors and frictionless magnetic bearing developments, as well as the integrated aesthetics of the turbine, which were intentionally created to ensure that there was minimal adverse visual and environmental impact. This will help in easier planning, consent, and acceptance of the community. Iterations were of the form:

- **Height Restrictions:** Precisely manipulating the height of the overall turbine and its support structure to stay well within the stipulated height limits in different zoning areas (e.g., residential and mixed-use as well as industrial) in order not to affect scenic routes or obscure other properties.
    - **Setbacks:** Fear that the turbine design will have too few clearance distances with the property lines and that the turbine will be within too close a distance

to the neighbouring buildings and thus lead to nuisance or risk factors to the surrounding homes.

  - **Noise Emissions:** Design-related decisions like a sophisticated magnetic bearing and a low noise adjustable generator were made to ensure that the noise at operation would be within municipal limits, which is a major worry in urban areas, to counteract the natural drag-blade noise.
  - **Visual Impact:** Aesthetic decisions such as the subtle positioning of the energy storage and inverter at the base were inspired by the objective of integrating the turbine with the city, taking into consideration visual issues expressed by the initial studies of public perception.

- **Environmental Impact Assessment (EIA**): It is generally known that a micro-turbine is not large enough to initiate a full EIA, but the iterative design process identified that a smaller-scale analysis of the environmental situation or expert reports could be necessary. The design will mitigate the occurrence of bird strikes (which is already reduced by the vertical axis design), reduce the occurrence of shadow flicker (which is less common than in horizontal axis turbines), and respond to the continuous noise concerns of the National Environmental Management Act (NEMA) 107 of 1998. Responsible environmental stewardship was integrated in the early design phases, such that such impacts stay low.
- **Electrical Wiring and Safety Standards (SANS 10142-1):** The entire electrical system, comprising generator output, rectification, bank of batteries, BMS, and the 45kW inverter, was re-examined in relation to SANS 10142-1, the South African standard, specifying the direction of wiring of premises and associated safety standards. This guarantees safe operation, earthing, sufficient protection against over-current, security, isolation, and safe procedures of grid interconnection in case of any possible microgrid connection.

5.5 Preliminary Structural and Load Analysis

Though this conceptual design project was beyond the realm of a full-scale Computational Fluid Dynamics (CFD) or Finite-Element Analysis (FEA), the CAD simulation was used to test the proof of concept under a set average wind condition. A much more rigorous structural analysis is required to accurately test the custom vertical-axis wind turbine by way of a detailed CFD simulation over an extended period. Through this process, I got the preliminary quantitative analysis through the CFD Analysis simulation, as can be seen in Figure 5.3, which entailed a step-by-step method of changing the geometries, component sizes, and material thicknesses. This was done to test and maximise the mechanical loads on the main shaft, thereby maximising all loads distributed as best possible throughout the entire structural system.

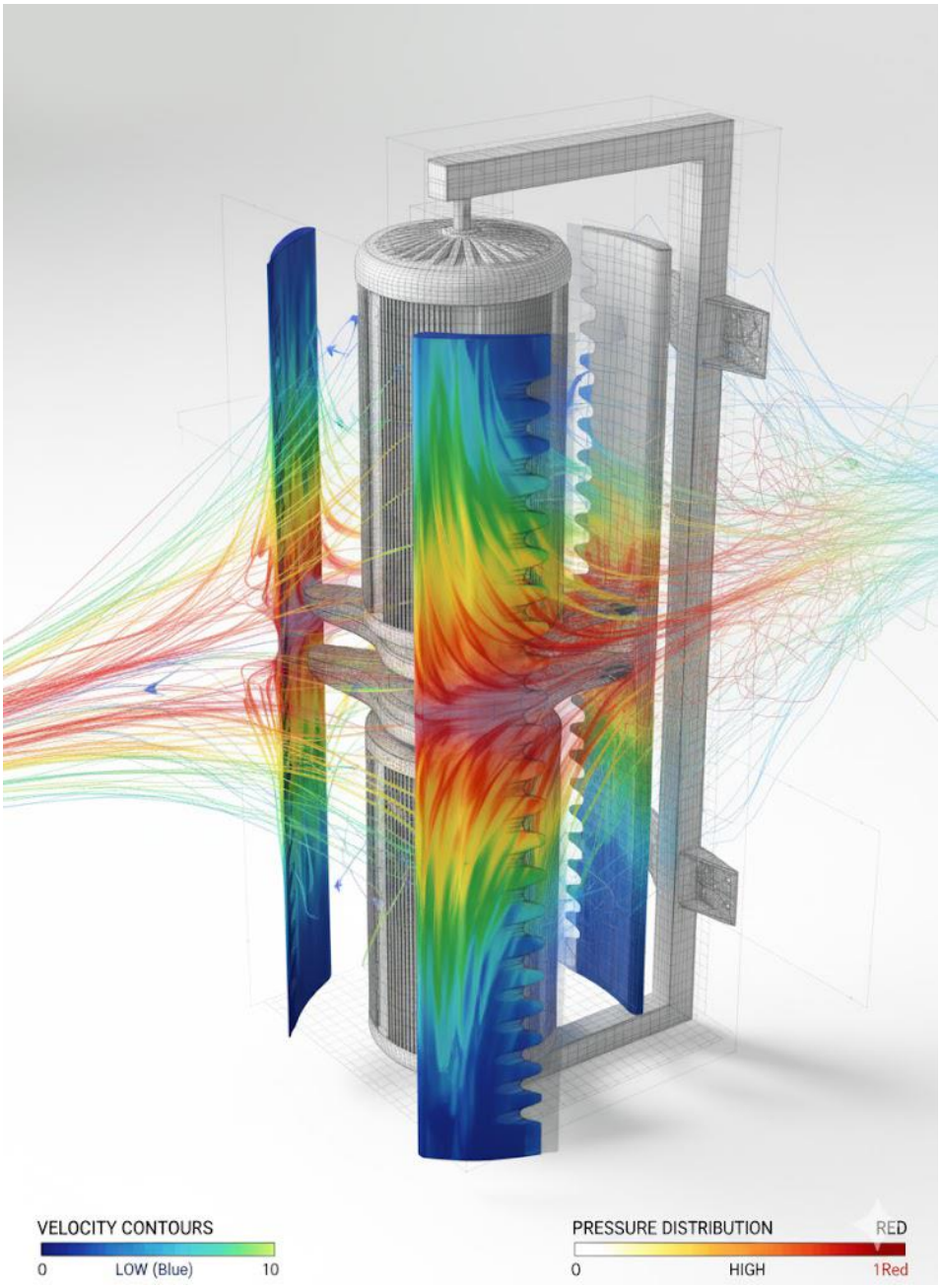


Figure 5.3: Computational Fluid Analysis (Author's own, 2025).

The importance of this is to fully assess the data under various climatic conditions, as illustrated by the windy patterns of Cape Town in Figures 2.1, 2.2, and 2.3. The blade upright supports and versatile mounting bracket were designed with due regard to the anticipated forces of wind pressure in dynamic loading, to gusts, and the turbulence that can be expected in view of the complex Cape Town urban wind regime, concerning the weight of the whole assembly under gravity loading (static loading). The newly developed inherent properties of the design include precise centre-of-gravity and interference-checking capabilities, as SolidWorks allowed me to check these elements of the proposed design:

- **Optimise Weight Distribution and Centre of Gravity:** The geometries and material distributions of the components were altered sequentially to maintain a low and central centre of gravity of the whole system. This was necessary to provide stability as well as avert overturning moments, such as in facade and lamppost mountings (where structural cantilevers may pose issues).
- **Identify and Mitigate Stress Points:** Through simple visual inspection of load paths and simplified stress indications in SolidWorks, I could determine the locations of potential high material concentration, or of high material thin sections that could lead to stress concentration when subjected to the theoretical load. Modifications were done to strike the right balance of material use and intended function. To gain better structural strength, supporting ribs were added in certain areas of the vertical-axis wind turbine and relieve structural stresses thereby distributing the force across wider areas.
- **Ensure Critical Clearances and Prevent Interference:** The cad model provided systematic methods of detecting and correcting any crossing or misalignment of parts or unintended contacts, the latter particularly in the cases of rotational motion. This thorough online examination served to prevent the pitfalls that normally result in serious flaws in design that could cause serious manufacturing issues, unproductive activity, or catastrophic structural failures on an actual prototype.
- **General Power output:** I reviewed existing engineering principles (e.g., the Betz law (Marnett, Roidl, Schröder, and Thönnißen, 2016:1) and the lift/drag coefficients of the selected air foils and predicted wind speed profiles in Cape Town to inform the designed blade geometry and compute the theoretical power output of the geometry. This gives background information on the energy produced by the proposed design.
- **Preliminary Load Estimates:** Estimated the anticipated loads of the components, aerodynamic (blade loading because of wind pressure), gravitational (structural loading of all elements), and conceptual dynamic loads (loads caused by rotation, turbulent winds). Such approximations determine the first material choice (e.g., steel alloy in structural components or composites in blades) and component sizes, resulting in a design that balances projected theoretical efficiency and projected durability in the projected urban environment.

5.6 Mounting Brackets

In an early iteration of the wind turbine blade, I explored a mounting bracket system (Figure 5.4) that was both flexible and strong to allow its usage in urban locations and installation without much work. The bracket was iteratively developed. I was attentive to fitting the custom vertical-axis wind turbine into the various fixed infrastructure of the city of Cape Town. The

weight distribution was key, and special emphasis was given to spreading out the loading weight in the right places. The result of this design process was to come up with a flexible bracket that can be easily and securely mounted to the facade of a building, a streetlamp post, or the top of a building. The design concentrates on effective load transfer that can be installed with the least amount of visual impact to the urban environment, and alignment with the structural constraints of typical urban infrastructure, which considers major logistical and regulatory challenges.

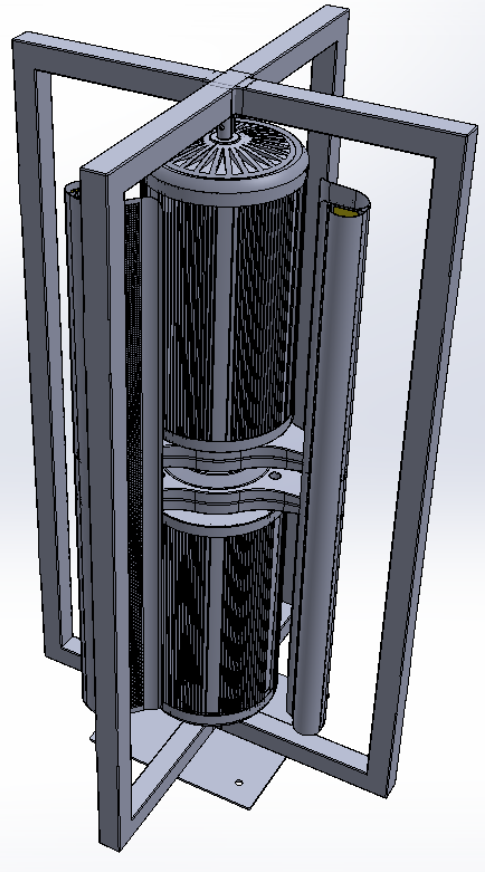


Figure 5.4: Early iteration of the Mounting Bracket (Author's own, 2025).

5.7 Blade Design Evolution

The fundamental criteria for successful energy capture are the airfoil-shaped blades in a vertical-axis turbine. This was achieved through the exploration of numerous iterative systematic rounds of design. I surveyed a series of designs and tried different vertical-axis wind turbine blade solutions. I then settled on Savonius drag blades and did a CAD model of the design, as can be seen in Figures 5.5 and 5.6. They are self-starting even under extremely low wind speeds, are simple to construct, and are stable in the unpredictable gusty winds of Urban settings.

The intersection of the blades was refined, and shapes like semicylindrical or concave-shaped were used. This is the most useful design that has a maximum effective surface area of differential drag and has a low-weight blade ratio, which is a strong structure.

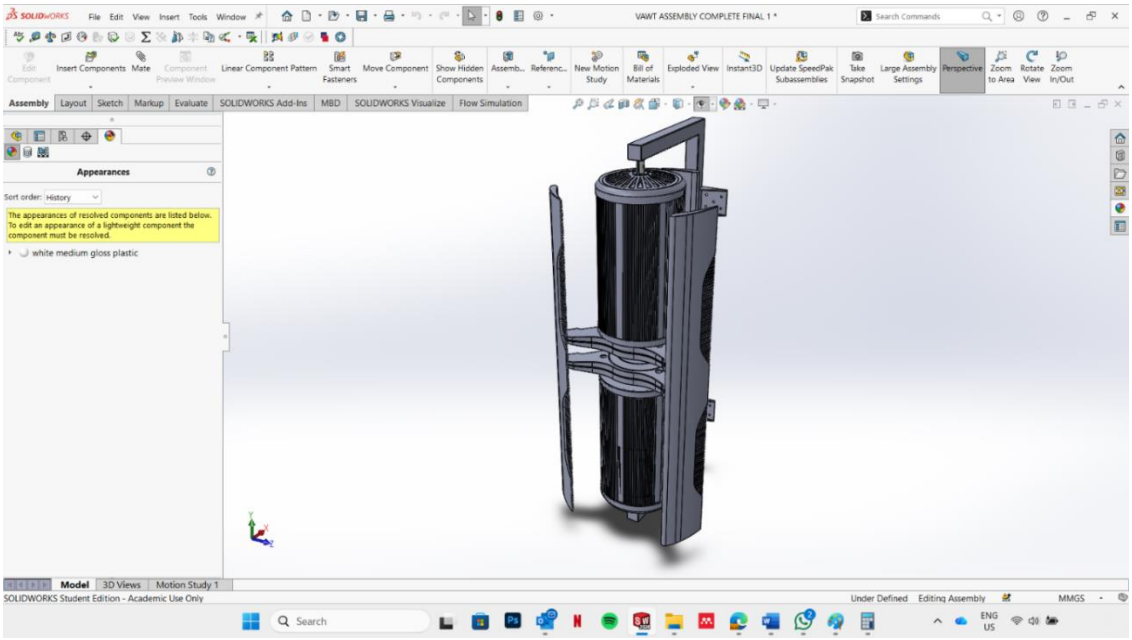


Figure 5.5: Blade design with silicone strand feathers (Author's own, 2025).

As evidenced by the CAD visualisation, the principles of biomimicry have been effectively converted to work as a functional, engineering-grade structure. It is evident with the three-blade rotor design with a streamlined Manta Ray profile that is parametrically extruded and mirrored. The fittings are rigidity-engineered with reduced wind disruption. The blades of this biomimetic design are the first blades to experience wind in the urban setting, and it is this point of view that validates the scalability and connectivity of the design with the surrounding energy-storage module.

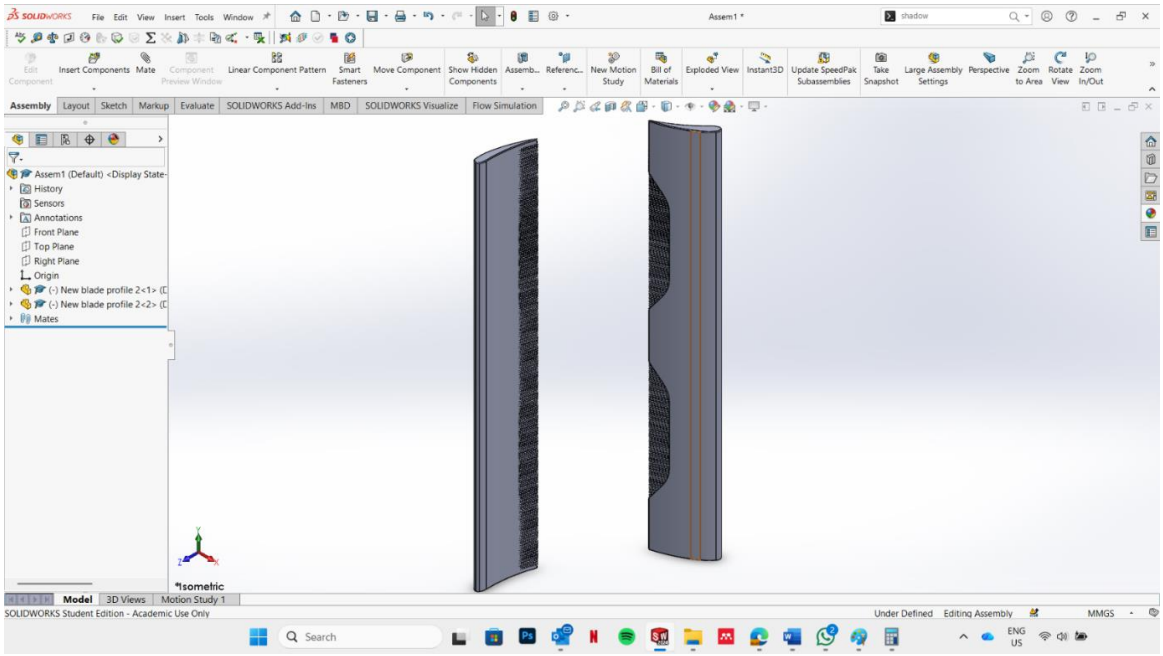


Figure 5.6: Initial Blade design with silicone feather strands, front and back (Author's own, 2025).

For illustrative purposes, I have included a screenshot of my SolidWorks model (Figure 5.7) to illustrate what the turbine blade looks like on the custom vertical-axis wind turbine.

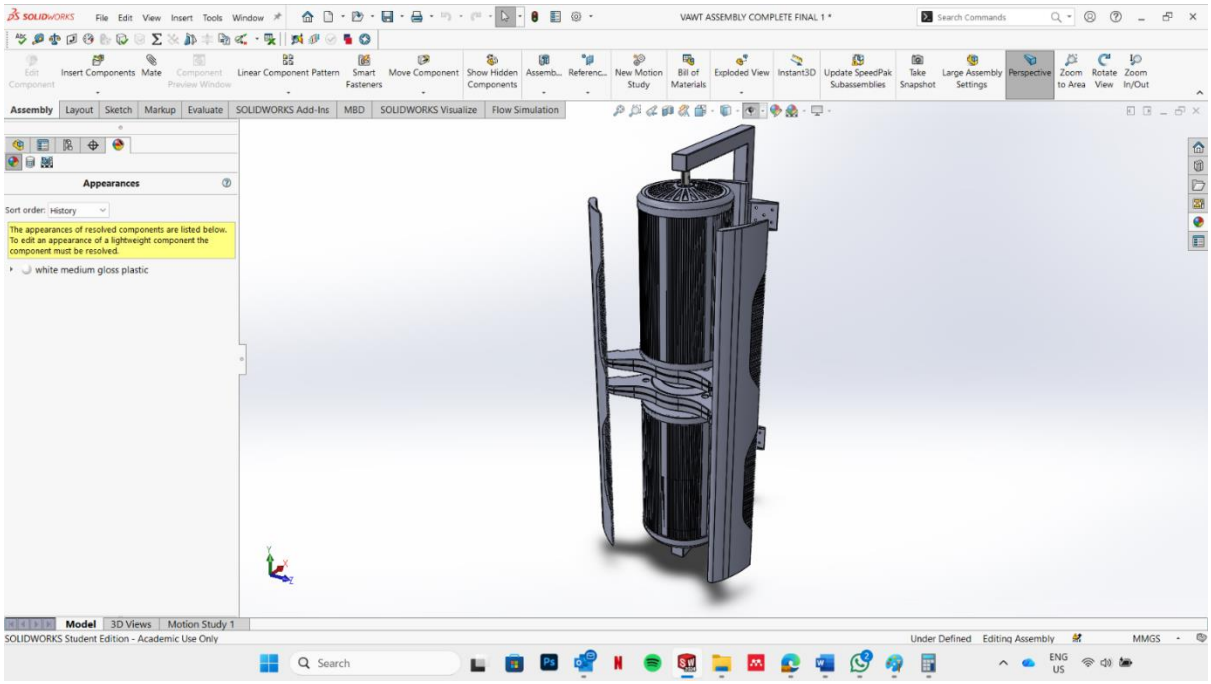


Figure 5.7: Blade design with silicone strand feathers (Author's own, 2025).

In the next iteration, I decided to investigate a modular solution where the blades are split into two sections (Figure 5.8). This configuration was found to create turbulent air flow since both sets of blades move simultaneously, which affects the quality of the energy generated.



Figure 5.8: SolidWorks CAD model of Savonius drag blades conceptualization (Author's own, 2025).

5.8 Performance Analysis and Contextual Relevance

During design development, power generation capacity and energy storage capacity were investigated. This analysis was used to verify the design decisions made, to determine the areas of possible bottlenecks in the performance or mismatches of the components, and to provide a realistic understanding of the performance that the system is expected to give in the city environment. This analysis was cyclical.

An in-depth review of the performance estimation and system sizing gave important considerations that the theoretical power generation and storage capabilities, and areas in which rationalisation is necessary, particularly in the scaling of power electronics.

In this design project, I have considered manufacturability, thorough pre-construction screening of the structural integrity, and alignment with the Cape Town building standards and compliance codes.

The developed design, illustrated and modeled in SolidWorks, offers a concrete and well-informed approach to changing urban energy supply by means of a segmented micro-/macro grid system. This design was achieved not only through the incorporation of the needs of the stakeholders, professionalism, and the unique contextual factors of Cape Town.

5.9 Expert Feedback and Refinement (Delphi Round 2)

I conducted a second Delphi round (to engage with the expert participants to evaluate my initial CAD design. The focus was on the blade geometry of the vertical-axis wind turbine as

well as the generator specifications, energy storage integration, and its structural components. The expert participant feedback guided the iterative refinement of the CAD model as detailed in Chapter 6 of this report.

5.10 Consensus & Prioritization Analysis

The findings obtained in the two assessments of the expert Delphi questionnaires were processed to obtain the areas of agreement, quantify the disagreement, and rank the design standards. This review played a vital role in ensuring that the design proposals made have been corrected and refined as the experts consider them appropriate.

- **Quantitative Metrics for Consensus and Divergence:** The questionnaires relied on Likert scales (e.g., a 1 to 5 scale rating the importance of a certain question), and tasks were ranked to be subject to rigorous application of descriptive statistics. The median scores were adopted as the primary measure of central tendency in terms of expert opinion due to their less sensitivity to outliers and the ability to give a clear picture of a group opinion in ordinal data compared with mean-based statistics. These measures were carefully compared across two Delphi rounds and followed a practice-led iterative process to determine where consensus and differences were emerging.
- **Qualitative Content Analysis for Nuanced Insights:** Besides numerical data, unstructured responses, reasons, and explanations of professionals at Delphi rounds were analysed using a directed content analysis. The ensuing qualitative data were amalgamated to give the fundamental reasons behind the quantitative scores that would be invaluable in terms of insight that guides design improvements.

5.11 Summary of Round Two Feedback

Claude.ai was utilised to synthesise the information from the first round of feedback, and each of the participants was able to look through the first results and offer additional comments, explanations, and perspectives. By doing this repeatedly, they were able to agree on the primary areas of design. Round Two of the Thematic Analysis provided consensus with respect to the number of key aspects in the context of the turbine design. Symmetrical airfoils were particularly popular as the design captures wind from every direction and is easy to build. The permanent magnet generator was still supported due to its low RPM efficiency, yet respondents stated that operating a variable output requires powerful power electronics.

The design of the thermal management and casing was still widely discussed. Engineers stressed that protection, manufacturability, and serviceability should be taken into consideration. Magnetic bearing systems were once more observed to be efficient, although alignment accuracy and radial load balance were observed to be more obvious concerns, and electromagnetic interference. The choice of material was debatable, particularly the cost-

performance of N55 neodymium magnets and Litz wire. The participants proposed alternative grades and the significance of scalable and standardised components. Themes of lifecycle strategy were further elaborated and gave deep recommendations, including aspects like modular access, predictive maintenance, and digital service documentation.

More was added to scalability and manufacturability. Although the modularity of the current design was verified, participants acknowledged that a redesign of the structural design would be necessary when it is implemented on a large scale, possibly through a full tower design or stackable module design. The major challenges regarding mass production were found to be problems in multi-material assembly and special parts, which enhanced the necessity of simplification and standardisation.

The Delphi round-two results have been condensed into thematic maps, which constitute the final design recommendations made in this report.

5.12 Thematic Analysis Two

The second thematic analysis followed the same method as was presented in Section 4.1. The qualitative coding scheme obtained in the second round of Delphi is presented here in Figures 5.9 and 5.10.

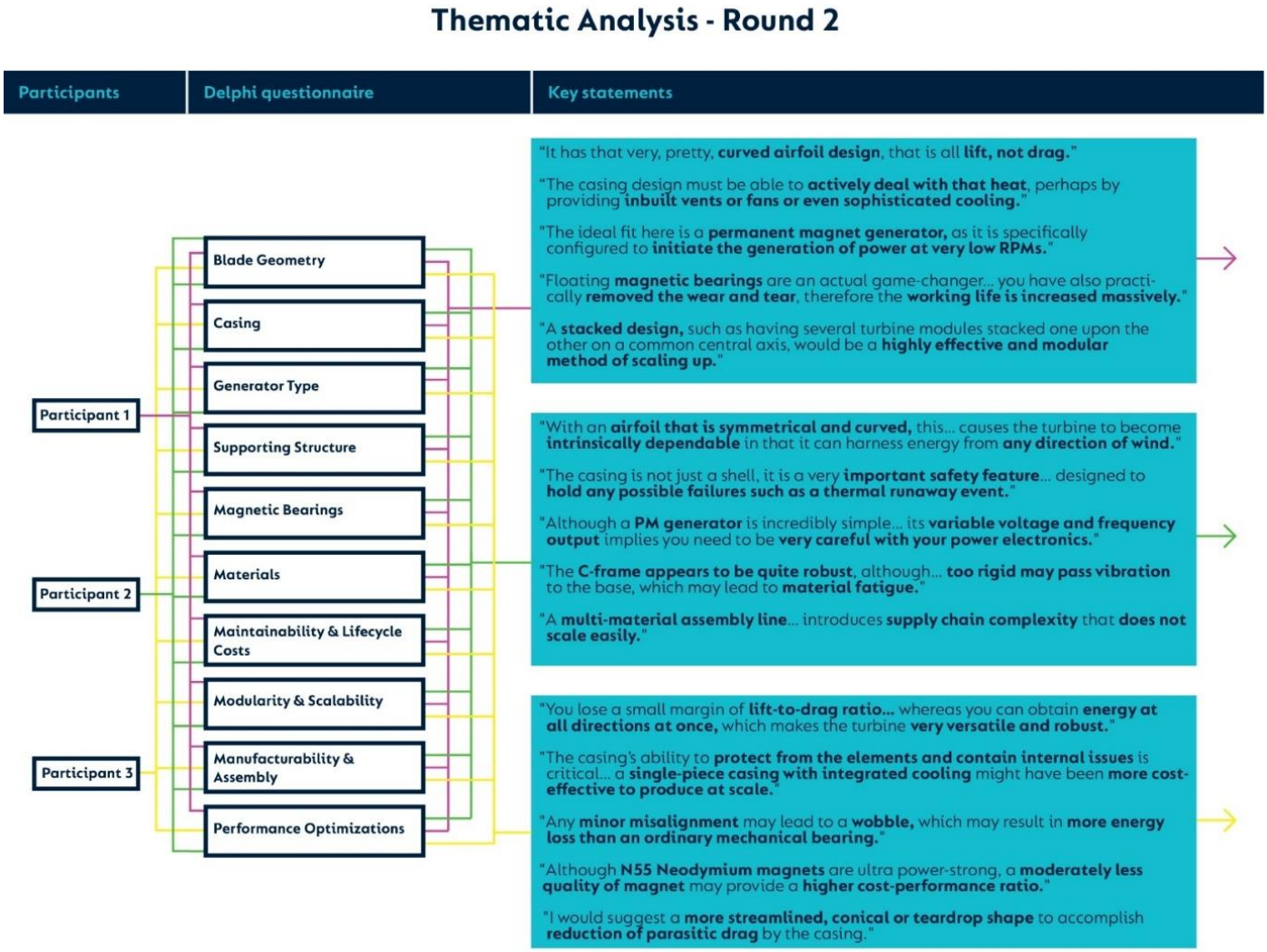


Figure 5.9: Thematic analysis of Delphi round 2 responses 1 (Author's own, 2025).

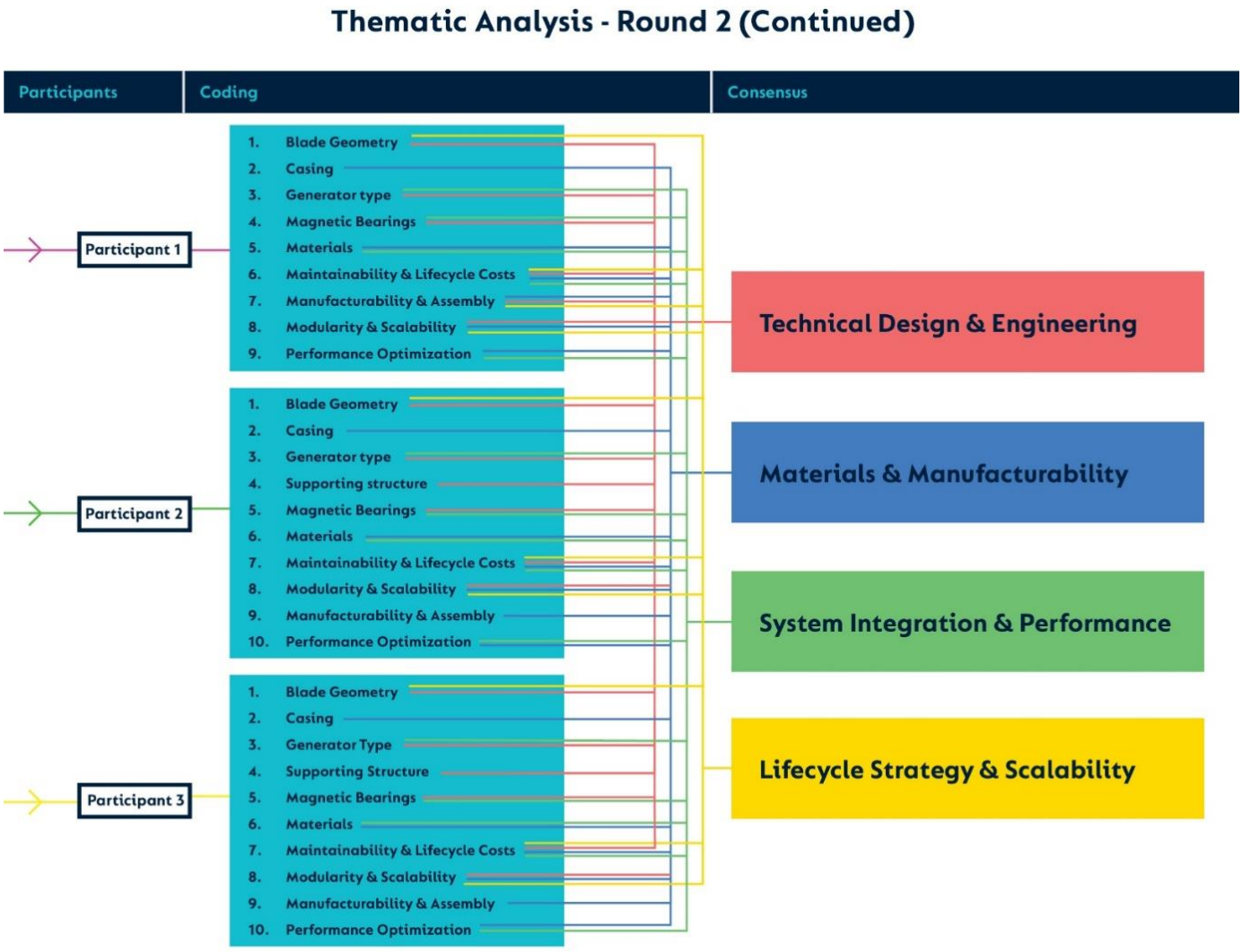


Figure 5.10: Thematic analysis of Delphi round 2 responses 2 (Author's own, 2025).

It was noted that the similarities between the Delphi rounds indicated the progressive refinement of the experts' opinions. Consistency of opinion indicates that the design is feasible, and recommendations regarding future design research.

5.13 Comparative Insights

The second round of the Delphi showed the improvement and established the agreement between professionals. It further supports the significant themes in the first round. The principles of symmetrical air foils, permanent-magnet generators, and the modular design were established. Also, Round Two provided more comprehensive suggestions, such as the ways of thermal control, magnetic-bearing alignment, and manufacturability.

Some recommendations were in detail, including the use of hybrid bearing systems and standardised fasteners, which were made by experts. This demonstrates that the second round specialised and broadened the original parameters and shifted broader concepts to specific suggestions and furthered the consensus formation.

5.14 Summary

The Development phase saw the design shift beyond what was defined in Chapter 4 into a developed, tested CAD model via discovery.

5.14.1 Key Development Activities

1. Creative Approaches - SCAMPER analysis generated 15+ design variants, and benefit mapping matched technical design features and the stakeholder value.
2. CAD Modeling SolidWorks facilitated the possibility of mass-property analysis, interference detection, and initial load assessment.
3. Material Refinement-Final materials were selected: SAE 316 stainless steel, 6061 aluminum, and HDPE, which was selected due to its ability to resist corrosion and the local manufacturability.
4. Regulatory Alignment - Compliance was checked by the SANS10400 -B (structural design), SANS10160 (wind loads), and Cape Town Municipal Planning By-Law.
5. Blade Evolution - The blade design **was** developed using the biomimetic Manta ray profiles, into **Savonius** variants, to the ultimate **three-blade** drag design.
6. System Sizing Correction - It has also been determined that battery capacity was decreased by 41.44kWh to 2.4kWh and **the** inverter **was** reduced by 45kW to 500VA depending on the real power calculations.

5.14.2 Delphi Round 2: Expert Validation

- Symmetrical airfoil strategy affirmed on the multidirectional wind capture.
- Low-RPM efficiency design permanently magnetized generator.
- Future refinement areas **have been** identified **for better** thermal management and electromagnetic interference.
- **A s**calable and **more** maintainable design **configuration**.

5.14.3 Critical Design Insights

- One turbine produces 55-75^{n}kWh/ year (.15- 0.21kWh/ day average).
- It is not a complete-house system, but rather **a** supplementary micro-generation.
- A significant contribution to energy can only be made with the deployment of an array of 10-50 units.
- The architecture focuses on deployability and not on the theoretical maximum efficiency.

Design is developed, and now it is prepared **for** final specifications and documentation of deliveries (Chapter 6).

Chapter 6 - Deliver

This chapter is the last convergent stage of the Double Diamond process. It is concerned with finishing, reporting, and certifying the design highlighted in Chapter 5. These measures will take care of the performance and regulatory requirements of the design. I present these advancements and innovations in an integrated overall design. The custom vertical-axis wind turbine is completely optimised. The performance analysis has been validated with the results of Cape Town's wind data, and the design has been improved accordingly to fit the urban installation requirements of the municipality.

The Deliver phase combines all of the previous research and development and creates a complete system specification, which is now ready to be prototyped and implemented.

The organization of the chapter is as follows:

- All design synthesis with end CAD renderings.
- Subsystem (blades, bearings, generator, storage, mounting) specifications.
- Production and assembly factors.
- Structural analysis and load analysis.
- Checking actual Cape Town wind data against performance.
- Records of regulatory compliance (SANS 10400, SANS 10160, municipal bylaws)
- Principles and implementation guidelines of urban integration.

This Deliver phase provides specifications as opposed to the previous chapters, which discussed possibilities. The design report presents a technically viable, regulation-conformant, and context-specific solution to the energy issues facing Cape Town.

The chapter is further concluded with an implementation checklist and a readiness test. Their combination of ideas offers a straightforward map of the ways to reach a physical prototype after the conceptual one is created.

6.1 Design Principles Summary

This section unites the most important design parameters and principles that were the result of an iterative process of development, expert validation, and regulatory analysis. It provides a feasible system to mount the custom vertical-axis wind turbines in urban microgrids with built-in energy storage, customised to fit Cape Town, though it can be extended to other urban cities globally.

I then created a Project Mind Map (Figure 6.1) and used it to plot a course for exploring and generating possible solutions for the project. On this map, I graphically compartmentalised the blueprint elements (or could otherwise be called foundational factors) to have a bird's-eye view of what needed to be done. This was followed by CAD models of the various components.

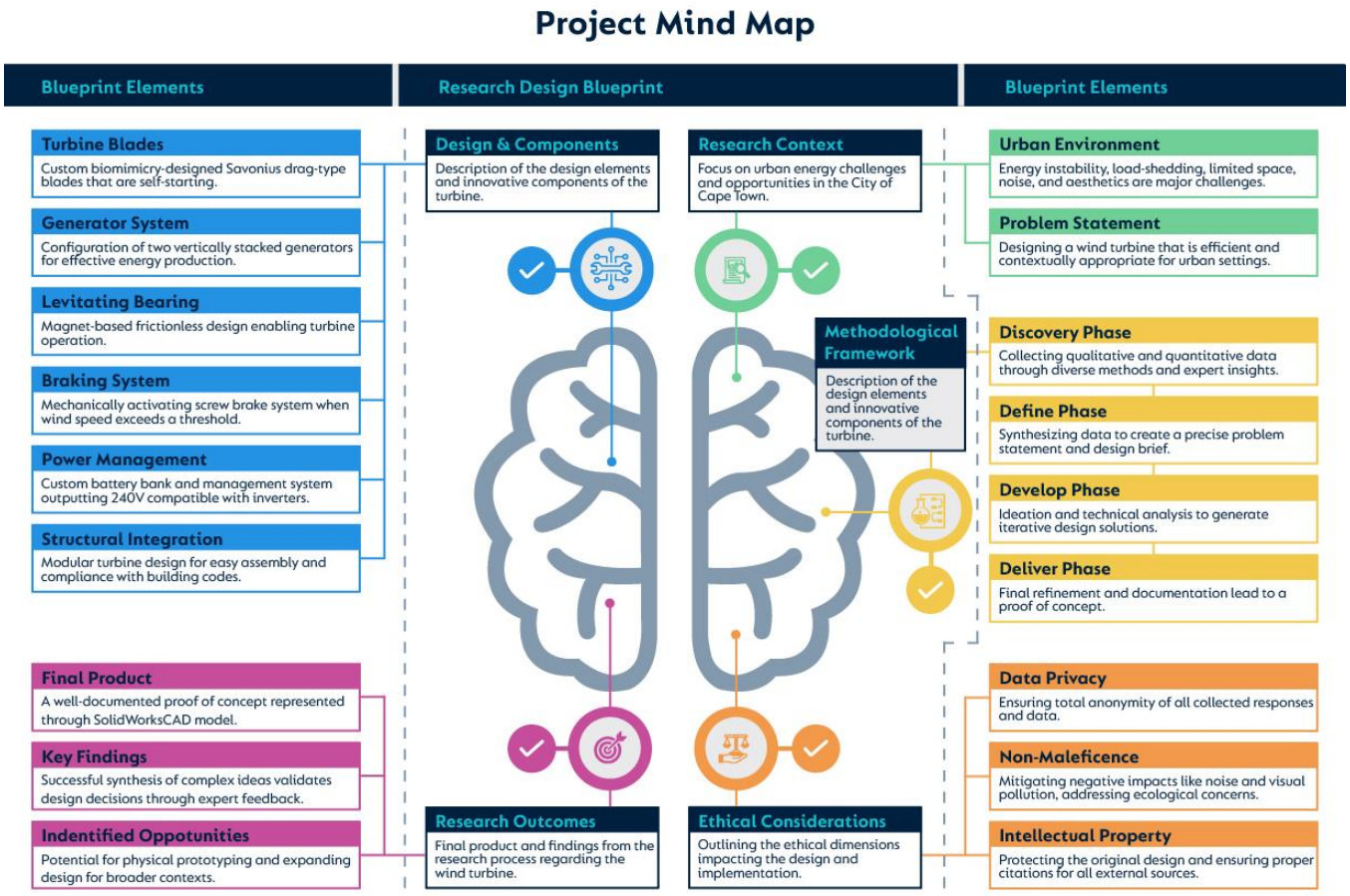


Figure 6.1: Project conceptualisation mind map (Author's own, 2024).

6.1 Final Design: Integrated System Assembly

The final phase was characterised by the accomplishment of the technical understanding of what is required for a custom vertical-axis wind turbine with a built-in energy storage system. The outcome of the final CAD rendered design can be seen in Figures 6.2 and 6.3, and a detailed view of the inner working is in Figure 6.4. These renders show the most fundamental parts that are required for a custom vertical-axis wind turbine and reflect the work undertaken in this research. All design documentation was stored in the form of the CAD model, which was the main deliverable of the project. A detailed view drawing was made to demonstrate the way the separate parts - the levitating bearing system and the two generators - would be assembled. The assembly and disassembling processes of the design were documented to fit the urban city environment, like Cape Town.



Figure 6.2: Final CAD model, front view (Author's own, 2025).

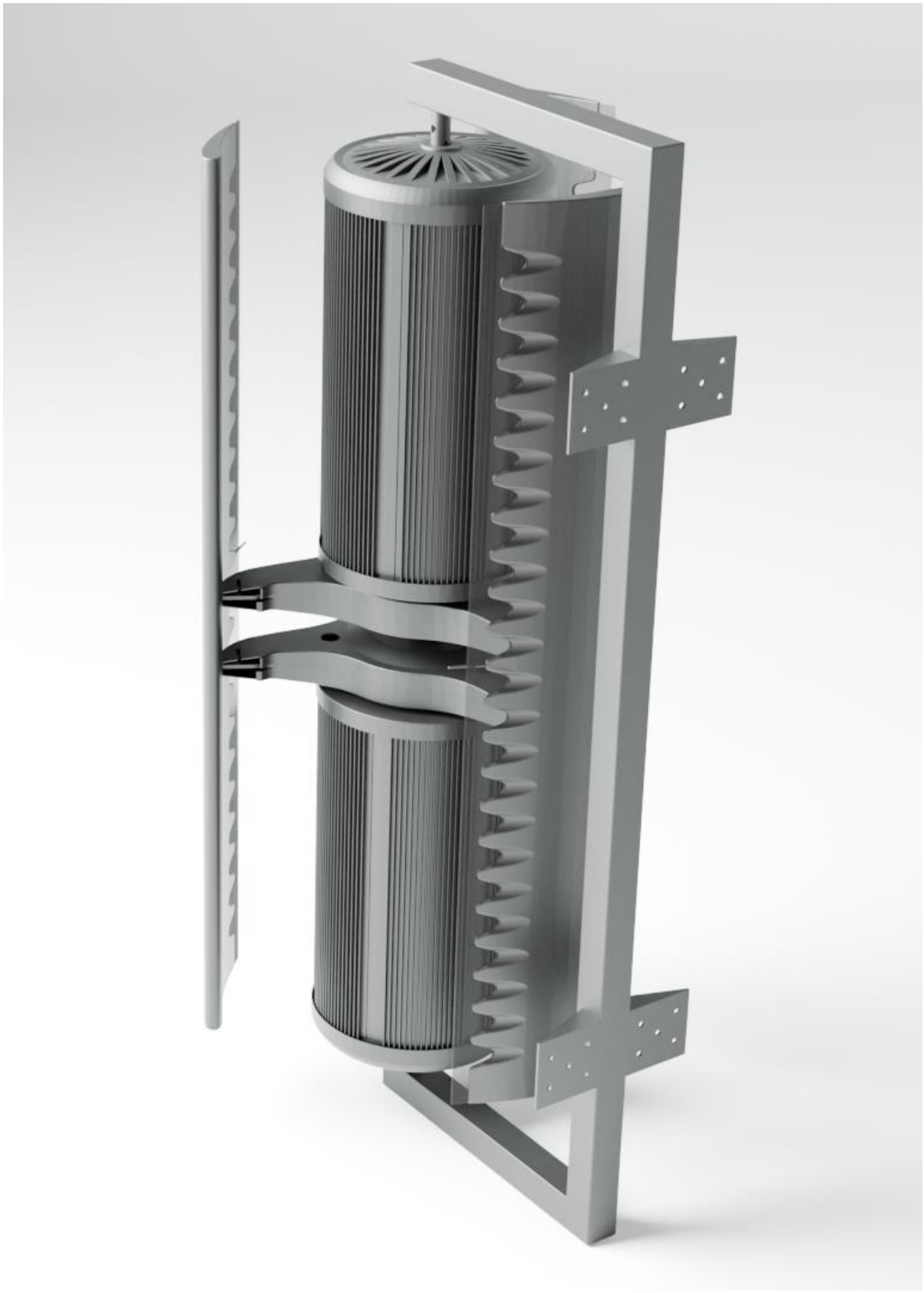


Figure 6.3: Final CAD model, back view (Author's own, 2025).



Figure 6.4: Final CAD model, semi-exploded view (Author's own, 2025).

6.2 Design Synthesis

Friction and wear technical difficulties were resolved through the development of an advanced levitating bearing system comprising magnets. The iterative design thinking process and CAD simulation streamlined the design of two sets of generators, seen in Figure 50. They have been iteratively developed in SolidWorks using custom concave and convex magnets. The outcome was a technically viable solution that was innovative and that dealt with the problems that had been identified during the Define stage.

The evaluation of the system performance potential is examined next, with consideration given to the established technical aspects. The analysis estimates the power generation, storage capacity, and overall system efficiency based on wind measurements of Cape Town and

confirmed simulation models. These numbers offer a numerical foundation to the effectiveness of such a design.

The choice of material to be used in installing wind turbines in urban areas should strike a balance between the structural performance and the environmental resilience, the manufacturability, and the lifecycle costs. The materials that were selected as the best ones at the Cape Town coastal urban environment are as follows:

6.2.1 Structural Components:

- Marine-grade stainless steel SAE 316 - Blade upright supports and mounting brackets were chosen due to their good strength/weight ratio, resistance to corrosion in salt-spray conditions, and their suitability in the local fabrication market.
- 6061 Alluminium Alloy - The generator housing and secondary structural materials assist in thermal management, decrease in weight, and weather resistance.

6.2.2 Blade Construction:

- High-Density Polyethylene (HPDE) - The drag blade material used was Savonius drag because of its impact resistance, resistance to UV, ease of production, and affordability compared to the cost of composite layups.
- Epoxy-coated mild steel - Reinforcement for the blade structure is done where additional rigidity is required.

6.2.3 All Applicable Enclosures and Non-Structural Components:

Acrylonitrile Styrene Acrylate plastic (ASA) - Aesthetic features and protective covers, which offer better UV resistance, colour stability, and weather resistance, will suit Cape Town with the high-solar-radiation environment.

6.2.4 All Electrical Components:

- Enamelled copper wire (0.6mm diameter) for all windings of the generators is in accordance with the standard conductivity and inter-turn insulation.
- N52 Neodymium Magnets for the highest commercially available grade are permanent magnet generator assemblies and magnetic bearing systems that provide the maximum flux density.
- Panasonic 26650 Li-ion (NMC/NCA Chemistry) cells (5000mAh, 4.7V) were used for the battery banks due to their energy density and thermal stability, as well as being readily available.

These material specifications focus on the long-term performance and durability with minimal maintenance in the coastal conditions of Cape Town. It was important to consider the compatibility with the South African manufacturing infrastructure.

6.3 Manufacturability and Assembly Considerations

The manufacturability and easy assembly were taken into consideration at the beginning of the design process. All the parts were crafted to be produced through traditional, widely accessible manufacturing methods that are viable in terms of possible manufacturing within South Africa. The Savonius drag blades were made by simple cutting and shaping of metal; metal structural parts were made by finely laser-cutting and welding; the generator and power electronics were made from the usual electrical components.

Since the integrated systems are “plug-and-play" in nature, like distinct battery banks, and one or other plug-and-play units of the battery management system, the initial on-site assembly is easy, and subsequent maintenance or replacement of parts is as well. I worked on every cycle to minimise the total number of parts, make the fasteners wherever possible, and make the routine maintenance and repair conveniently available. This strategy was informed by the professional opinion on the operational logistics and the ownership cost in the long term.

6.4 Manufacturing and Assembly

During the design, design-for-manufacture principles were used to ensure that it can fit South African fabrication capacity and allow the effective assembly sequences.

6.4.1 Manufacturing Methods

- Sheet laser cutting as well as CNC machining of certain metal parts that required precision.
- Welding and mechanical bonding of steel structural elements.
- Blade components are made by injection or rotational molding of plastics - the choice is determined by the amount of production.
- usual electrical assembly of generator windings, by conventional means of coil winding.

6.4.2 Modular Design Philosophy

- Plug-and-play subsystems: Battery banks, Battery Management Systems units, and inverters are self-contained and can be installed, changed, or upgraded without having to open up the entire turbine to do so.
- Consistent fasteners: Mandatory limit the custom hardware to lessen the intricacy of the inventory and ease field upkeep.

- Easy service access: Generator access panels, battery compartment doors, and electrical connection points are about to be placed in such a way that they can be easily maintained without having special lifting tools.

When assembling the chips, it is necessary to consider the assembly sequence because it can readily cause defects in the completed chips.

6.4.3 Consideration of Assembly Sequence

Once the chips are assembled, the sequence is highly relevant since it may easily expose the chips to defects in the final chips.

- Parts have been formed in logical development, so they do not have to be taken to pieces to have later parts added.
- Limiting the number of parts as much as possible through design consolidation.
- Visual alignment features and mechanical keys should be used to avoid wrong assembly.

These manufacturability rules allow cost-effective production, simplify quality control procedures, as well as factory time and complexity of installation processes.

6.5 Structural Design and Load Analysis

Before construction and installation, the original structural analysis should take into consideration the distinct loading conditions of wind turbines that are placed in urban areas.

6.5.1 Load Categories

- Static Loading: Gravity at the assembly, the whole assembly of the turbine, blades, generator, battery banks, and mounting hardware were found by the SolidWorks program of mass properties analysis.
- Aerodynamic Loading: The blades and the structural elements, when in operation, i.e., the force of the wind as calculated using SANS 10160 wind pressure coefficients to the Cape Town wind regime at the Cape Town coastal wind.
- Dynamic Loading: Cyclic forces due to the movement of doors and blades, unsteady winds of the air, and potential resonance conditions that may either result in vibration or fatigue failure.

6.5.2 Design Optimisation Strategies

- Centre of Gravity Management: Heavy parts, like the generator and battery banks, are placed on the bottom and top of the assembly, so that overturning moments come to a minimum, which is necessary to install the facade-mounted and lamppost lamps.

- Stress Distribution: Visual SolidWorks visual stress analysis and load-path analysis identify areas of concentration, and the distribution can be refinished by adding reinforcement rib support, adding solid bulk, or using a different geometry to evenly distribute the forces.
- Clearance and Interference Prevention: Take a systematic interference detection during CAD assembly to be sure that there is enough clearance between parts that are under rotation, as well as that the moving parts do not come into contact, and that the assembly sequences are correct.

6.5.3 Universal Mounting Bracket System

This universal bracket is constructed so that it can be installed flexibly to the broadest possible variety of urban structures:

- Building facades - this disperses the force by several anchors into the structure of the building.
- Streetlamp posts - it fits to cylindrical posts and adapts to all sizes.
- Rooftop installations - they provide a stable mounting base and will not be swept away by the wind.

Where load-transfer calculations are being made, ensure that the combined effects of the gravitational, wind, and dynamic loads can be borne by each anchor without surpassing the established stress limits of the mounting surfaces.

6.5.4 Blade Upright Supports

The blade uprights, as seen in Figure 6.5, are raised vertically to give structural rigidity and stability of alignment, particularly in response to varying wind conditions. These are components that can resist:

- Cyclic bending forces caused by the rotation of the blade at different wind loads.
- Torsional forces in conditions of turbulent wind.
- Loading fatigue during multi-year lifespan operations.

Structural analysis provided the assistance on which the design was repeatedly refined to be more rigid, but with less material and weight.

The supports attached to the blades are essential to allow the blades to be aligned and to provide structural strength.

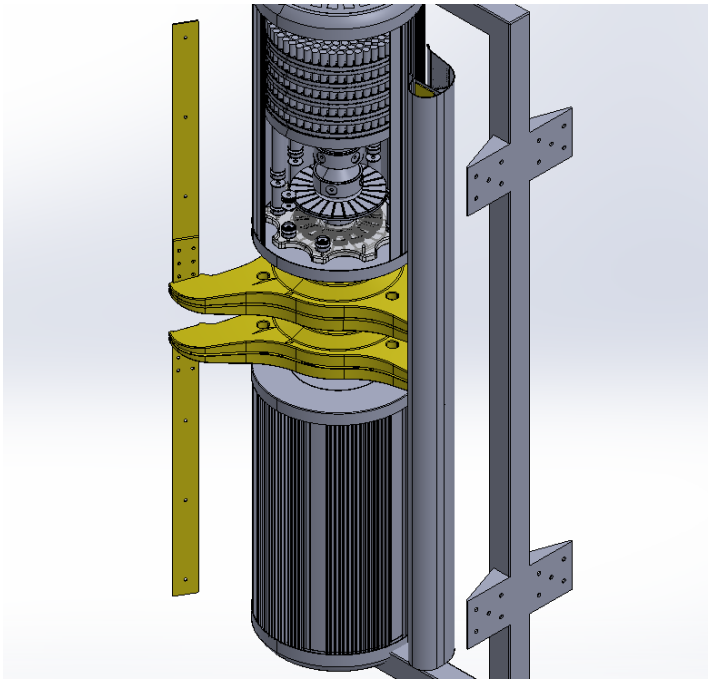


Figure 6.5: Blade upright supports (Author's own, 2025).

The upright support verifications relied on a continuous initial structural analysis in SolidWorks, along with the essential feedback related to the projected wind loading, fatigue, and structural resonance. This iterative process aimed to make the structure stiffer in turbulent winds and aided in the most effective possible transfer of the forces between the rotating blades to ensure high accuracy so that the turbine can be allowed to operate safely over the long term in urban environments.

6.5.5 Mounting Brackets

Enhancing the design of the mounting bracket was necessitated by the need to develop high versatility and adaptability in a diverse and extensive urban environment. Ease of installation, access to maintenance, and seamless integration into municipal infrastructures in Cape Town were accentuated by experts in the field. (Figure 6.6)

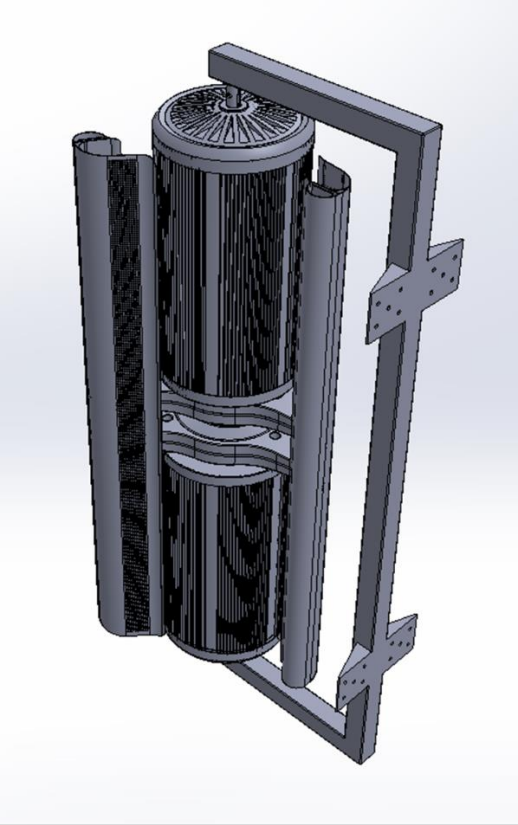


Figure 6.6: Mounting Bracket (Author's own, 2025).

The adaptability to the environment was key; the thought process was to create a design that was flexible enough to adapt to any municipal structure. This enabler increased with every revision within diverse urban environments.

6.5.6 Blade Design Evolution

Figure 6.7 is a CAD model of the blade, which is composed of three evenly spaced Savonius drag blades, effectively harnessing wind energy on a smaller footprint: 2.38m in height and 1m in diameter, providing an area of 2.38m 2 in the process. As evidenced by the CAD visualisation, the principles of biomimicry have been effectively converted to work as a functional, engineering-grade structure. It is evident with the three-blade rotor design with a streamlined Manta Ray profile that is parametrically extruded and mirrored. The fittings are rigidity-engineered with reduced wind disruption.

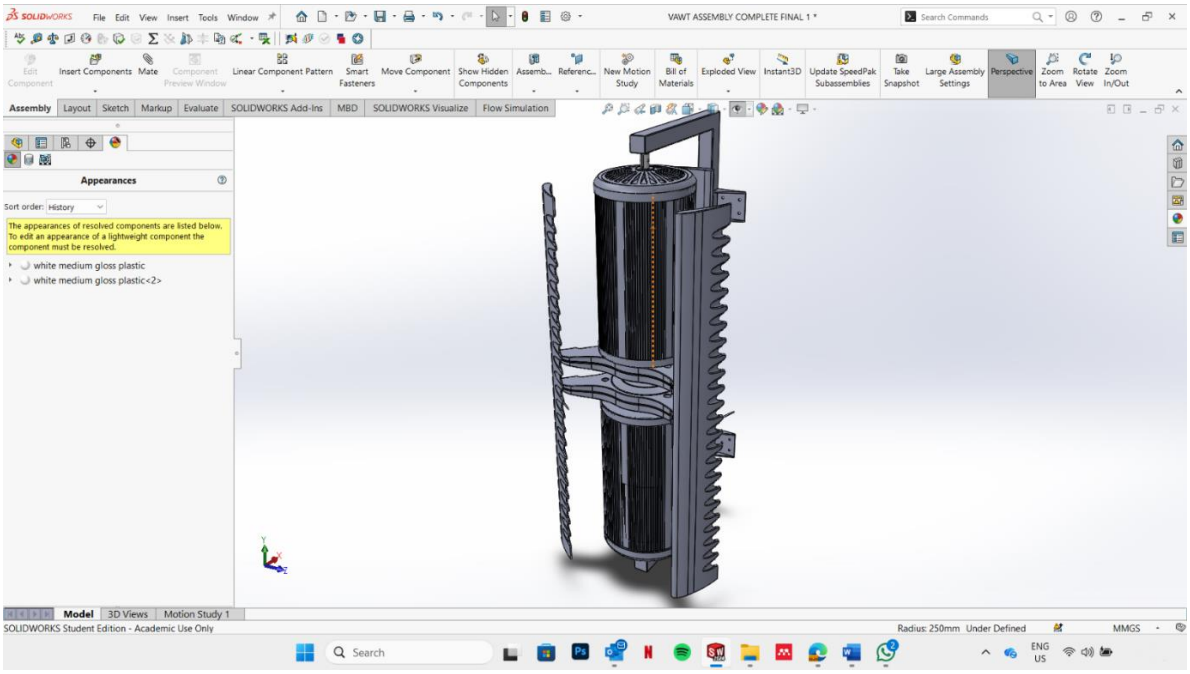


Figure 6.7: SolidWorks CAD model of final blade design with ridge fins and silicone feather strands (Author's own, 2025).

The blades of this biomimetic design are the first blades to experience wind in the urban setting, and it is this point of view that validates the scalability and connectivity of the design with the surrounding energy-storage module. This relationship preconditions the next stage of performance analysis and validation of the system.

6.5.7 Stator and Copper Windings

The power generation mechanism includes stators (Figure 6.8). They are made up of four stators, which have been modelled carefully so that they allow fourteen pairs of copper windings. These windings will be in a delta connection configuration. This is to optimise the power generation capacity of the system and meet the city's limitations. The copper windings are constructed using enamelled copper wire for insulation between wire overlaps, which has a 0.6mm diameter, a standard in the industry due to conductance and durability. It is assumed that each winding set has a hundred turns.

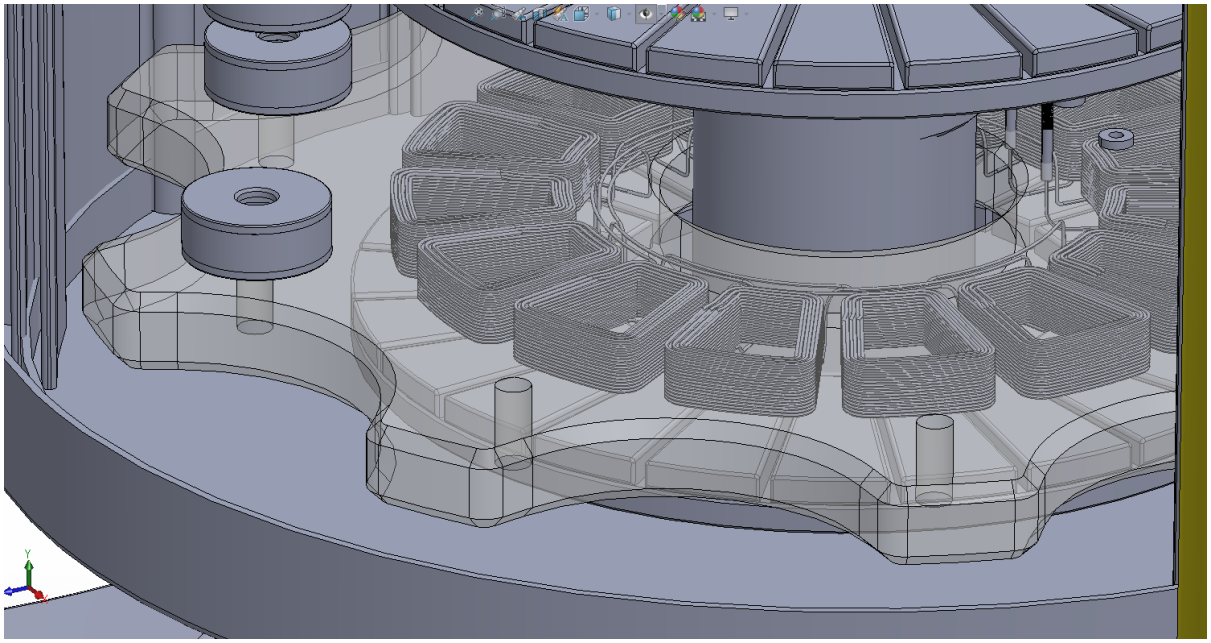


Figure 6.8: SolidWorks CAD model of Stator and Copper windings (Author's own, 2025).

Theoretical output-power calculations were the basis of stator and winding iterations; these mathematical calculations can be seen in sections 6.6.1 to 6.6.3. The sole principle was to achieve maximum electrical generation efficiency in the system. These adjustments were directed towards the anticipated low-to-moderate city-centre winds and the ordered N52 magnets. The change to an offered delta-connected 14-set winding scheme was motivated by the shift to a proposed delta-connected solid-core axial-flux generator, with that shift of direction informed by a consultation with a Delphi Round advisor on principles of axial-flux generator design.

6.5.8 Magnet Assemblies for Power Generation

In Figure 6.9, I illustrate the magnetic bearing assembly. The precise position, intensity, and number of the magnets were thoroughly and repeatedly considered to optimise the strength of the magnetic field and increase the efficiency of power generation when the contact between the windings on the stator and the magnets is achieved. Previous ideas had considered a smaller number of magnets, inferior grades, or alternative packaging, which would cut down flux density. The last construction employs N52 neodymium magnets, which are the best grade available commercially. These strong permanent magnets are mounted on the top and bottom of each of the four stators, effectively sandwiching the windings and forming a high-performance axial flux generator system.

Two sets of N52 magnets are located with a specific 10mm distance between opposite magnets on the stator. They are shaped in a concave and convex configuration to avoid any

interlinking polarity magnetic fields. This decision allowed for the magnetic fields to be more centred and hence created a much more stable bearing system. This design generates powerful, efficient dynamic magnetic flux because opposite poles move to implement contrary to each other out, which induces current in the windings of the stator. The orientation and precise positioning of the magnets are crucial to attain the best spacing that will give the best electrical performance and attain an optimal running frequency with lower rotational speeds.

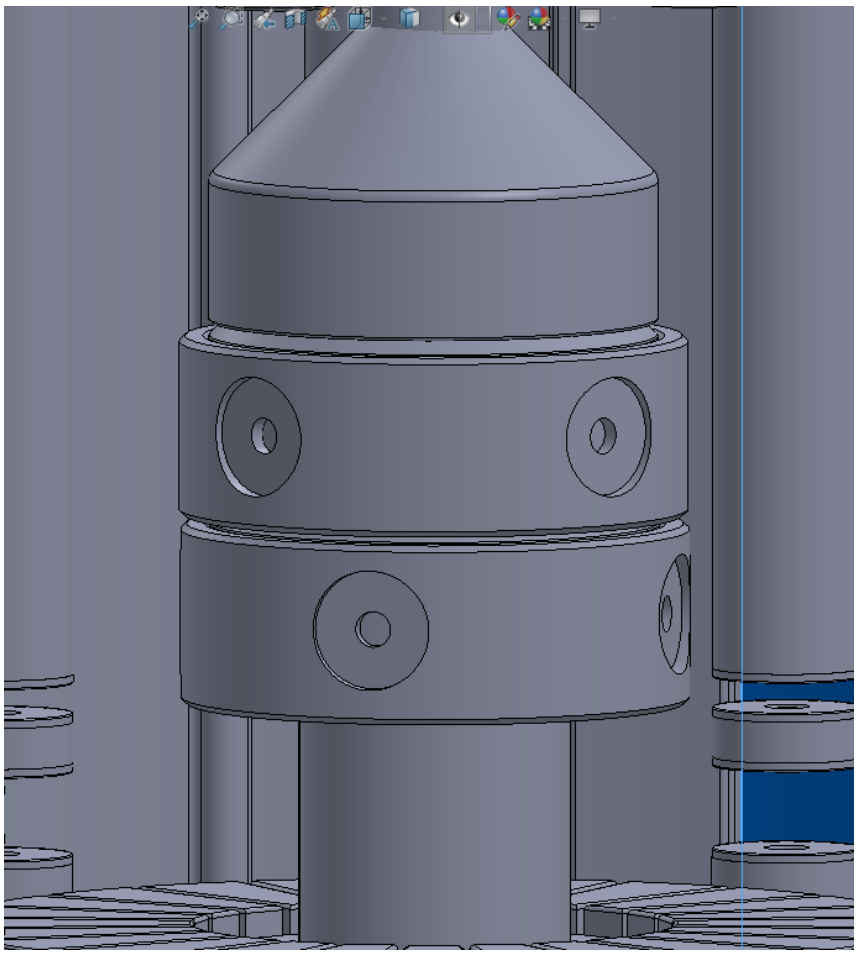


Figure 6.9: SolidWorks CAD model of Magnetic bearing assembly (Author's own, 2025).

The location, strength, and amount of the magnets were very closely assessed on time to drive the maximum strength of the magnetic field and enhance power generation efficiency. The windings in the stator are in direct contact with the magnets. The designs previously may have contained fewer magnets, lower-grade, or other packaging, which would have resulted in reduced flux density. The ultimate design incorporated N52 neodymium magnets, the best grade that could be used commercially. These strong permanent magnets find a place at the

top and bottom of the four stators and essentially within the windings. Such a design yields an axial-flux generator system that is high-performance.

Two sets of N52 magnets are placed with an identical distance of 5mm between opposite magnets in the stator. The resulting spacing results in effective magnetic flux as the opposing poles pass over each other and create a current in the windings in the stator. The correct arrangement and orientation of these magnets, with the intention of implementing optimal separation, determines electrical performance with an optimal running speed and the lowest rotational speeds.

6.5.9 Integrated Energy Storage System and Inverter

The assembly of the energy storage system with the battery management system (Figure 6.10) was the centre of attention of the iterative design cycle. I focused on modularity, safety, and working space, with high efficiency and stability in delivering power. Some of the propositions were external battery compartments or auxiliary parts, but these were hard to install and would have affected appearance and safety.

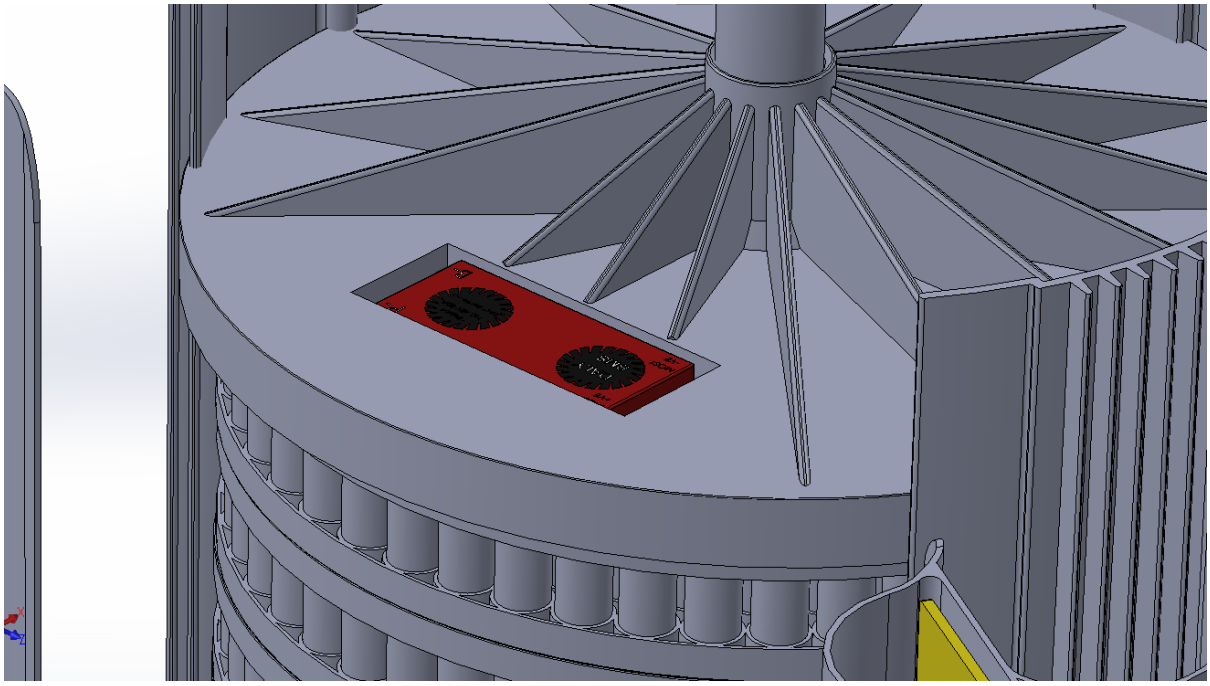


Figure 6.10: SolidWorks CAD model of Battery management system (Author's own, 2025).

The concept is an integrated design that employs two independent battery banks (Figure 6.11). They make 2240 x Panasonic 26650 Li-ion (NMC/NCA Chemistry) cells, which are 5,000 mAh and 3.7 V. The total capacity is 41.44 kWh. Two special battery-management systems (BMS) are functional to manage charging, discharging, and balancing of the cells in

the best way possible. The external Victron Quattro 48/15000 inverter with a three-phase configuration, totalling 45kW charger, is used to convert power, which is selected due to its power ability and an input of 48 VDC with 230V/400V. This inverter is efficient in converting the direct current stored in the batteries into clean alternating current, which can be used to operate the household appliances or as may be necessary, feed the grid.

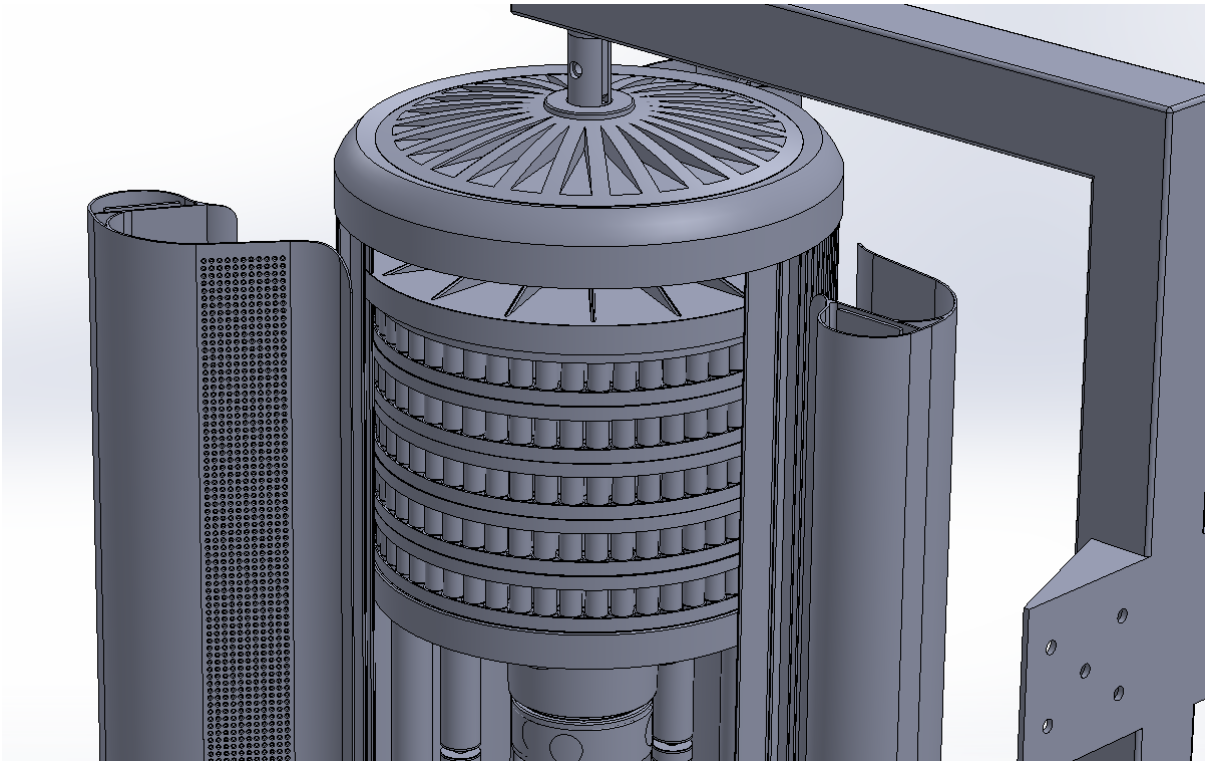


Figure 6.11: SolidWorks CAD model of Battery Bank (Author's own, 2025).

The integration of energy storage was developed successively to develop a dense system that is safe and easily manageable with a high capacity. The rationale behind the choice of two individual banks, each having its own battery management system, and being strategically located inside the vehicle, relied on the expertise in battery safety, thermal, and the ease of installation (Delphi Round 2). The inverter I selected had a large capacity, although it might be a bit oversized for the usual output of low wind, to allow it to support full-load conditions when peak afternoon demand needs to be met, and to allow it to later be integrated into a microgrid without any changes.

6.5.10 Magnetic Bearing System

Cutting off friction means extending the life of the turbine; to this end, I designed a magnetic bearing system (Figure 6.12). This technological breakthrough is that the main shaft may now

turn virtually without friction. The bearing underwent stringent refinement so that the central shaft assembly could be fit and aligned properly and be reliable over the long term.

Initially, traditional mechanical bearings were proposed, but these were more suited to low-wind-speed city conditions. This assessment led to the adoption of magnetic bearings. The resulting design introduces a magnetic bearing adjacent to the central shaft axis of the turbine, allowing smooth rotation with frictionless movement. This positively influences maintenance, and noise output requirements where wind energy is utilised in cities.

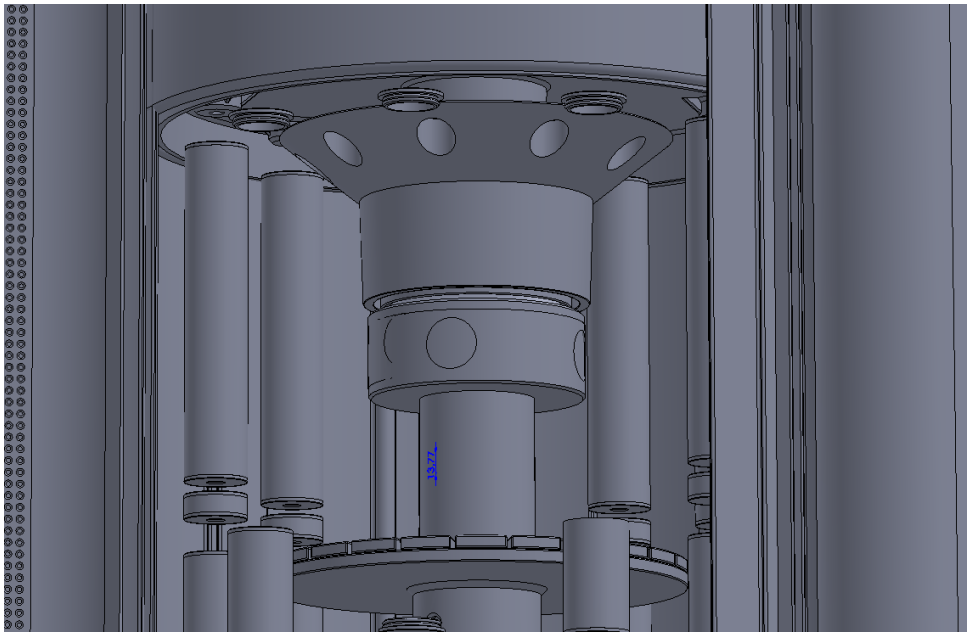


Figure 6.12: Magnetic bearing system (Author's own, 2025).

6.6 Performance Analysis

One of the key critical and continuous elements of the design research was an extensive exploration of the potential to generate power by the system and its ability to store energy. This analysis validated design decisions, discovered the possible performance bottlenecks or component-not-fit situations, and gave a realistic report of the expected performance of the system in its target urban environment. Repetition of such an analysis would allow anticipating the problems at an early stage and drive further design optimisation.

6.6.1 Power Generation and System Sizing

The theoretical calculations revealed a fundamental sizing challenge that required iterative refinement of the energy storage and power conversion subsystems. In this section, I document the reconciliation process between the generation capacity of the vertical-axis wind turbine, storage as well as the conversion rate.

6.6.1.1 Realistic Power Output Assessment

I then used Cape Town's wind data that I had gathered from Meteoblue and applied the standard wind power equation with conservative Savonius efficiency (Cp = 0.15):

At an average urban wind speed of 4.17 m/s (15 km/h):

- Theoretical wind power available: 71.1 W
- Mechanical power captured (15% efficiency): 10.66 W
- Electrical power output (80% generator efficiency): 8.5 W average

6.6.1.2 Annual Energy Production Estimate

The wind speed distribution in Cape Town (Figure 3, Chapter 2), I applied Weibull distribution analysis:

- Mean wind speed: 4.2 m/s
- Operating hours: ~6,500 hrs/year (accounting for cut-in speed of 2.1 m/s)
- Estimated Annual Energy Production: 55-75 kWh/year
- Daily average: 0.15-0.21 kWh/day

This data then pointed towards a very modest output, which reflects the inherent limitations of:

1. Savonius drag-type efficiency (15-25% vs. 35-45% for lift-type)
2. Small swept area (2.38 m²)
3. Highly turbulent urban wind conditions
4. Low average wind speeds in built environments

6.6.1.3 System Sizing

a) Energy Storage:

- Specification: 2.4 kWh (480 cells in 80S6P configuration)

- Justification: The structure gives 10 to 15 days of buffering capacity at average generation rates, enabling electricity to be stored during high-winds to be used when the wind dies.

b) Battery Configuration:

- 480 × Panasonic 26650 Li-ion cells (5000 mAh, 3.7V)

- Configuration: 80 cells in series, 6 parallel strings (80S6P)
- Nominal voltage: 296V DC
- Usable capacity: ~2.0 kWh (assuming 80% depth of discharge)

c) Inverter/Charger:

- Specification: Victron Phoenix 500VA (300W continuous)
- Input: 48V DC (requires DC-DC converter from 296V battery bank)
- Output: 230V AC, 50Hz

The system has been scaled to realistic loads but maintains the lowest standby losses (approximately 8W). This design also allows the vertical-axis wind turbine to charge up the battery even when the wind is low.

6.6.2 System Efficiency Analysis

The development of this innovative system addresses the most critical concerns about standby losses exceeding generation and is represented in Table 6.1 below:

Table 6.1: System Efficiency Analysis (Author's own, 2026).

Component	Power Draw	Impact
500VA Inverter	8W standby	Allows net 0.5W charging at low wind
Battery Management System and monitoring	3W continuous	Acceptable overhead

6.6.3 Performance Context and Limitations:

This single-turbine system is not designed to meet all the electricity demand of a South African house, which would be between 15 000 and 25 000 W each day. Instead, it functions as:

1. Supplementary micro-generation, which attempts to assist in offsetting 5-10% of household consumption

2. Emergency backup: Maintaining critical loads such as the lights, communication devices, and refrigeration during load-shedding, when coupled with the 2.4 kWh LiFePO4 battery

3. Scalable building block: Multiple units configured together could contribute to building-scalable microgrids

4. Technology demonstration: Proof-of-concept for urban-integrated renewable generation

6.6.4 Scaling Scenarios

Predictably, these systems could be scaled in communities in the following way:

10-unit rooftop array: 550-750 kWh/year (15-20% of household demand)

Street-scale deployment (50 units on lamp posts): 2,750-3,750 kWh/year

District microgrid (200+ units): Meaningful contribution to commercial building base loads

The design prioritizes technical feasibility, modularity, and realistic performance claims over overstated capacity assertions.

6.7 System Validation

The performance estimation and system sizing analysis give information regarding the theoretical power generation and storage capacity, and they can show where optimisation is required, particularly on scaling. To determine the viability of the proposed vertical-axis wind turbine system within the urban energy context in Cape Town, performance estimation that involved the theoretical wind power was carried out. According to the generic wind power equation, the graph below demonstrates the power output of the turbine with a wind speed of between 2 and 20 m/s.

$$P = \frac{1}{2} \times \rho \times A \times Cp \times v^3$$

Where:

- P = Power output (in watts)
- ρ = Air density (typically 1.225 kg/m³ at sea level)
- A = Swept area of the turbine blades (in m²)
- Cp = Power coefficient (efficiency factor, typically ≤ 0.59; for Savonius VAWTs ~0.15-0.25)
- v = Wind speed (in m/s)

This equation takes into consideration the density of air, the size of the swept area, and the power coefficient, also based on the system design. It is indicated in Figure 59 that there is a cubic dependence of power production on wind speed; a one-minute increase in speed increases energy gained. This performance curve gives a good basis on which the system can be sized that it is possible to make sound predictions of the energy yield as the wind conditions vary. It also assists in laying out the turbine's location and approximating the contribution provided to microgrid stability. The data points are labelled to make them understandable. The graph graphically verifies the use of the turbine in windy conditions of Cape Town.

The calculated data in Figure 6.13 below is a generic theory with a standard wind power equation to estimate the potential performance of the proposed vertical-axis turbine. The graph illustrates the relationship between the speed of the wind and the power output and provides a summary of the capacity to be expected of the turbine, taken under ideal conditions.

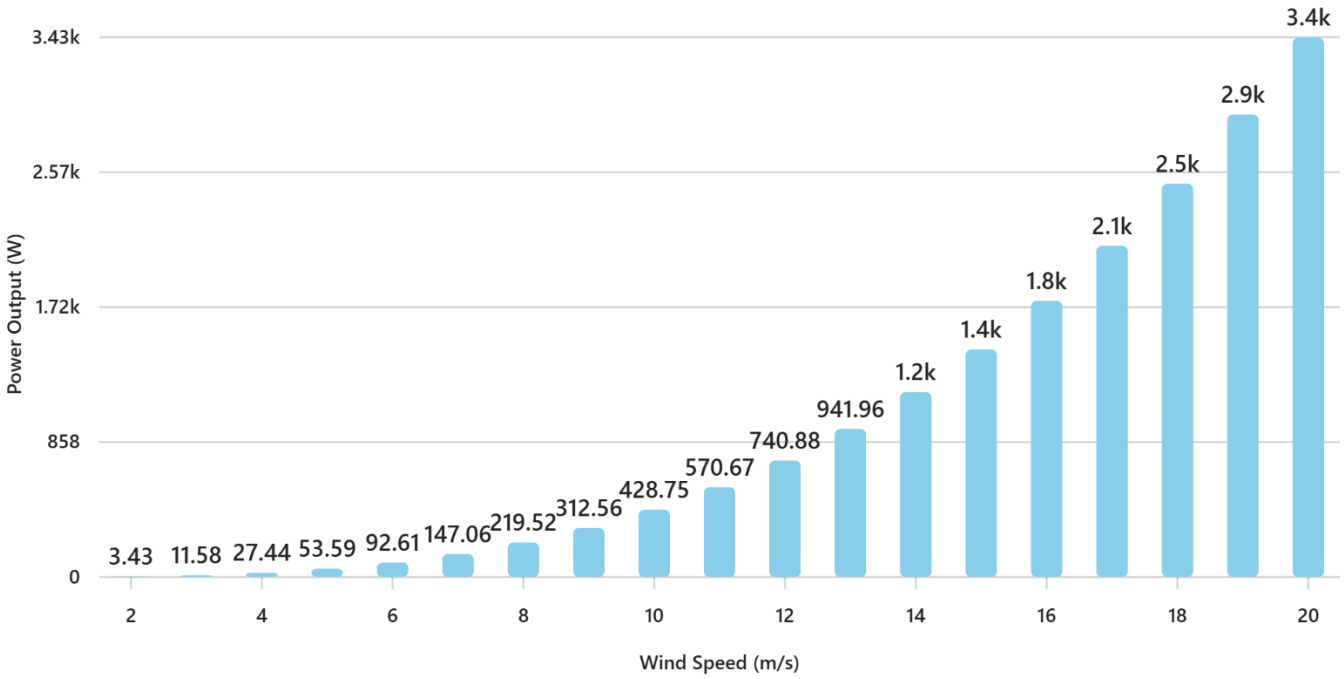


Figure 6.13: Performance Output (Author's own, 2025).

To put this information into perspective within a real-life context, I acquired weather-pattern data through Meteoblue.com and plotted it on a graph (Figure 6.14), which shows the wind speeds in Cape Town between 24 and 30 September 2025.

With that data, I was able to determine the potential energy that the turbine would have produced had it been installed at such a time. This outlines the theoretical power output on the vertical axis of the wind turbine per day during those dates, including the average wind speed, and how that power could be formulated within a system of battery banks. The output gives an approximate estimate of the performance and the energy supply of the system in the city scenario in Cape Town.

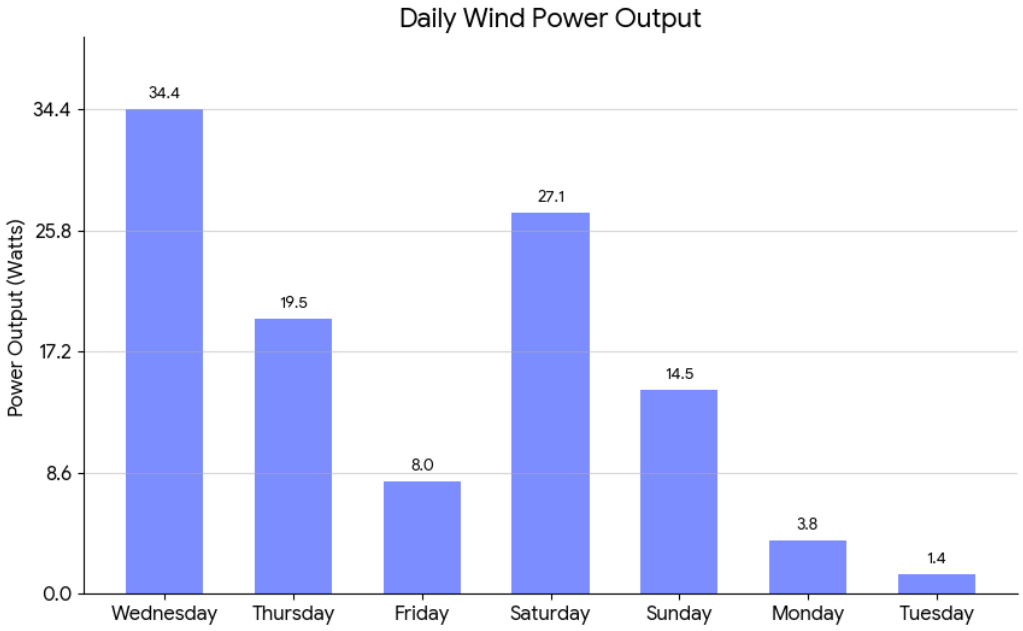


Figure 6.14: Average wind data for Cape Town, 24–30 September 2025 (Author's own, 2025).

These values were calculated with the air density of = 1.225 kg/m³, the swept area A = 2 m², and the power coefficient Cp = 0.20 (representing a realistic Savonius turbine efficiency in urban conditions). Using the assumption that the turbine was operating 24 hours/day at various average wind speeds throughout each day:

Daily Energy Production Calculations:

- Wednesday (avg. wind speed 5.2 m/s):
  - P = 0.5 x 1.225 x 2 x 0.20 x (5.2) ³ = 34.5 W
  - Daily energy = 34.5 W x 24 h = 0.83 kWh

- Thursday (avg. wind speed 4.3 m/s):
  - P = 0.5 x 1.225 x 2 x 0.20 x (4.3) ³ = 19.5 W
  - Daily energy = 19.5 W x 24 h = 0.47 kWh

- Friday (avg. wind speed 3.2 m/s):
  - P = 0.5 x 1.225 x 2 x 0.20 x (3.2) ³ = 8.0 W
  - Daily energy = 8.0 W x 24 h = 0.19 kWh

- Saturday (avg. wind speed 4.8 m/s):

- P = 0.5 x 1.225 x 2 x 0.20 x (4.8) ³ = 27.1 W
- Daily energy = 27.1 W x 24 h = 0.65 kWh

- Sunday (avg. wind speed 3.9 m/s):
  - P = 0.5 x 1.225 x 2 x 0.20 x (3.9) ³ = 14.5 W
  - Daily energy = 14.5 W x 24 h = 0.35 kWh

- Monday (avg. wind speed 2.5 m/s):
  - P = 0.5 x 1.225 x 2 x 0.20 x (2.5) ³ = 3.8 W
  - Daily energy = 3.8 W x 24 h = 0.09 kWh

- Tuesday (avg. wind speed 1.8 m/s):
  - P = 0.5 × 1.225 × 2 × 0.20 × (1.8) ³ = 1.4 W
  - Daily energy = 1.4 W × 24 h = 0.03 kWh

Total weekly production **= 2.61 kWh**

These numbers draw realistic approximates of the performance of the turbine in eventual urban wind conditions. Although the turbine generates approximately 2.61 kWh/week of energy, when coupled with a 41.44 kWh battery storage, the turbine can be used to provide additional energy and ensure energy stability during a grid outage. The system demonstrates that urban micro-generation is not impossible but will primarily be used to provide a supplementary power source to a household, consisting of 3 to 4 family members, consuming 15-25 kWh per day.

The turbine needs to be grouped in an array or placed within locations with higher average wind speed over time, like along the coastline or on unhindered rooftops, to be most efficient. Those measures can have a substantial effect on the total energy contribution of the system.

6.8 Regulatory Compliance

The installation of urban wind turbines in Cape Town should adhere to a number of regulatory schemes to achieve safety, security of the population, and acceptance by the community.

6.8.1 National Building Regulations (SANS 10400):

- Part A - General Principles and Requirements: Before construction commences, every installation has to meet at least the minimum safety standards and have the necessary approvals.

- Part B - Structural Design: The structural analysis should demonstrate that the turbine assembly and frame can support all the required loads, including the static and dynamic ones.
- Part D - Public Safety Mounting Systems: Should not allow the components to separate and fall, causing pedestrian harm or property damage.
- SANS 10160 Structural Design Actions: The wind load should be calculated with reference to the wind pressure profiles, gust factors, and the dispersal of direction that vary in the urban environment of the city of Cape Town.

6.8.2 By-Law of the Municipality of Cape Town Planning (2015)

- Height Requirements: The installation of turbines should comply with height restrictions specified by every zoning type. The residential areas tend to have higher heights compared to the mixed-use or industrial areas.
- Setback Requirement: Property lines should be adhered to, and wind turbines should not be too close to property lines. This will prevent nuisance claims and impacts with neighbours.
- Noise Emissions: Municipal by-laws dictate that low noise levels should be maintained. At night in residential areas, this is normally 4550 dB (A).
- Visual Impact Assessment: Design Make the turbine blend in Clark the building facades in colours, as well as ensure that the turbine is in a spot that minimises shadow flickering.

6.8.3 Electrical Safety Standards (SANS 10142-1):

- All the electrical systems, such as the wiring, inverters, and battery management system, should be kept in view in the South African regulations on wiring.
- Must have proper earthing, overcurrent protection, isolation mechanisms, and safety disconnects.
- Where grid interconnection is involved, the equipment must be certified and installed by professional electricians.

6.8.4 Environmental Considerations (NEMA 107 of 1998):

- Even though micro-scale turbines normally do not necessitate complete Environmental Impact Assessments, every installation must also be supported by documents that demonstrate how the project protects the inherent wildlife and the people living nearby. The documentation must cover actions undertaken to reduce the risk of bird strikes, limit constant noise exposure, and prevent the effects of shadow flicker on adjacent properties.

Early involvement of the municipal planning department, provision of certifications by a structural engineer, and professional installation of the electrical systems by licensed contractors are required. These measures will be necessary in the process of receiving regulatory consent and safe operation.

6.9 City Integration Principles

Implementation of vertical-axis-wind turbines within the urban geography of Cape Town must give much attention to the spatial, aesthetic, and community acceptability.

6.9.1 Spatial Requirements

- Minimum clearance areas: This area should have sufficient spacing around the rotating blades to avoid any collision with the building structures, pedestrian paths, and any overhead obstacles.
- Access to mainframe: Adequate space to allow technicians to perform routine maintenance inspection, bearing system tests, and replacement of components.
- Spacing of multiple turbines: In a situation where turbine arrays are used, sufficient spacing between turbines should be considered to limit the effects of the wake interference that causes diminished downstream work of turbines.

6.9.2 Aesthetical Approach

- Colour matching: Turbine finishes must be in harmony with the colours of the building facades or the colour palette in the street landscapes to minimise the visual effects.
- Small size: The 2.38m high and 1 m diameter design reduces the visual size but does not reduce its functional swept area.
- Design of enclosed components: The tanks containing battery banks, inverters, and electric connections are enclosed in streamlined shapes that blend in with the turbine structure but not as secondary-looking attachments.

6.10 Acoustic Performance

The design structure is integrated with various sound minimisation measures and technologies necessary in the city.

- Magnetic bearing system: Reduces mechanical friction noise of conventional bearing assemblies.
- Savonius blade geometry: With drag working operation, lower tip-speed ratios are generated compared to lift working turbines, and this leads to lower aerodynamic noise.

- Biomimetic blade surface structure: The ridge structures on the pectoral fins of the Manta Rays and the special shape of the trailing edges allow for the deceleration of turbulent air flow, leading to a greater reduction in noise.

6.11 Community Engagement

- There should be clear communication on the location of the installation, anticipated functionality, and visual aesthetic/noise.
- Experimental setups on public amenities to cultivate recognition and embracement.
- The labelling and safety information should be used to address the concerns of the people regarding the safety of operation.

6.12 Rules of Thumb for Performance Optimisation

The design criteria should eventually provide credible energy production under the local wind regime of Cape Town.

6.12.1 Wind Resource Utilisation

- Target wind speed range: Tuned to 10-25 km/h, which are the most common wind speeds in Cape Town city according to historical data provided by Meteoblue.
- Omnidirectional capability: A vertical-axis design can capture the wind from any direction, without the need for yaw devices, as turbulent urban wind direction changes rapidly.
- Self-starting qualities: A Savonius-style of drag blade design can be started rotating at low wind speeds, without any starting means.

6.12.2 Generator Specifications

- N52 neodymium magnets are utilised in the dual axial flux permanent magnet generator to achieve the maximum flux density.
- Four stator designs with 14 copper winding sets on each stator, but each with 100 turns of 0.6 mm enamelled wire in a delta connection.
- Low-RPM optimisation: Design based on operating speed of about 80 RPM is equivalent to the tip-speed ratio of Savonius turbines operating at the target wind speeds.
- Electromechanical efficiency: There is a conversion efficiency of about 80% in the conversion of mechanical shaft energy to electrical power.

6.12.3 Energy Storage Integration

- Capacity: The total storage capacity is 52.64 kWh (2,240 x Panasonic 26650 Li-ion NMC/NCA Chemistry cells), which gives a large buffer against intermittency by the wind.
- Dual Battery Management Systems (BMS): Each battery bank has its own inherent, independent BMS, which controls the safety of charging/discharging, balancing the cells, and thermal conditioning.
- Modular bank format: Batteries are stacked into a cylindrical format around a central axis, which is known to be the best way of using spaces and thermal distribution.

6.12.4 Power Conversion

- Rectification phase: Three-phase bridge rectifiers, by themselves or in combination, convert the output of AC generators to charge batteries.
- Inverter Sizing: Future implementation should consider efficiently matching inverter capacity that which I recommend being external Victron Quattro 48/15000 inverters with a three-phase configuration to supply the 45kW, has been recommended to realistically match turbine output instead of over-sizing, which improves efficiency at realistic operating power levels.
- Grid compatibility: 230/240V single-phase output is compatible with the residential voltage in South Africa.

6.12.5 Performance Validation

- Cape Town wind data are used to compare theoretical power output calculations (Meteoblue, September 2025).
- The validity of the estimations of the energy produced weekly indicates a significant source of energy consumption at household levels (average generation: 84.52 kWh generated).
- System sizing makes sure that the battery maintains a higher capacity than the daily potential of generating energy, so that storage will be provided when the wind is high to use the energy when the wind is calm.

6.13 Implementation Checklist

The critical considerations or prerequisites to successful implementation are summarised in the following checklist:

6.13.1 Pre-Installation

- Assessment of the sites' wind resources by using anemometer data, which is an accumulation of at least three months.

- Evaluation of the structural capacity of the proposed mounting surface by a qualified engineer.
- Municipal approval of planning, including height, setback, and noise factors.
- Planned electrical installation needs to be accepted and signed off by a licenced electrician.

6.13.2 Design Verification

- Material specifications must be verified to be corrosion-resistant when implemented in the local environment.
- Load calculations should be done in compliance with SANS 10160 in line with the particular location of installation.
- Rotating component and maintenance access clearances.
- Acoustic testing will determine that the noise level is not too loud over urban areas.

6.13.3 Installation and Commissioning

- Mounting brackets fitted by a qualified contractor with certified anchor systems.
- Turbine assembly started and completed according to the recorded order of assembling the turbine.
- Electric links by a qualified electrician according to SANS 10142 -1.
- Tested and configured battery management system.
- Inverter options based on the nature of the generator output.
- Preliminary end-to-end tests in wind diversities.

6.13.4 Post-Installation

- Community informed of the state of operations and given contact details if they have concerns.
- Maintenance scheme instituted (suggested: visual inspection quarterly, service, annual).
- A performance control system that will aid the monitoring to track the amount of energy generated and detect anomalies.
- Documentation package signed, with as-built drawings, equipment specifications, and maintenance procedures.

These principles of design thinking involve the techniques of technical analysis, expert consultation using the Delphi process, regulatory research, and refinement of the design. Their developed system constitutes an overall framework of the implementation of the urban

vertical-axis wind turbines, technically working, regulation-compliant, community-acceptable, and commercially produced within a South African context.

6.14 Implementation Readiness

The custom vertical-axis wind turbine model will be made using Design for Manufacturing and Assembly (DFMA) principles, meaning it can be constructed with the production capacity of South Africans. The standard methods of structural parts include laser cutting, CNC machining, and welding, which can be found locally in fabrication. The volume-based injection or rotational type of moulding process is optimised in terms of blade geometry without the complexity and expense of composite lay-ups. Electrical subassemblies comprise standard components, and assemblies are comparable to the currently existing infrastructure in South Africa. The complexity of assembly is also reduced by a modular approach: plug-and-play battery banks, discrete units of the battery management system, and convenient service panels should be placed to promote easy quality control. Large-scale fasteners are used, which minimise inventory requirements and make the assembly process and long-term maintenance easier. This preparedness ensures that the design can be transferred to CAD to a physical production without the specific equipment, which is not available in South Africa.

The universal mounting bracket system is applicable to building facades, streetlamp posts, and rooftops. The universal bracket distributes the load of several anchor points and conforms to various mounting surface geometries. Modular assembly enables the turbine to be assembled into components of major size, i.e., blade, generator, and energy storage, that can be delivered separately and assembled on-site with little special equipment. Electrical connections have a logical order and apparently differentiated junctions and coloured wires. Maintenance points are installed so that they can be easily subjected to routine inspections and have the components without requiring complete disassembly. Section 6.8 has a checklist on implementation, which includes site preparation, structural checks, regulatory compliance, and commissioning.

The next important step is physical prototyping to prove theoretical computations, structural load analysis, and the predictions of acoustics. The power output of Cape Town variable winds will be verified by tests, the stability of the magnetic bearing system in handling loads and the stability of the load handling system, and the noise produced by the operation of the system will be measured. Setting on-site a pilot unit on-site will be useful in offering real-life knowledge in areas of installation, maintenance, accessibility, and the integration challenges with the existing urban infrastructure. In chapter 8, a particular set of recommendations is given to such a prototyping phase, such as advanced FEA or CFD validation, economic feasibility analysis, and development of the SIMS. The details presented in this chapter provide the technical basis

to transform this research into a deployable system that can provide the urban energy resiliency of Cape Town.

6.15 Summary

The Deliver phase has completed a fully tested engineering design of a vertical axis wind turbine with in-built energy storage, but tailored to suit the Cape Town urban microgrid.

Final System Specification

- Dimensions - 2.38 m high x 1.0 m in diameter (2.38 m 2 swept area)
- Blade Design - Three biomimetic surface HDPE Savonius drag blades.
- Bearing System - N52 neodymium magnets with a gap of 10mm in between are used to levitate magnetically.
- Generator - Dual axial-flux permanent-magnet, 4 stators, 56 copper windings, best speed of 80 RPM.
- Energy Storage - 2.4 kWh with 480 Panasonic 26650 Li -ion cell, in 80 S 6P.
- Power Conversion - 500 300 W continuous inverter (VA), 48 V DC in, 230 V AC out.
- Mounting - Universal bracket system of marine-grade SAE 316 stainless steel.

Validated Performance

- Power output: The output at 15km/h wind speed is 8.5W average.
- Annual energy production: 55 -75kWh/unit.
- Daily average: 0.15–0.21 kWh
- Household input: there is a 510% additional production on a unit basis.
- Scaling potential: A 10-unit array can produce 550-750 units per year.

Regulatory Compliance

- SANS 10400-B (design) - load tests are in line with SANS 10160.
- SANS 10142 -1 (electrical safety) - wiring, earthing, over-current protection compliant.
- Cape Town Municipal Planning By-law - satisfies height limits, setback limits, noise levels (less than 45dB(A)), and visual impact.
- NEMA 107/1998 (environmental) low risk of bird strike, shadow flicker, and noise pollution.

Manufacturing Readiness

- Fabrication capability of all the parts is possible in South Africa.
- Prefabricated, plug-in construction saves labour on-site.

- Use of standardized fasteners reduces inventory and maintenance.
- Design is based on DFMA on simplicity.

Implementation Path

When the following steps are accomplished, the design is ready to be prototyped physically:

1. Individual FEA and CFD verification.
2. Economic feasibility study (ROI, lifecycle cost)
3. Pilot installation to ensure real-world performance.

This chapter forms a concrete, practical design that will bring potential integration of urban renewable energy into practice.

Chapter 7 – Conclusion and Recommendations for Future Research

This Master of Design project addressed the following research question:

- What are the critical design parameters for maximizing the efficiency and urban compatibility of vertical-axis wind turbines for microgrid applications?

Using the Double Diamond model, the project resulted in:

1. **A Complete Vertical-Axis Wind Turbine System Design:** Custom 2.38m × 1.0m Savonius turbine with magnetic levitation bearings, integrated 2.4 kWh battery storage, and appropriately sized 500VA power conversion.
2. **Validated Performance Specifications:** There is 55-75 kWh generation potential per annum, thereby validating actual Cape Town wind data (Meteoblue, 2024).
3. **A regulatory compliance framework** that is compliant with SANS 10400, SANS 10160, SANS 10142-1, and Cape Town municipal bylaws.
4. **Manufacturing preparedness:** A DFMA-optimised design, which could be fabricated using the South African manufacturing facility. The Major Contributions to Knowledge.

7.1 The Major Contributions to Knowledge

The project promotes urban renewable power and product development by:

7.1.1 Design parameters specific to context

- Urban micro-generation is empirically sized by an association between 55-75 kWh /year generation capacity, 2.4 kWH storage to a 500 VA converter
- Turbulent urban wind performance Savonius VAWTs: 0.15 Cp 0.25 and 0.9 TSR 1.0.

7.1.2 Methodological innovation

- A practice-led project made use of the Delphi approach to technical decisions.
- Engineering requirements were based on biomimetic principles (Barn owl acoustics, Manta ray hydrodynamics).

7.1.3 Integration frameworks of regulation

- Reported compliance route of urban integrated renewable generation in South Africa.
- Rationales of the selection of materials to be used in coastal urban settings: marine-grade steel and UV-resistant polymers.

7.1.4 Realistic performance evaluation

- Open recognition of system limits: one unit will counteract 5-10% of household demand and is not a household solution.

- Scaling simulations demonstrate that 10 units in an array would be able to satisfy 15-20 percent of household demand.

7.2 Reflective Critique on the Design Product

7.2.1 Strengths

- The design has balanced the technical performance, community approvals (low noise), regulatory compliance, and manufacturability.
- It has a plug-and-play as well as a modular architecture that can be deployed and maintained easily.
- A Savonius design is selected because it is deployable; a deployed turbine is more useful than a design that is efficient but not deployed.

7.2.2 Acknowledged limitations

- **Weak absolute power production:** 8.5 W average needs an array installation to have an effect.
- **Long-term payback:** 25-30 years payback at present tariffs is too difficult to maintain without subsidies.
- **No validation of physical performance:** digital prototypes may be theoretically validated, but cannot be sure of acoustics in the real world, structural behaviour, and stability of the bearing over time.

7.3 Design Philosophy Realised

The project illustrates that urban renewal systems need to be optimised to integrate, rather than to generate. A quiet (less than 45 dB(A)) 55kWh/year turbine, which can be mounted, needs minimal maintenance (magnetic bearings), is acceptable by the community, and meets all the requirements, will be of greater value to the Cape Town energy resilience system than a 150kWh/year system, which falls short on all criteria.

7.3.1 The Responses to the Research Questions

Key question: What are the design parameters that will be critical towards maximizing efficiency and urban compatibility? The study was able to find six key parameter groups:

1. **Aerodynamic:** Savonius drag-type, Cp 0.15-0.25, self-initiating at 2.1m/s.
2. **Mechanical:** Bearings, magnetic levitation (N52 magnets, 10mm distance), 80RPM optimum speed.
3. **Electrical:** Dual axial flux generator, 56 copper windings (0.6 mm), 80 percent electromechanical.
4. **Storage:** 2.4kW storage capacity, 10-15 days buffering, 80S6P Li-ion set up.

5. **Structural:** Marine steel (SAE 316), blades made of HDPE according to SANS 10160 wind loads.
6. **Regulatory:** Height, setbacks, noise of less than 45 dB(A), and visual impact reduction.

Sub-question 1: limited space, technical problems, and complicated wind patterns, answered:

- **Multidirectional and turbulent wind:** solved omnidirectional Savonius construction does not require a mechanism to yaw.
- **Small area of sweeps (2.38 m 2):** handled by realistic performance requirements and an array-based deployment strategy.
- **Low average wind speeds (4.17m/s urban):** optimised at a small cut-in speed (2.1m/s) and low-RPM generator.

Sub-question 2: Optimisation of microgrid installations provided:

- Built-in storage moves production forward to the demand curves.
- Modular architecture allows many units to supply building-scale or street-scale microgrids.
- Ease of grid interconnection (480 V DC bus) with a plug.
- Smart BMS facilitates the integration of demand in the future.

Sub-question 3: The choice of material and manufacturing has defined a framework that focuses on the priorities:

- **Corrosion resistance:** marine grade metals (SAE 316) and UV-resistant polymers (ASA, HDPE).
- **Domestic production:** laser cutting and welding as well as thermoforming, can all be found in South Africa.
- **Lifecycle cost:** long-lasting materials cut down maintenance costs on installations that are difficult to reach.
- **Sustainability:** recyclable metals and plastics, conflict-free magnets.

7.4 Future Research Directions

7.4.1 Field testing (top priority) and physical prototyping.

- Construct and establish 1-3 pilot units in representative Cape Town locations.
- Authenticate energy production within a period of 12 months.

- Evaluate actual acoustics (<45dB(A)) and structural performance in the presence of gusts.
- Evaluate magnetic bearing and maintenance requirements.

7.4.2 Lifecycle and economic analysis

- Pricing of the suppliers in South Africa.
- Prototyping serial cost models of 100, 500, and 1000 units.
- Total cost of ownership, which is a combination of installation, maintenance, and replacement.
- Return on investment, tariff, wind quality, system life.
- Compare Photovoltaic on the roof on a cost-per-kWh basis.

7.4.3 High-level simulation and optimisation

- Full 3 -D turbulent flow CFD to optimize blade profile and spacing.
- Stress analysis under SANS10160 wind loads FEA.
- Multi-objective optimisation of blade geometry to Cp, starting torque, and noise: This is achieved using genetic algorithms.

7.4.4 Intelligent integration and controls

- Smart gridded BMS (demand response, peak shaving).
- Internet of Things predictive maintenance sensors.
- array-scale SCADA dashboard deployment.
- Investigate peer-to-peer trading with blockchain in community micro grids.

7.4.5 Hybrid and alternative designs

- Trial Savonius hybrids in hybrids with Darrieus to increase efficiency by 1015% improvement.
- Power increase of 15-20 per cent with deflector plates or shrouds.
- Test rotor stages with more than one to get a higher swept area in high-constrained facilities.

7.5 Implications for Practice

7.5.1 Planners and policymakers of energy

- Urban Vertical-Axis Wind Turbines can be used as an additional generation to be crowded built environments.
- The regulations should be a trade-off between safety and ease of deployment.
- Economic viability may need feed-in tariffs or subsidies.

7.5.2 Designers and engineers

- Accept deployability in the place of theoretical effectiveness.
- The magnetic bearings are demonstrated to be used with low maintenance.
- Co-design generation and storage, not specified individually.

7.5.3 The owners and developers of the buildings

- 5-10 percent of demand is subsidized by single units; array planning.
- It has the capability of rooftop and facade integration using a universal mounting system.
- Residential deployment is made possible due to low noise and low visual impact.

7.6 Final Reflection

The project demonstrates that more than engineering optimisation is needed in order to solve complex socio-technical issues. It requires situational particularity, stakeholder combination, actual performance evaluation, and refining through results. The resultant Vertical-Axis Wind Turbine system might not achieve theoretical maximum efficacy, but instead, it achieves a maximum likelihood of success in the real-life environment. Urban renewable energy. In urban renewable energy, a built system shown to work at 15% efficiency offers greater benefits than a 40% efficient design that never emerges out of the laboratory.

Such a basis makes it possible to conduct future research and commercial development. The roadmap is clear:

1. Create and develop physical models.
2. Refine based on field data.
3. Manufacturing should be optimised to reduce the cost.
4. Create intelligent integration capabilities.

5. Pilot array implementation in the Cape Town municipality.

This is the avenue through which the image of district urban micro grids that run on built-in VAWTs can be achieved, which will enhance energy security and climate resilience of Cape Town.

7.7 Closing Statement

Cape Town is experiencing an energy crisis, and there is a need to find innovative and distributed solutions. This project offers a viable, contextually relevant, and deployable system of VAWT. It is not a perfect design, though it is good enough to build, test, and learn. That is the final test of success in practice-based design research.

Future researchers and practitioners are encouraged to further develop this work, correcting the design in a process of prototyping, testing, and implementation to transform the possibility of a concept on a conceptual level into a sustainable reality.

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8. Appendices:

8.1 Delphi First Round Questionnaire



Delphi Technique Questionnaire: Advancing Urban Energy through Vertical Axis Wind Turbines and Microgrid Integration

B I U

This questionnaire is designed to gather expert opinions on the potential of vertical axis wind turbines (VAWTs) and microgrid systems as solutions for urban energy challenges. Your responses will contribute to a comprehensive understanding of the technical, economic, environmental, and policy considerations associated with VAWT integration and microgrid development.

Please provide your honest and informed responses to the following questions. Your feedback will be used to inform research and policy decisions in the field of urban energy.

1. What are the most critical factors to consider when designing vertical-axis wind turbines for urban environments? *

Please elaborate on the factors related to efficiency, noise reduction, aesthetics, and structural integrity.

Short answer text

2. What are the optimal turbine sizes and locations within urban areas to maximize energy production while minimizing visual impact and noise pollution? *

Consider factors such as building heights, wind patterns, and local regulations.

Short answer text

3. How can vertical-axis wind turbines be most effectively integrated into existing microgrid systems? *

Address issues related to power output variability, grid stability, and energy storage solutions.

Short answer text

4. What are the key challenges and potential solutions for ensuring the reliability and resilience of microgrids incorporating vertical-axis wind turbines? *

Discuss factors such as grid security, fault tolerance, and backup power sources.

Short answer text

5. In your opinion, what are the economic and environmental benefits of deploying vertical-axis wind turbines in urban microgrids? *

Quantify potential savings in energy costs, reductions in greenhouse gas emissions, and other positive impacts.

Short answer text

6. What are the regulatory and policy barriers to the widespread adoption of vertical-axis wind turbines in urban areas? *

Identify potential obstacles and suggest strategies for overcoming them.

Short answer text

7. What are the most promising advancements in vertical-axis wind turbine technology that could improve their performance and efficiency? *

Discuss innovations related to blade design, control systems, and materials.

Short answer text

8. How can public acceptance and support for vertical-axis wind turbines be fostered in urban communities? *

Consider strategies for education, outreach, and addressing concerns about visual impact and noise.

Short answer text

9. What are the long-term maintenance and operational costs associated with vertical-axis wind turbines in urban environments? *

Evaluate factors such as accessibility, repair frequency, and the need for specialized expertise.

Short answer text

10. How can data analytics and smart grid technologies be leveraged to optimize the performance of vertical-axis wind turbines and microgrids? *

Discuss the potential benefits of real-time monitoring, predictive maintenance, and demand response.

Short answer text

11. What are the potential synergies between vertical-axis wind turbines and other renewable energy sources (e.g., solar PV, battery storage) in urban microgrids? *

Explore opportunities for complementary energy production and consumption.

Short answer text

12. Based on your expertise, what are the most promising future applications of vertical-axis wind turbines and microgrids in urban settings? *

Consider potential uses in residential, commercial, and industrial sectors, as well as for critical infrastructure.

Short answer text

8.1.1 Delphi Questionnaire 1 - Participant One Response

Delphi Technique Questionnaire 1: Advancing Urban Energy through Vertical Axis Wind Turbines and Microgrid Integration

This questionnaire is designed to gather expert opinions on the potential of vertical axis wind turbines (VAWTs) and microgrid systems as solutions for urban energy challenges. Your responses will contribute to a comprehensive understanding of the technical, economic, environmental, and policy considerations associated with VAWT integration and microgrid development.

Please provide your honest and informed responses to the following questions. Your feedback will be used to inform research and policy decisions in the field of urban energy.

1. What are the most critical factors to consider when designing vertical-axis wind turbines for urban environments? *

Please elaborate on the factors related to efficiency, noise reduction, aesthetics, and structural integrity.

When designing vertical-axis wind turbines (VAWTs) for urban environments, it's crucial to optimize for efficiency in low, turbulent wind conditions by using aerodynamic blade designs like helical shapes and ensuring low cut-in speeds. Noise reduction is achieved through slower rotational speeds, vibration-dampening materials, and aerodynamic blade adjustments to minimize mechanical and aerodynamic sounds. Aesthetics play a key role in urban acceptance, requiring compact, visually appealing designs that blend with modern architecture, using customizable colors and materials. Structural integrity must ensure durability against variable weather conditions, with corrosion-resistant materials, balanced load distribution, vibration isolation, and robust safety mechanisms to protect surrounding structures and people, while maintaining easy access for maintenance.

2. What are the optimal turbine sizes and locations within urban areas to maximize energy production while minimizing visual impact and noise pollution? *

Consider factors such as building heights, wind patterns, and local regulations.

The optimal size and placement of vertical-axis wind turbines (VAWTs) in urban areas balance energy production with minimal visual and noise impact. Turbine sizes typically range from 1 to 10 kW with heights of 3 to 15 meters, as smaller turbines are less intrusive and better suited to variable, turbulent urban wind conditions. Rooftop installations on buildings at least 15-30 meters high can capture stronger, less obstructed wind flows, especially when placed near edges or corners where wind speeds accelerate due to the Venturi effect. Turbines should be located at least 1.5 times the building height above ground level to avoid turbulence from surrounding structures, while maintaining a safe distance from windows and balconies to reduce noise disturbance. Clustered installations on high-rise buildings or open areas like parking structures can improve efficiency without dominating the skyline. Local regulations often impose height restrictions, noise limits, and aesthetic guidelines, necessitating compliance with zoning laws and noise ordinances, typically limiting sound levels to below 50 dB at property boundaries. Additionally, conducting wind assessments and environmental impact studies ensures turbines are positioned to capture optimal wind flows while minimizing impact on the urban landscape and community.

3. How can vertical-axis wind turbines be most effectively integrated into existing microgrid systems? *

Address issues related to power output variability, grid stability, and energy storage solutions.

Effective integration of VAWTs into existing microgrid systems requires addressing power output variability, grid stability, and energy storage. Power output variability, driven by fluctuating urban wind conditions, can be managed using inverters with Maximum Power Point Tracking (MPPT) to optimize energy conversion and smooth out fluctuations. To maintain grid stability, integrating smart grid controllers and employing voltage-frequency regulation or droop control techniques ensures consistent power quality and prevents voltage sags or frequency deviations. Energy storage solutions, such as lithium-ion or flow batteries, are essential for buffering intermittent output, storing surplus energy during peak wind periods, and supplying power during low-wind intervals. Combining VAWTs with other renewable sources in hybrid systems, like solar PV, can further stabilize generation due to complementary energy patterns. Additionally, demand response strategies help align energy consumption with turbine output. Real-time SCADA systems or IoT-based platforms enhance monitoring, predictive maintenance, and dynamic load management, ensuring optimized energy dispatch and seamless microgrid performance.

4. What are the key challenges and potential solutions for ensuring the reliability and resilience of microgrids incorporating vertical-axis wind turbines? *

Discuss factors such as grid security, fault tolerance, and backup power sources.

Ensuring the reliability and resilience of microgrids with vertical-axis wind turbines (VAWTs) involves addressing challenges related to grid security, fault tolerance, and backup power. Grid security risks, such as cyber threats, can be mitigated with encrypted communication, firewalls, and regular security audits. Fault tolerance is improved through real-time monitoring, advanced grid controllers, protective relays, and microgrid islanding capabilities to maintain operation during disturbances. To counteract power variability, backup power sources like battery energy storage systems, diesel generators, and hybrid renewable setups with solar PV ensure consistent energy supply. Together, these solutions enhance microgrid stability and reliability.

5. In your opinion, what are the economic and environmental benefits of deploying vertical-axis wind turbines in urban microgrids? *

Quantify potential savings in energy costs, reductions in greenhouse gas emissions, and other positive impacts.

Deploying vertical-axis wind turbines (VAWTs) in urban microgrids offers significant economic and environmental benefits. Economically, a 5 kW VAWT can generate approximately 8,000 kWh per year, leading to annual savings of around R17,674 (based on the current Eskom tariff of 220.92 cents per kWh, effective from 1 April 2025). Environmentally, each 5 kW VAWT can reduce about 7.5 tons of CO_2 emissions annually, equivalent to the emissions from burning approximately 850 liters of petrol. These benefits make VAWTs a viable solution for cities aiming to reduce energy costs and carbon footprints while supporting local economies.

6. What are the regulatory and policy barriers to the widespread adoption of vertical-axis wind turbines in urban areas? *

Identify potential obstacles and suggest strategies for overcoming them.

The widespread adoption of vertical-axis wind turbines (VAWTs) in urban areas faces several regulatory and policy barriers, including zoning restrictions, lack of targeted policy support, and absence of standardized technical guidelines. To overcome these obstacles, it is essential to reform policies to support small-scale urban wind projects, implement educational campaigns to inform stakeholders about VAWT benefits, and develop standardized technical guidelines to ensure safety and performance compliance. Addressing these challenges through targeted reforms and strategic initiatives can facilitate the integration of VAWTs into urban energy systems, contributing to sustainable urban development.

7. What are the most promising advancements in vertical-axis wind turbine technology that could improve their performance and efficiency? *

Discuss innovations related to blade design, control systems, and materials.

Recent advancements in vertical-axis wind turbine (VAWT) technology have focused on enhancing performance and efficiency through innovations in blade design, control systems, and materials. In blade design, the development of V-shaped blades and trailing-edge serrations has led to improved aerodynamic performance and noise reduction in Darrieus VAWTs. Advanced control strategies, such as intracycle angular velocity control, optimize turbine rotation rates based on blade position, significantly increasing power output. Material innovations, including the use of advanced composite materials like carbon fiber-reinforced polymers, offer high strength-to-weight ratios, improving durability and performance. Additionally, aluminum is recommended for Savonius-type VAWT blades due to its low cost, lightweight nature, corrosion resistance, and sufficient durability. These developments collectively contribute to more efficient, durable, and adaptable VAWTs, making them increasingly viable for urban and offshore wind energy applications.

8. How can public acceptance and support for vertical-axis wind turbines be fostered in urban communities? *

Consider strategies for education, outreach, and addressing concerns about visual impact and noise.

Fostering public acceptance of vertical-axis wind turbines (VAWTs) in urban areas involves engaging communities through educational initiatives, integrating aesthetically pleasing designs, and addressing concerns about noise and visual impact. Involving residents in planning and providing transparent information can build support, while innovative designs that blend with urban landscapes can mitigate visual concerns. Implementing noise reduction technologies and clearly communicating these efforts can alleviate noise-related apprehensions. These strategies can enhance public receptiveness to VAWTs in urban settings.

9. What are the long-term maintenance and operational costs associated with vertical-axis wind turbines in urban environments? *

Evaluate factors such as accessibility, repair frequency, and the need for specialized expertise.

Vertical-axis wind turbines (VAWTs) in urban environments offer advantages such as easier access for maintenance due to ground-level placement of components like gearboxes and generators. However, urban settings present unique challenges, including exposure to pollution, temperature fluctuations, and debris, which can accelerate wear and tear, potentially increasing maintenance frequency and reducing operational lifespan. The compact nature of urban areas can also complicate access for repairs. To mitigate these issues, regular inspections, cleaning, lubrication, and timely repairs are essential. Implementing predictive maintenance strategies can help identify potential failures before they occur, reducing downtime and extending the turbine's lifespan. While VAWTs generally have fewer moving parts than horizontal-axis turbines, reducing the need for specialized expertise, the urban environment's complexities may still necessitate skilled personnel for effective maintenance and operation.

10. How can data analytics and smart grid technologies be leveraged to optimize the performance of vertical-axis wind turbines and microgrids? *

Discuss the potential benefits of real-time monitoring, predictive maintenance, and demand response.

Leveraging data analytics and smart grid technologies can significantly enhance the performance of vertical-axis wind turbines (VAWTs) within microgrids. Real-time monitoring enables immediate detection of anomalies, facilitating swift corrective actions to maintain optimal operation. Predictive maintenance utilizes historical and real-time data to forecast potential component failures, minimizing unplanned downtime and reducing maintenance costs. Demand response strategies adjust energy consumption patterns in response to supply fluctuations, effectively managing the intermittent nature of wind energy and ensuring a balance between generation and consumption. Incorporating these data-driven approaches enhances the efficiency, reliability, and longevity of VAWTs, contributing to a more resilient and sustainable energy infrastructure.

11. What are the potential synergies between vertical-axis wind turbines and other renewable energy sources (e.g., solar PV, battery storage) in urban microgrids? *

Explore opportunities for complementary energy production and consumption.

Integrating vertical-axis wind turbines (VAWTs) with other renewable energy sources, such as solar photovoltaic (PV) systems and battery storage, in urban microgrids can enhance energy reliability and efficiency. Solar PV generates electricity during daylight hours, while VAWTs can operate continuously, including at night and during overcast conditions, providing a more consistent energy supply. Battery storage systems can store excess energy from both sources, ensuring availability during periods of low generation and high demand. This combination reduces reliance on the main grid and fossil fuels, contributing to lower greenhouse gas emissions and supporting urban sustainability goals. Additionally, smart grid technologies enable real-time monitoring and control, optimizing energy distribution and consumption within the microgrid.

12. Based on your expertise, what are the most promising future applications of vertical-axis wind turbines and microgrids in urban settings? *

Consider potential uses in residential, commercial, and industrial sectors, as well as for critical infrastructure.

Vertical-axis wind turbines (VAWTs) are increasingly recognized for their potential in urban microgrids across residential, commercial, industrial, and critical infrastructure sectors. In residential settings, VAWTs can be installed on rooftops to provide on-site renewable energy, reducing reliance on the main grid and lowering electricity costs. Commercial and industrial applications benefit from VAWTs' ability to offset energy consumption, leading to significant cost savings and enhanced sustainability profiles. For example, the Pearl River Tower in Guangzhou, China, integrates VAWTs within its structure to harness wind energy. In critical infrastructure, such as hospitals and emergency response centers, VAWTs offer a resilient power source, ensuring continuous energy supply during grid outages. By embracing VAWTs, urban areas can enhance energy resilience, reduce environmental impact, and promote sustainable development across various sectors.

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8.1.2 Delphi Questionnaire 1 - Participant Two Response

Delphi Technique Questionnaire 1: Advancing Urban Energy through Vertical Axis Wind Turbines and Microgrid Integration

This questionnaire is designed to gather expert opinions on the potential of vertical axis wind turbines (VAWTs) and microgrid systems as solutions for urban energy challenges. Your responses will contribute to a comprehensive understanding of the technical, economic, environmental, and policy considerations associated with VAWT integration and microgrid development.

Please provide your honest and informed responses to the following questions. Your feedback will be used to inform research and policy decisions in the field of urban energy.

1. What are the most critical factors to consider when designing vertical-axis wind turbines for urban environments? *

Please elaborate on the factors related to efficiency, noise reduction, aesthetics, and structural integrity.

When designing vertical-axis wind turbines for urban environments, it is important to consider factors such as safety which is paramount due to the proximity to people and buildings, necessitating robust design and safety mechanisms. Noise reduction is essential for community acceptance in densely populated areas. Efficiency in turbulent and multidirectional winds, which are typical in urban settings, needs to be optimized through innovative blade designs and control systems. Space constraints dictate compact and aesthetically pleasing designs that can be integrated into the built environment, including rooftops and building facades. Cost-effectiveness, including installation and maintenance, is essential for the economic viability of an urban wind energy concept.

2. What are the optimal turbine sizes and locations within urban areas to maximize energy production while minimizing visual impact and noise pollution? *

Consider factors such as building heights, wind patterns, and local regulations.

The optimal turbine sizes and locations in urban areas to maximize energy production while minimizing visual impact and noise pollution involve a careful balance. Generally, smaller turbines are more suitable for urban integration due to less visual intrusion and lower noise levels. Rooftops of taller buildings with flat surfaces and open areas away from immediate residential zones are often considered optimal locations as they can capture stronger, less turbulent winds found at higher elevations and reduce noise impact at ground level. Integrating turbines into building design or using aesthetically pleasing designs can further mitigate visual impact. Computational fluid dynamics (CFD) simulations and on-site wind measurements are important for identifying specific locations with favorable wind resources while considering the surrounding urban environment to minimize negative impacts.

3. How can vertical-axis wind turbines be most effectively integrated into existing microgrid systems? *

Address issues related to power output variability, grid stability, and energy storage solutions.

Vertical-axis wind turbines can be most effectively integrated into existing microgrid systems by strategically locating them to complement other distributed generation sources, such as solar photovoltaic systems. Since wind resources can be more available at different times than solar, a hybrid approach enhances the reliability and stability of the microgrid's power supply. Implementing smart grid technologies and control systems is needed for managing the intermittent nature of wind energy, allowing for efficient energy storage and dispatch. Designing a microgrid with adequate energy storage solutions, like batteries, ensures that the energy generated by the turbines can be utilized even when the wind is not blowing. Considering the local wind resource assessment and tailoring the turbine size and placement to maximize energy capture while minimizing any negative impacts on the microgrid's operation is also essential.

4. What are the key challenges and potential solutions for ensuring the reliability and resilience of microgrids incorporating vertical-axis wind turbines? *

Discuss factors such as grid security, fault tolerance, and backup power sources.

Ensuring the reliability and resilience of microgrids incorporating vertical-axis wind turbines requires a focus on system architecture and component integration. Designing the microgrid with redundant power pathways and modular components enhances fault tolerance, allowing for isolation of failures without system-wide disruption. Strategic placement of turbines and other generation sources within the microgrid layout can optimize energy flow and minimize transmission losses. Physical security considerations, such as robust enclosures and access control, are vital for protecting critical infrastructure. The sizing and selection of energy storage solutions must be carefully considered to match the expected wind energy generation profile and load demands, providing sufficient backup during periods of low wind. The overall design should prioritize simplicity and maintainability, allowing for ease of inspection, repair, and upgrades, contributing to long-term reliability and resilience.

5. In your opinion, what are the economic and environmental benefits of deploying vertical-axis wind turbines in urban microgrids? *

Quantify potential savings in energy costs, reductions in greenhouse gas emissions, and other positive impacts.

Deploying vertical-axis wind turbines in urban microgrids offers several economic and environmental advantages. Economically, designing the microgrid to offset a portion of the urban area's electricity demand with locally generated wind power can lead to significant reductions in energy costs, potentially ranging from 10% to 30% depending on wind resources and turbine integration. Environmentally, this localized generation directly reduces reliance on fossil fuel-based power plants, leading to a quantifiable decrease in greenhouse gas emissions. For example, a well-designed urban microgrid incorporating vertical axis wind turbines could potentially reduce carbon dioxide emissions by 50 to 150 kilograms per megawatt-hour of generated wind energy. The reduced need for extensive transmission infrastructure associated with centralized power generation translates to lower material use and minimized environmental impact from construction. Designing for noise reduction and aesthetic integration also contributes to a more positive environmental and social impact within the urban landscape.

6. What are the regulatory and policy barriers to the widespread adoption of vertical-axis wind turbines in urban areas? *

Identify potential obstacles and suggest strategies for overcoming them.

The widespread adoption of vertical-axis wind turbines in urban areas faces multiple regulatory and policy barriers. Zoning regulations often lack specific guidelines for small-scale wind energy systems, particularly in built environments, creating uncertainty for project development. Building codes may not adequately address the structural integration and safety requirements of rooftop or building-mounted turbines. Permitting processes can be complex and lengthy, involving multiple agencies with potentially conflicting requirements regarding noise, visual impact, and safety clearances. Strategies to overcome these obstacles include advocating for clear and specific inclusion of small wind energy in urban zoning ordinances and building codes. Developing streamlined permitting processes with standardized application requirements and timelines would also be beneficial. Demonstrating successful pilot projects with well-designed, aesthetically integrated, and quiet turbines can help build public and regulatory acceptance, paving the way for more supportive policies and regulations.

7. What are the most promising advancements in vertical-axis wind turbine technology that could improve their performance and efficiency? *

Discuss innovations related to blade design, control systems, and materials.

Promising advancements in vertical-axis wind turbine technologies are focused on enhancing performance and efficiency through innovative design choices such as the blade design, these significant improvements are being explored with variable pitch blades that can adjust their angle in response to changing wind conditions, optimizing energy capture and reducing stress. Aerodynamic profiling, inspired by nature (like the tubercles on whale fins), aims to increase lift and reduce drag. Hybrid designs, combining Savonius and Darrieus features, seek to improve both starting torque and high-speed efficiency. Advancements include smart sensors and real-time monitoring to optimize turbine operation based on wind conditions and load demands. Implementing active control of blade pitch or other aerodynamic surfaces allows for dynamic adjustments to maximize power extraction and mitigate structural loads. The main stream focus is on developing lightweight and high-strength composites, such as carbon fiber and advanced polymers, which enable the design of larger, more efficient blades without compromising structural integrity. Modular designs using advanced materials can also simplify manufacturing and installation. Designing for durability and reduced fatigue in the materials used is crucial for the longevity and reliability of vertical axis wind turbines in urban environments.

8. How can public acceptance and support for vertical-axis wind turbines be fostered in urban communities? *

Consider strategies for education, outreach, and addressing concerns about visual impact and noise.

Fostering public acceptance and support for vertical-axis wind turbines in urban communities requires a focus on thoughtful integration and clear communication. Designing turbines with aesthetically pleasing forms and finishes that blend with the urban landscape can significantly mitigate negative visual impacts. Implementing noise reduction technologies in the turbine design, such as optimized blade profiles and vibration dampening, is vital for addressing noise concerns. Designing interactive displays or demonstration projects within urban spaces can provide tangible examples of the technology and its positive contributions. Transparency regarding project planning, noise levels, and safety measures is essential for building trust and gaining public support for these types of installations.

9. What are the long-term maintenance and operational costs associated with vertical-axis wind turbines in urban environments? *

Evaluate factors such as accessibility, repair frequency, and the need for specialized expertise.

Long-term maintenance and operational costs of vertical-axis wind turbines in urban environments are influenced by design choices made through the development process. Designing for easy accessibility for inspection and maintenance is important, impacting labor costs and downtime. Modular designs with readily replaceable components can reduce repair frequency and complexity. The need for specialized expertise can be minimized by selecting robust and reliable components and designing systems with built-in monitoring and diagnostics. Factors such as protection against urban pollutants and potential vandalism should also be considered in the design to reduce wear and tear. While specific costs vary, a well-designed vertical axis wind turbine system in an urban setting should aim for infrequent major overhauls, focusing on routine inspections and easily manageable component replacements to keep operational costs predictable and relatively low over its lifespan.

10. How can data analytics and smart grid technologies be leveraged to optimize the performance of vertical-axis wind turbines and microgrids? *

Discuss the potential benefits of real-time monitoring, predictive maintenance, and demand response.

Data analytics and smart grid technologies offer significant opportunities to optimize the performance of vertical-axis wind turbines and microgrids. Real-time monitoring systems, integrated into the turbine and microgrid design, can provide continuous data on wind conditions, turbine performance, and energy flow, allowing for immediate adjustments to maximize energy capture. Predictive maintenance algorithms, utilizing historical and real-time data, can anticipate potential failures in turbine components, enabling proactive maintenance interventions and reducing downtime. Demand response capabilities, facilitated by smart grid technologies, allow the microgrid to dynamically adjust energy consumption based on available wind generation and grid conditions, optimizing energy use and reducing reliance on backup sources. Designing the system with robust data acquisition and communication infrastructure is essential to fully leverage these benefits, leading to improved efficiency, reliability, and cost-effectiveness.

11. What are the potential synergies between vertical-axis wind turbines and other renewable energy sources (e.g., solar PV, battery storage) in urban microgrids? *

Explore opportunities for complementary energy production and consumption.

Significant synergies exist between vertical-axis wind turbines and other renewable energy sources like solar photovoltaic (PV) and battery storage within urban microgrids. Designing the microgrid to incorporate complementary energy production profiles is key; for instance, solar PV typically generates during the day, while wind resources might be stronger at night or during different seasons. Strategic placement of vertical axis wind turbines to capture urban wind patterns that differ from optimal solar locations maximizes overall energy yield. Battery storage systems act as an important interface, smoothing out the intermittent nature of both wind and solar, ensuring a more consistent and reliable power supply to meet demand. The design should optimize the sizing and control of these combined assets to leverage periods of high renewable generation, storing excess energy for later use and enhancing the microgrid's self-sufficiency and resilience.

12. Based on your expertise, what are the most promising future applications of vertical-axis wind turbines and microgrids in urban settings? *

Consider potential uses in residential, commercial, and industrial sectors, as well as for critical infrastructure.

The future holds promising applications for vertical-axis wind turbines and microgrids in urban settings, moving beyond simple electricity generation. Building-integrated wind energy systems will likely become more prevalent, with vertical-axis wind turbines designed as architectural elements providing on-site power for residential and commercial buildings. We may see hybrid urban energy hubs that combine vertical-axis wind turbines with solar PV, battery storage, and even electric vehicle charging infrastructure, creating localized, resilient energy ecosystems. Small-scale, portable vertical-axis wind turbines designs could emerge for temporary power needs at events or construction sites, integrated within a mobile microgrid unit. The development of smart city infrastructure will see vertical-axis wind turbines and microgrids playing a huge role in powering public amenities like street lighting, traffic management systems, and community centers, enhancing urban sustainability and energy independence.

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8.1.3 Delphi Questionnaire 1 - Participant Three Response

Delphi Technique Questionnaire 1: Advancing Urban Energy through Vertical Axis Wind Turbines and Microgrid Integration

This questionnaire is designed to gather expert opinions on the potential of vertical axis wind turbines (VAWTs) and microgrid systems as solutions for urban energy challenges. Your responses will contribute to a comprehensive understanding of the technical, economic, environmental, and policy considerations associated with VAWT integration and microgrid development.

Please provide your honest and informed responses to the following questions. Your feedback will be used to inform research and policy decisions in the field of urban energy.

1. What are the most critical factors to consider when designing vertical-axis wind turbines for urban environments? *

Please elaborate on the factors related to efficiency, noise reduction, aesthetics, and structural integrity.

Thinking about designing vertical-axis wind turbines for our cities, there are some really key things that jump out from a design perspective. Efficiency in those gusty, unpredictable urban winds is a big one – we need designs that can actually capture energy effectively even when the wind is swirling around buildings. Then there's noise reduction; nobody wants a noisy turbine right outside their window, so quiet operation is paramount in the design. Aesthetics are also surprisingly important – these turbines will be part of the cityscape, so they need to look decent and maybe even be visually appealing. Structural integrity is non-negotiable; these things need to be safe and stand up to the stresses of urban environments, including strong winds and potential impacts. Getting these four aspects right is key for successful urban vertical-axis wind turbines deployment.

2. What are the optimal turbine sizes and locations within urban areas to maximize energy production while minimizing visual impact and noise pollution? *

Consider factors such as building heights, wind patterns, and local regulations.

Figuring out the sweet spot for turbine size and location in cities is a balancing act. Generally, smaller turbines, maybe in the range of a few kilowatts up to around 50 kilowatts, tend to be a better fit as they're less visually obtrusive and produce less noise. Location-wise, higher elevations like rooftops of suitable buildings can often access better wind resources above the urban clutter. We need to consider the building's structural capacity and local regulations about height and rooftop installations. Thinking about integrating turbines into the building's design itself can help minimize visual impact. When assessing potential spots, you'd need to look closely at wind patterns around buildings – Computational Fluid Dynamics (CFD) can be really helpful here – and factor in local noise ordinances to ensure we're not creating a nuisance for the neighbors. It's all about finding that clever design solution that maximizes energy without compromising the urban environment.

3. How can vertical-axis wind turbines be most effectively integrated into existing microgrid systems? *

Address issues related to power output variability, grid stability, and energy storage solutions.

When thinking about plugging vertical-axis wind turbines into existing microgrids, the design approach needs to be smart about a few things. Power output from wind can be a bit all over the place, so the integration needs to handle that variability smoothly. Designing the microgrid with robust control systems is key – these can help manage the fluctuating wind power and balance it with other energy sources in the grid. Grid stability is paramount, so the design should include features that prevent sudden changes in wind power from causing disruptions. And then there's energy storage, like batteries; these are key factors for soaking up excess wind energy when it's available and releasing it when it's not, making the whole system more reliable and predictable. So, a well-designed integration considers these factors upfront to ensure the vertical-axis wind turbines and the microgrid play well together.

4. What are the key challenges and potential solutions for ensuring the reliability and resilience of microgrids incorporating vertical-axis wind turbines? *

Discuss factors such as grid security, fault tolerance, and backup power sources.

Designing microgrids with vertical-axis wind turbines and keeping them reliable and resilient throws up a few interesting challenges. Grid security is definitely on the list – these localized grids need to be protected from cyber threats and physical tampering. Then there's fault tolerance; we need the system to keep running even if a component fails, so built-in redundancy and smart isolation designs are important. And because the wind doesn't always blow, having backup power sources integrated into the design, like solar or generators, is pivotal for ensuring a continuous supply. Potential solutions involve designing with layered security measures, incorporating modularity and automated fault detection, and carefully planning the capacity and type of backup generation to complement the wind resource. It's about designing a system that's both robust and adaptable.

5. In your opinion, what are the economic and environmental benefits of deploying vertical-axis wind turbines in urban microgrids? *

Quantify potential savings in energy costs, reductions in greenhouse gas emissions, and other positive impacts.

Weaving vertical-axis wind turbines into urban microgrids brings some pretty neat economic and environmental perks. Economically, by designing the microgrid to tap into local wind, we can see potential savings on energy costs, maybe in the ballpark of 15% to 35% depending on how windy the location is and how well the system is optimized. Environmentally, it’s a direct win as we're reducing our reliance on traditional, often fossil-fuel-based power, which translates to a tangible drop in greenhouse gas emissions. For every megawatt-hour of wind energy we generate, we could be looking at avoiding, say, 0.5 to 1 tonne of CO2 emissions compared to coal-fired power. Plus, designing for local energy generation can cut down on transmission losses from long-distance power lines, which is another subtle environmental benefit. It’s about designing a more sustainable and potentially cheaper energy future right in the heart of our cities.

6. What are the regulatory and policy barriers to the widespread adoption of vertical-axis wind turbines in urban areas? *

Identify potential obstacles and suggest strategies for overcoming them.

From a design and project management angle, the path to widespread vertical-axis wind turbine adoption in cities definitely has some regulatory and policy hurdles. We often see zoning regulations that weren't really written with small-scale urban wind in mind, so navigating those can be tricky. Then there are building codes that might not have clear guidelines for integrating turbines onto or into structures, which creates uncertainty. And let's not forget the permitting processes – they can be complex and involve multiple approvals, sometimes with conflicting requirements around things like noise and visual impact. To smooth things out, we could focus on advocating for clearer, specific policies that address urban wind energy explicitly. Developing standardized permitting pathways and providing clear technical guidelines for safe and effective integration into buildings would also make a big difference. Demonstrating successful, well-designed pilot projects can also help build confidence and inform better regulations down the line. It's about working to create a more enabling framework for these technologies.

7. What are the most promising advancements in vertical-axis wind turbine technology that could improve their performance and efficiency? *

Discuss innovations related to blade design, control systems, and materials.

The future for vertical-axis wind turbines is looking pretty interesting thanks to some cool tech advancements. When it comes to blade design, we're seeing potential in things like variable pitch blades that can adjust on the fly to catch the wind better, and also in aerodynamic tweaks inspired by nature, like those bumps on whale fins, to improve lift and reduce drag. For control systems, the move towards smarter sensors and real-time adjustments will allow turbines to optimize their operation based on the ever-changing urban wind. And in terms of materials, the development of lighter, stronger composites means we can design bigger, more efficient blades that can still handle the stresses of urban environments without being too heavy or cumbersome. These innovations across blade design, control, and materials are all pointing towards a significant boost in how well VAWTs can perform and how efficiently they can capture energy in our cities.

8. How can public acceptance and support for vertical-axis wind turbines be fostered in urban communities? *

Consider strategies for education, outreach, and addressing concerns about visual impact and noise.

Getting the public on board with vertical-axis wind turbines in urban areas really boils down to smart integration and clear communication. On the design front, one can focus on creating turbines that are aesthetically pleasing – think sleek, modern designs that blend in or even enhance the urban landscape. Priority should be given to noise reduction in the engineering, making them as quiet as possible so they don't disrupt daily life. Then, from a project side, education and outreach are key. Clear communication is need to explain the benefits of urban wind energy to the community, address any concerns about visual impact or noise head-on with facts and visualizations. Showing successful examples and highlighting the positive environmental and potentially economic impacts can go a long way in building trust and support. It's about designing not just the technology, but also the way it fits into the community.

9. What are the long-term maintenance and operational costs associated with vertical-axis wind turbines in urban environments? *

Evaluate factors such as accessibility, repair frequency, and the need for specialized expertise.

Thinking about the long haul with vertical-axis wind turbines in our cities, the maintenance and operational costs are definitely something we consider right from the design stage. One would be looking at designing for good accessibility so that inspections and any necessary work are straightforward without needing specialized equipment or causing major disruptions. Aiming for a design that minimizes repair frequency through robust component selection and smart engineering is also key for keeping costs down. And ideally, the design would allow for maintenance that doesn't always require highly specialized expertise, making it more cost-effective and easier to manage over the turbine's lifespan. Factors like the urban environment itself – potential for more wear and tear from pollutants or even vandalism – would also influence our design choices to try and keep those long-term costs predictable and manageable.

10. How can data analytics and smart grid technologies be leveraged to optimize the performance of vertical-axis wind turbines and microgrids? *

Discuss the potential benefits of real-time monitoring, predictive maintenance, and demand response.

Data analytics and smart grid tech are game-changers for getting the most out of vertical-axis wind turbines and microgrids. By designing systems with real-time monitoring capabilities, we can constantly track how the turbines are performing and how the microgrid is behaving, allowing for immediate tweaks to optimize energy capture. Then there's predictive maintenance – using data to spot potential issues before they become big problems, which saves on downtime and repair costs. And with demand response built into the smart grid design, we can intelligently manage energy consumption based on when the wind is blowing strongest, making the whole system more efficient and reducing reliance on other power sources. It's all about designing a smart, data-driven energy ecosystem.

11. What are the potential synergies between vertical-axis wind turbines and other renewable energy sources (e.g., solar PV, battery storage) in urban microgrids? *

Explore opportunities for complementary energy production and consumption.

The potential for vertical-axis wind turbines to team up with other renewables like solar PV and battery storage is pretty exciting. We can design systems that really leverage their complementary energy production patterns. Such an example could be solar, which is great during the day, while urban winds might pick up more in the evenings or different seasons – so together, they can provide a more consistent power supply. Battery storage acts as the perfect partner, this could aid in smoothing out the peaks and troughs from both wind and solar, storing energy when it's abundant and releasing it when it's needed. Careful designing of the size and control of these different elements can create a much more reliable and self-sufficient urban energy system. It's about designing a well-orchestrated renewable energy system.

12. Based on your expertise, what are the most promising future applications of vertical-axis wind turbines and microgrids in urban settings? *

Consider potential uses in residential, commercial, and industrial sectors, as well as for critical infrastructure.

I see some really interesting avenues for vertical-axis wind turbines and microgrids in our cities. For residential areas, there might be more building-integrated vertical-axis wind turbines, designed as part of the architecture to provide localized power. In the commercial sector, think about businesses using microgrids with on-site wind and solar to reduce their energy costs and enhance resilience. Industrial sites within urban areas could also benefit from these localized energy solutions, especially for processes that require a reliable power supply. Perhaps most importantly, for critical infrastructure like hospitals or emergency services, microgrids with vertical-axis wind turbines and storage could offer vital backup power, increasing their resilience during grid outages. We might even see innovative applications like powering electric vehicle charging stations or integrating them into smart city infrastructure for street lighting and other urban services. It's about designing distributed, resilient, and sustainable energy solutions right where people live and work.

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8.2 Delphi First Round Questionnaire

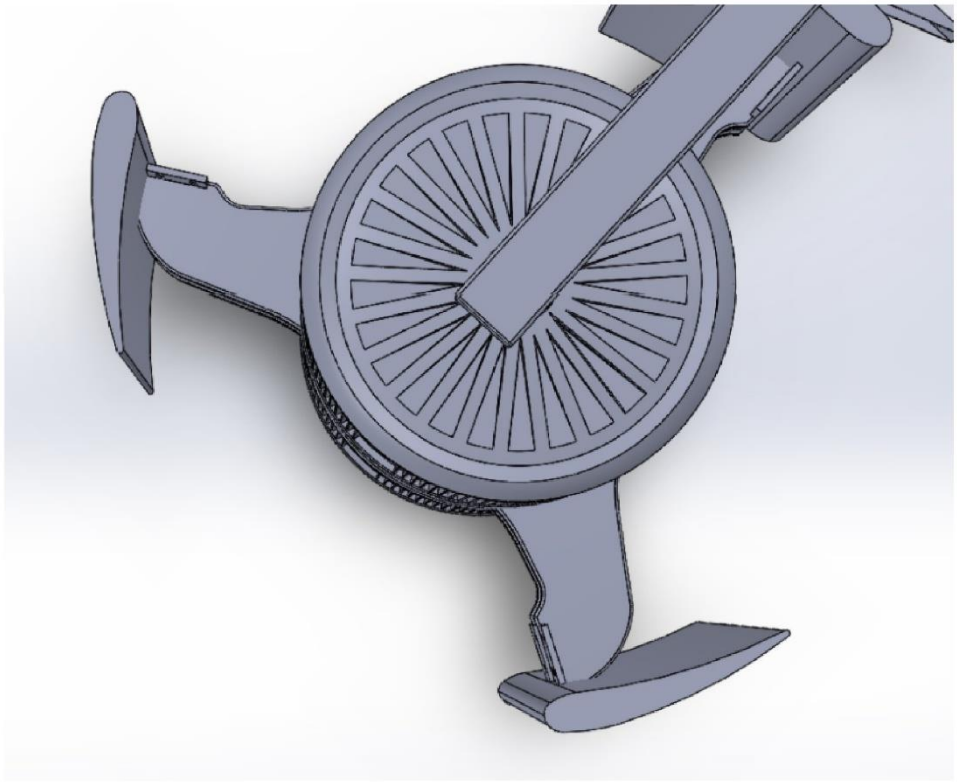


Delphi Technique Questionnaire 2: Advancing Urban Energy through Vertical Axis Wind Turbines and Microgrid Integration

The second-round survey will focus on obtaining more detailed expert research on the initial design concept and SolidWorks CAD model developed on a vertical axis wind turbine (VAWT) comprised of a microgrid system. The feedback will be directed directly to the next process of design refinement and will concentrate on the technical feasibility of the design, soundness of the structure, material selection and on the system optimization. The discrete design elements that I would have you critically assess are the blade geometry, energy storage casting operating, generators choice and support structures and the points of integration of microgrids with their joints. This experience will help in enhancing functionality, serviceability, and cost-effectiveness of the proposed solution to urban energy resilience. Please review the screenshots of the CAD model and answer the following questions in an informed way. Your knowledge will be very essential in the research process and development of realistic energy models that are practical in the urban setting.

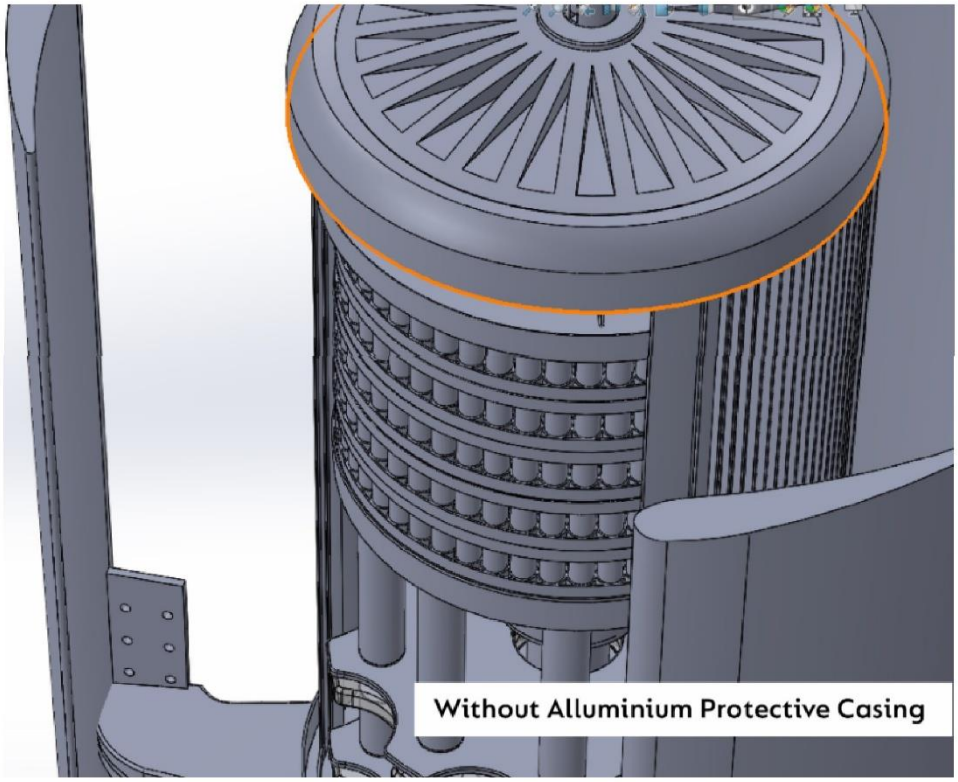
Owing to your time, wisdom and information. I can not overestimate your role in this project.

1. How effective is the current blade geometry in optimizing aerodynamic performance and structural integrity? *
(Refer to Screenshot 1: Blade geometry CAD view)



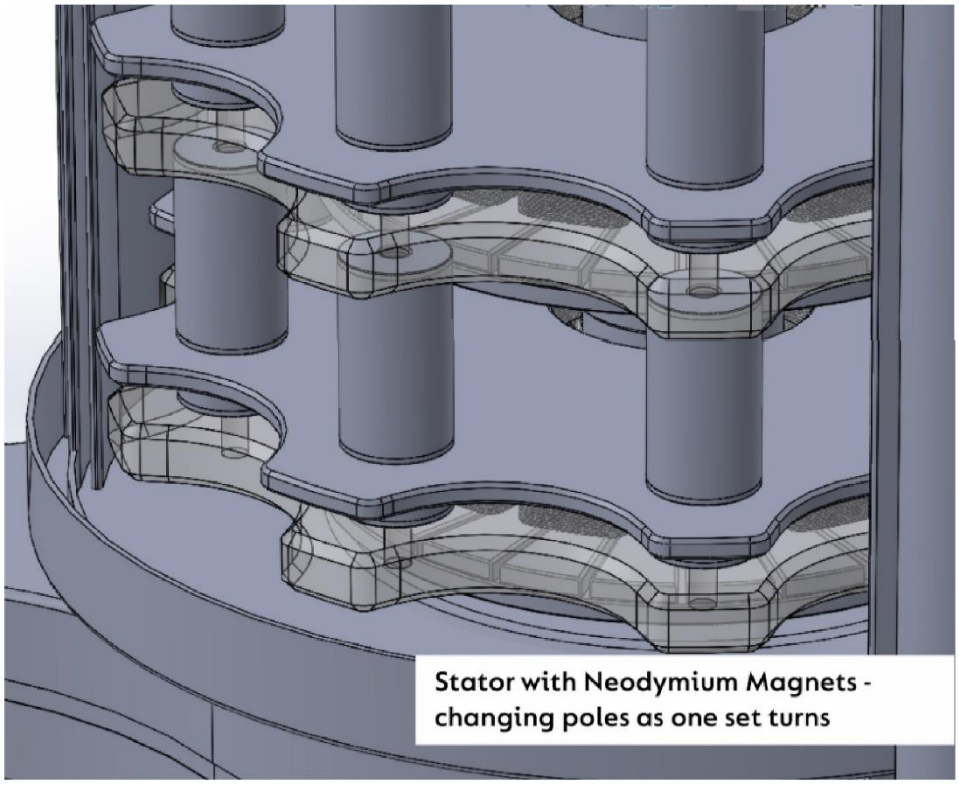
Short answer text

2. Does the proposed casing mechanism for the energy storage system present any foreseeable manufacturing or operational challenges? *(Refer to Screenshot 2: Energy storage system layout)* *



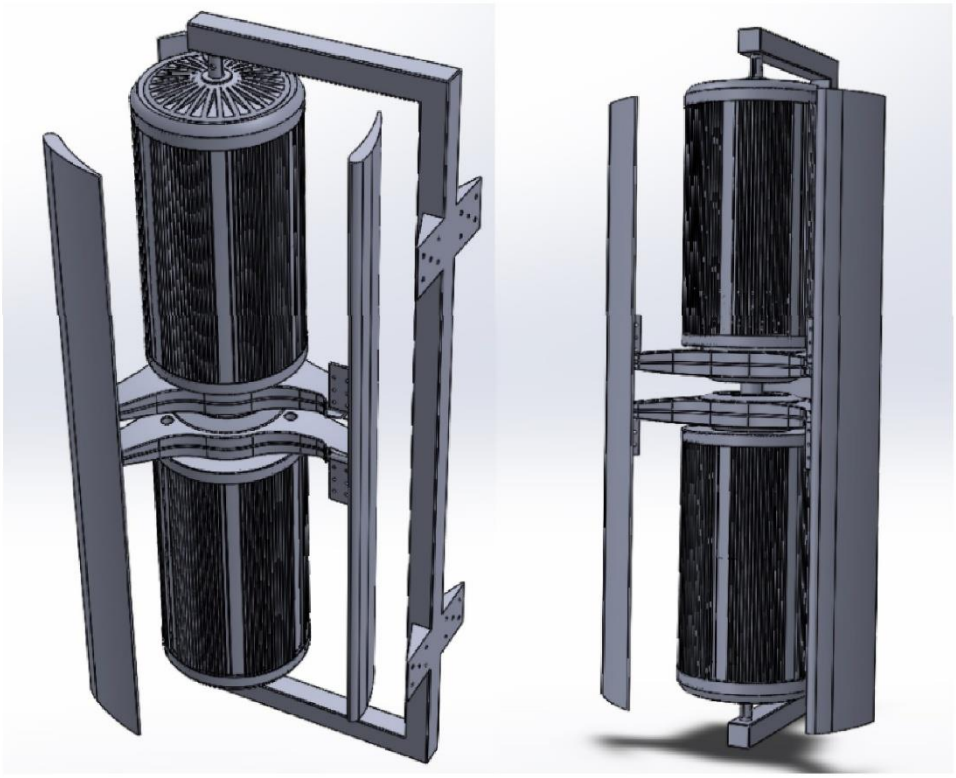
Short answer text

3. Is the selected generator type appropriate for the intended energy output and environmental conditions? Please elaborate. *(Refer to Screenshot 3: Generator integration model)* *



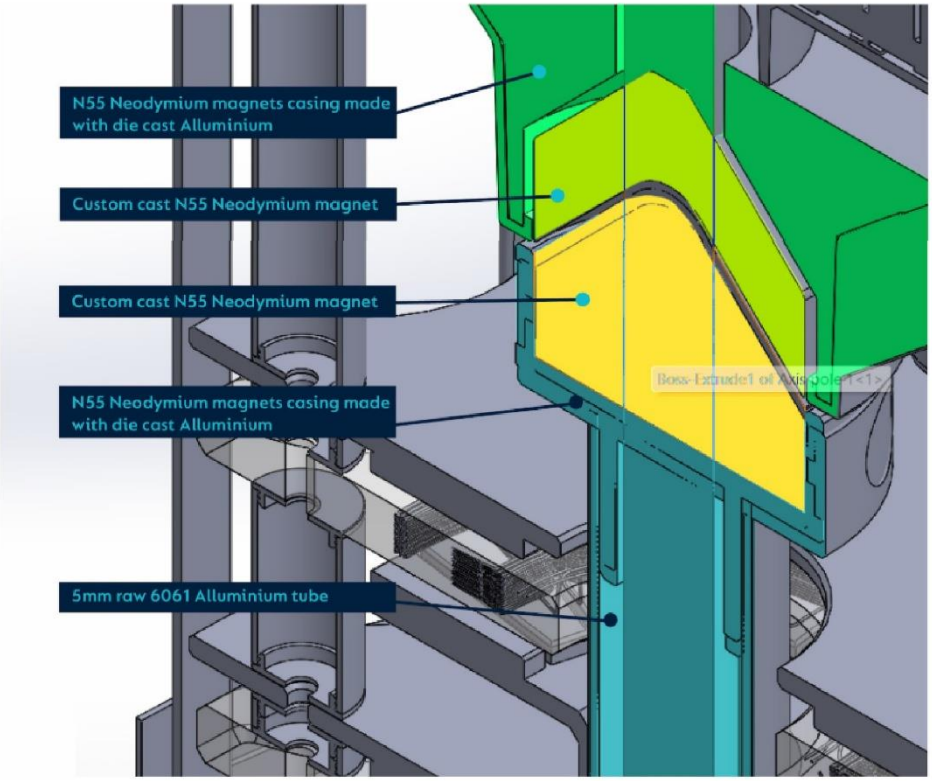
Short answer text

4. Evaluate the soundness and stability of the supporting structures under expected load conditions. Are there any areas of concern? *(Refer to Screenshot 4: Structural framework)* *



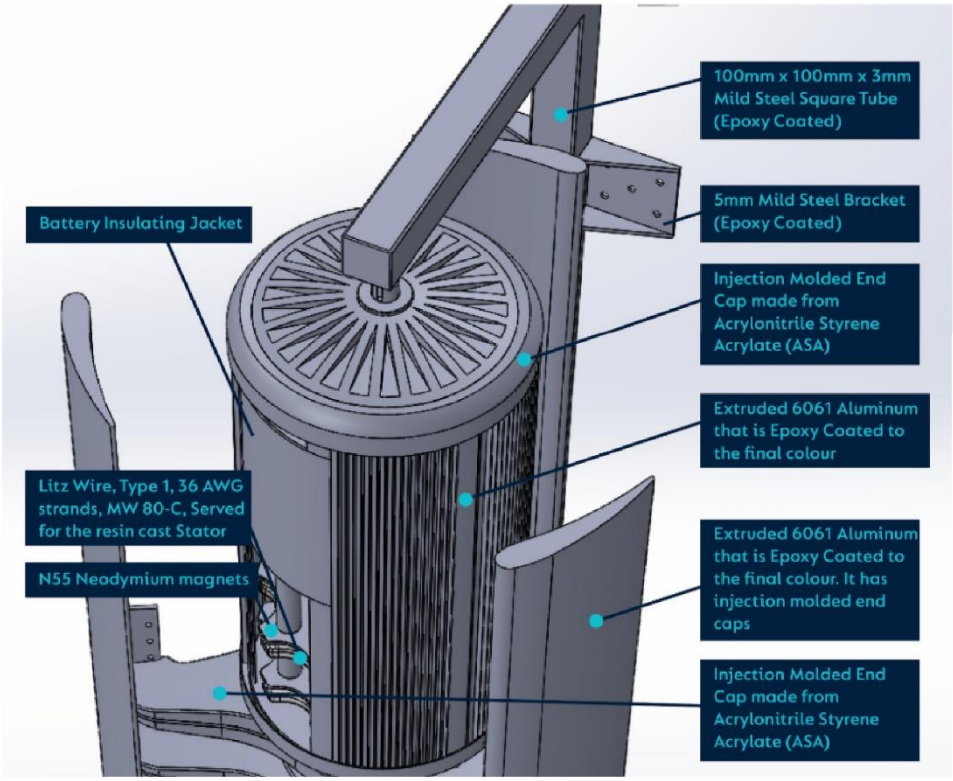
Short answer text

5. How effective is the integration of floating magnetic bearings within the axis tube in minimizing friction, enhancing rotational stability, and extending the operational lifespan of the vertical axis wind turbine? Please refer to the figure below for a visual representation of the bearing placement and axis configuration, and comment on any potential limitations or suggested improvements. *



Short answer text

6. Are the proposed materials suitable for long-term durability, cost efficiency, and environmental resilience? *(Refer to Screenshot 6: Material specification overlay)* *



Short answer text

7. What technical forethoughts should be considered to enhance maintainability and reduce lifecycle costs? *

Short answer text

8. Do you think that the current design allows for modular upgrades or scalability in future iterations? If not, what changes would you suggest? *

Short answer text

9. Are there any design elements that might hinder manufacturability or assembly at scale? Please specify. *

Short answer text

10. Based on your domain expertise, what performance optimizations would you recommend to improve system efficiency or reduce energy loss? *

Short answer text

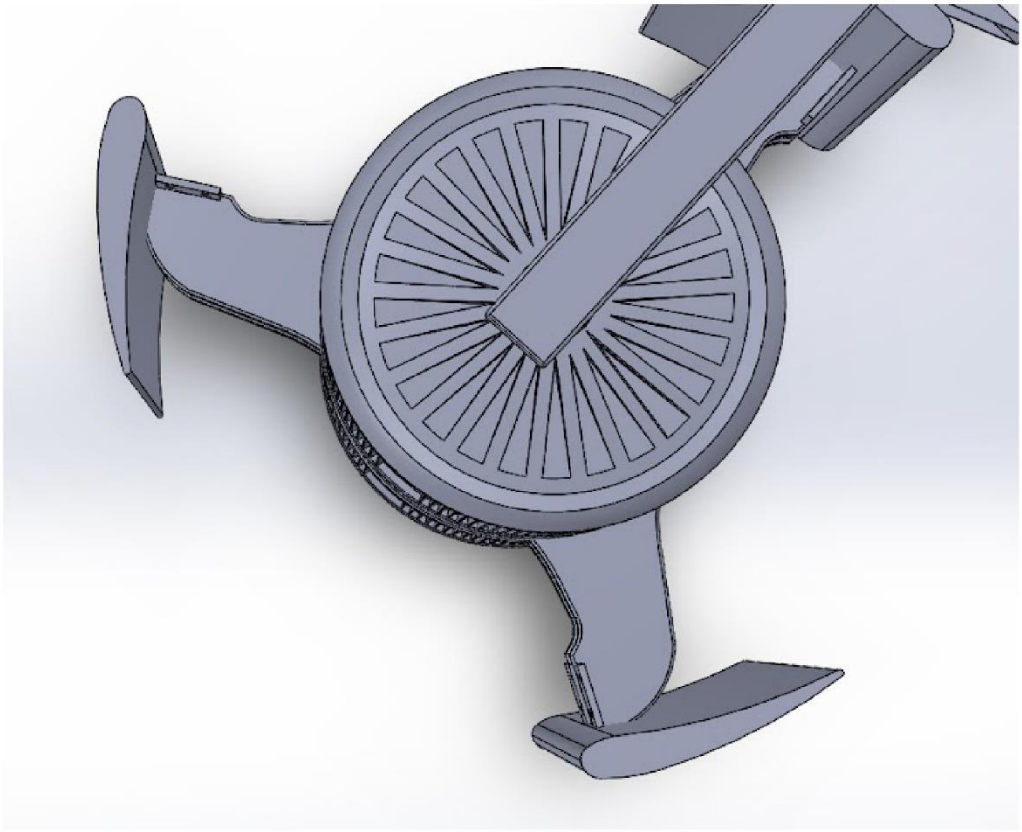
8.2.1 Delphi Questionnaire 2 - Participant One Response

Delphi Technique Questionnaire 2: Advancing Urban Energy through Vertical Axis Wind Turbines and Microgrid Integration

The second-round survey will focus on obtaining more detailed expert research on the initial design concept and SolidWorks CAD model developed on a vertical axis wind turbine (VAWT) comprised of a microgrid system. The feedback will be directed directly to the next process of design refinement and will concentrate on the technical feasibility of the design, soundness of the structure, material selection and on the system optimization.
The discrete design elements that I would have you critically assess are the blade geometry, energy storage casting operating, generators choice and support structures and the points of integration of microgrids with their joints. This experience will help in enhancing functionality, serviceability, and cost-effectiveness of the proposed solution to urban energy resilience.
Please review the screenshots of the CAD model and answer the following questions in an informed way. Your knowledge will be very essential in the research process and development of realistic energy models that are practical in the urban setting.

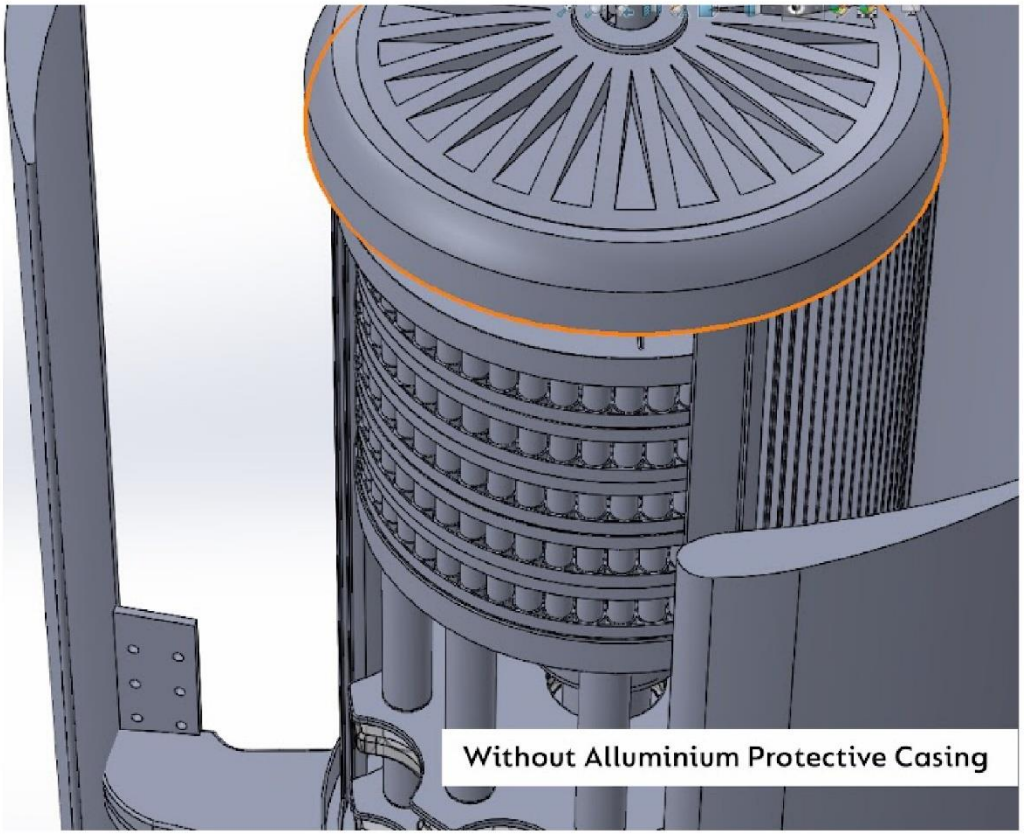
Owing to your time, wisdom and information. I can not overestimate your role in this project.

1. How effective is the current blade geometry in optimizing aerodynamic performance and structural integrity? *
(Refer to Screenshot 1: Blade geometry CAD view)



Your geometry is a classic to a vertical-axis wind turbine, and you know why. It has that very, pretty, curved airfoil design, that is all lift, not drag.

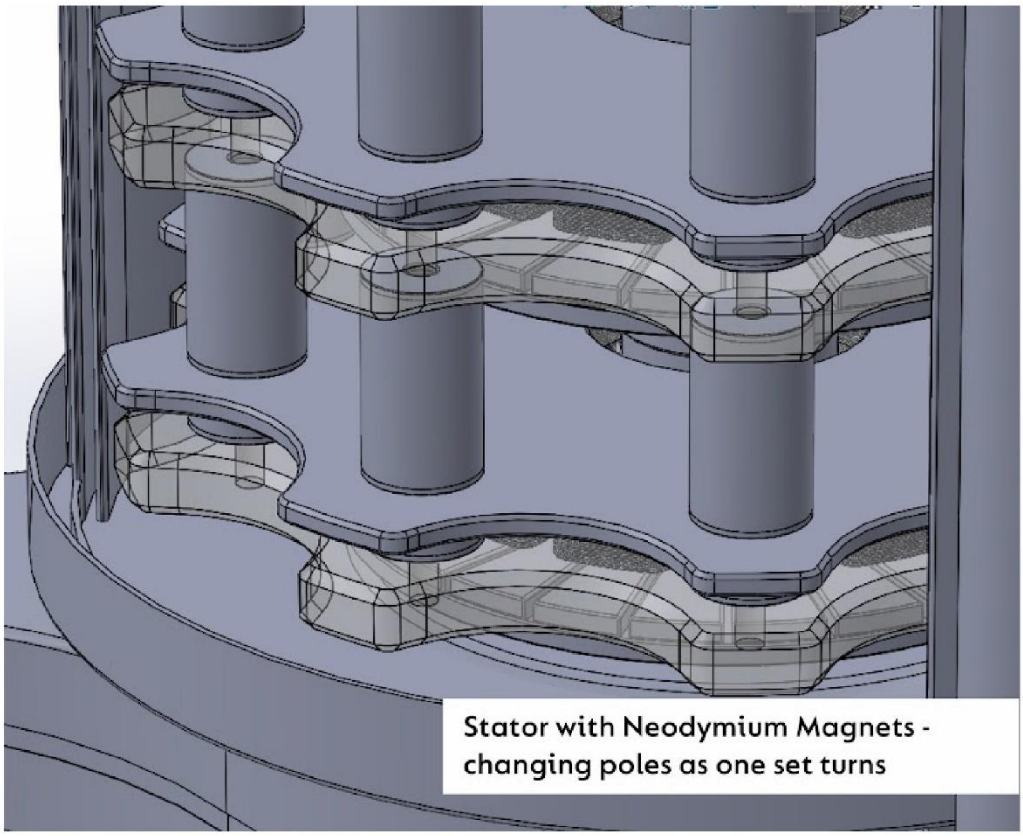
2. Does the proposed casing mechanism for the energy storage system present * any foreseeable manufacturing or operational challenges? *(Refer to Screenshot 2: Energy storage system layout)*



I can tell that there has been plenty of thought put into that casing design. The good news is that the first line of defense is to put in place a proper casing, and that you are apparently on the right track. Thermal management is always going to be the largest operational challenge. Batteries, particularly during times of charging or discharging at a high rate, produce a lot of heat. The heat has to go somewhere or you will find yourself with a reduction in efficiency and more importantly, a potential of damage or even thermal run away. The casing design must be able to actively deal with that heat, perhaps by providing inbuilt vents or fans or even sophisticated cooling. The devil is in the details when you are constructing the casing of this kind. The tolerances should be nailed in order to achieve a perfect seal. Even a bit of way out and you are not only admitting dust and moisture, but you are also undermining its structural integrity. This may be tricky when dealing with materials, which may either swell or shrink during the welding or molding exercise. Having a reliable and quality build is going to be a priority and that usually comes with a greater initial price. On the working part, there is the wear and tear, which will be long term. As this is in case of a wind turbine, it will be subject to vibrations and any type of weather. The casing must be so hard that it can take many years to wear out. You will also have to ensure that it does not inflict pain when having to maintain it. A design that is either too closed or too complicated to unseal will make a simple check of a battery look like a big headache and thus

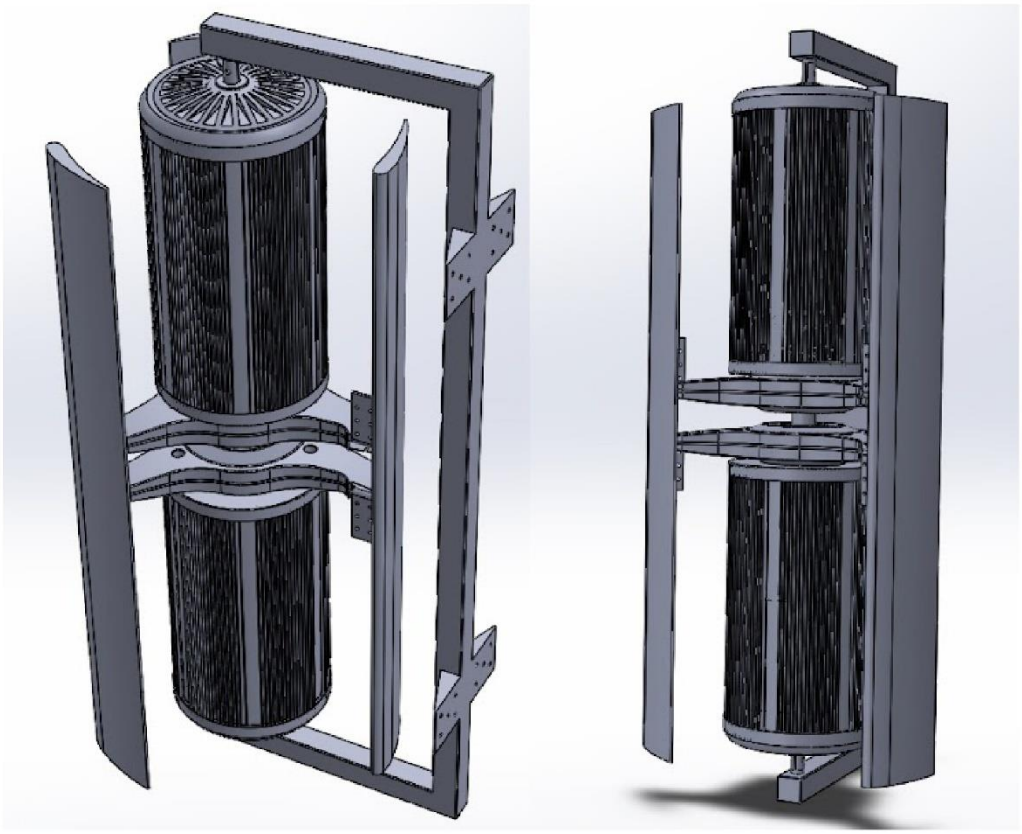
unnecessary downtime will be experienced. The idea is to install a casing that you can leave behind and do not worry about it long enough knowing that the batteries inside are safe and healthy.

3. Is the selected generator type appropriate for the intended energy output and environmental conditions? Please elaborate. *(Refer to Screenshot 3: Generator integration model)* *



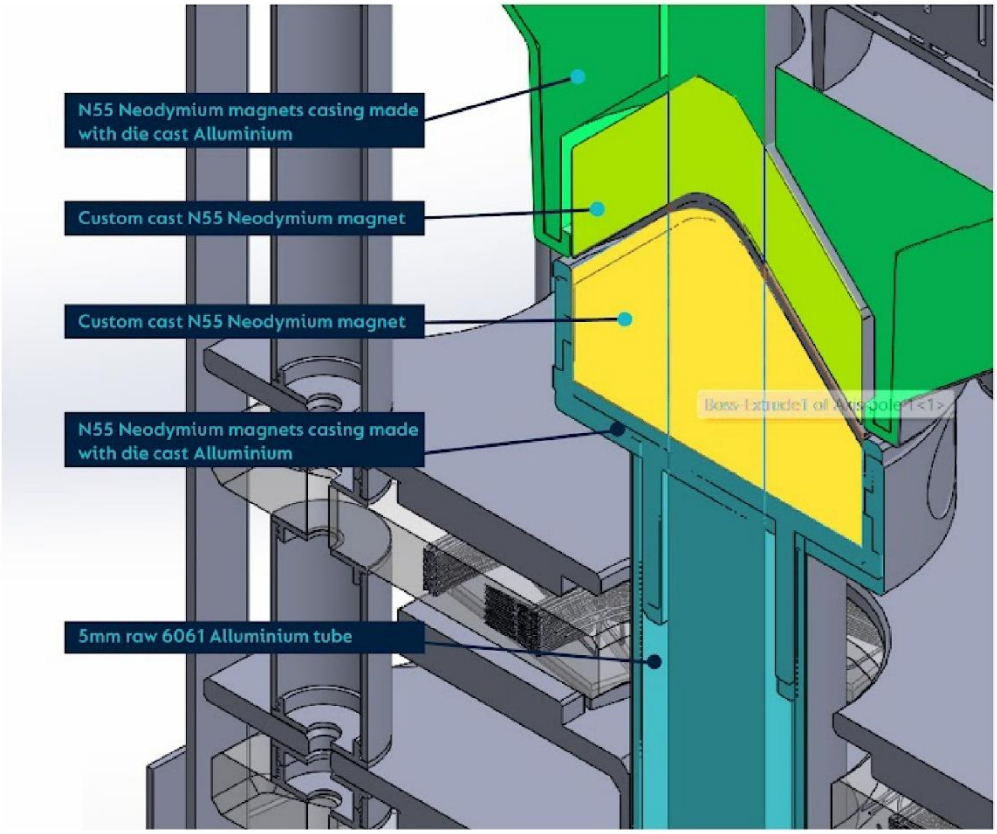
The thing is that VAWTs do not rotate so rapidly as the great horizontal windmills, particularly at low wind speeds. The ideal fit here is a permanent magnet generator, as it is specifically configured to initiate the generation of power at very low RPMs, no huge, elaborate gearbox is required to push it to speed. It is to say that your wind turbine will be more productive and efficient and will be able to harvest energy even on those days when wind is only a gentle breeze. And the durability, that is where the PM generator is really shining. There is much less to go wrong since it does not have brushes, which may wear out, or does not have a commutator which requires cleaning. It is a kind of a set it and forget it component. That low maintenance is an enormous plus to a system that will be subjected to all types of weather, dust and whatever. Yea, there you are a really smart guy with that call. It's the right tool for the job.

4. Evaluate the soundness and stability of the supporting structures under expected load conditions. Are there any areas of concern? *(Refer to Screenshot 4: Structural framework)* *



Looking at this structure, I must say, it is really a solid and steady structure. The manner in which the C-frame has been designed to accommodate those torsional loads, is a massive success in the long-term reliability department. It demonstrates that you have considered the way the structure will perform under pressure, rather than the appearance. And with the vibration issues out of the way, then you have basically produced a system that can stand the test of time. A good design does not only stand the wind, but also takes care of the internal forces that are continually in operation. To counter that fatigue caused by the dynamic loads implies that this turbine is designed to stand. It is obvious that you have established a solid base of the whole project.

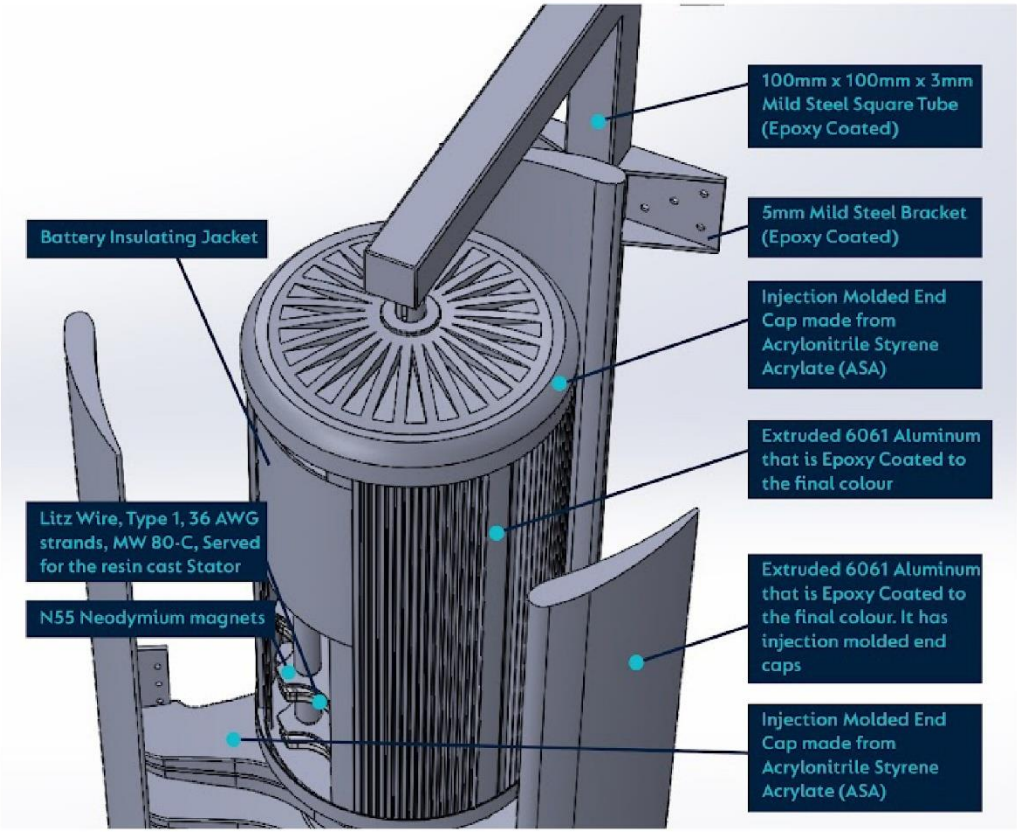
5. How effective is the integration of floating magnetic bearings within the axis tube in minimizing friction, enhancing rotational stability, and extending the operational lifespan of the vertical axis wind turbine? Please refer to the figure below for a visual representation of the bearing placement and axis configuration, and comment on any potential limitations or suggested improvements. *



Your design demonstrates that you are thinking outside the box. Floating magnetic bearings are an actual game-changer to a wind turbine such as this one. It is a more feature that would solve some of the biggest problems in the design of turbines. The design is quite efficient in reducing the friction since it will result in a system that has practically no friction among the moving components. This is a massive victory in efficiency as the turbine is able to move in the wind much more freely, particularly in low winds and this is directly transferred to an increased energy production. You have also practically removed the wear and tear therefore the working life is increased massively, only restricted by the strength of the magnets and the casing. The design is great in respect to the axial load, in this case, the downward force of the entire weight of the rotating assembly, although it is important to also consider radial loads, as the wind pushes on the blades sideways. Such a passive magnetic system will not normally provide the forces to counter such forces, and may become unstable, or wobble. That is why, the hybrid bearing system, where the magnetic bearings are utilized when the main weight is carried and the radial forces

are rotated with the aid of a little, yet sturdy, mechanical bearing will be the most appropriate choice. Also worth noting is that it is an expensive and a precision decision to use custom-cast N55 Neodymium magnets, which can easily be demagnetized at high temperatures thus a proper thermal management arrangement is essential. This is a really smart design you have chosen. Considering a hybrid design on the radial loads you will have a turbine that is not only extremely efficient but also incredibly stable.

6. Are the proposed materials suitable for long-term durability, cost efficiency, and environmental resilience? *(Refer to Screenshot 6: Material specification overlay)* *



It is clear that the proposed materials are quite appropriate, with high-performance and long-term performance being given a lot of attention. The aluminum and epoxy-coated mild steel are very suitable material to use as the structural component because it offers a strong resistance against corrosion and other environmental conditions such as rain and humidity. The idea of using ASA plastic to make the end caps is ingenious because this type of plastic has high resistance to degradation in UV conditions than other plastics which are commonly used. These materials will be very durable in the long run although they are expensive. The largest cost is the N55 Neodymium magnets which are a high performance, high quality option. In the same way, the Litz wire is costly than normal wire though it is needed to have the efficiency of the generator. The general choice of the materials used is very robust and durable, which is a good investment in the quality of the turbine. The only thing to be aware of is that the N55 magnets might be heat sensitive, thus proper thermal management is the key in the long term operation of the magnets.

7. What technical forethoughts should be considered to enhance maintainability and reduce lifecycle costs? *

Some technical hindsights are essential to achieve the desired maintainability and lower the cost of the lifecycle. One of these is a modular design; so that when the generator fails to work or when you are changing the energy storage unit, you do not need to deassemble the entire turbine to replace it. This saves on the cost of labor and repair time drastically. On the same note, it is also important to have the important parts accessible easily through maintenance hatches or removable panels so that routine checks and troubleshooting become very efficient. In addition to the physical access, remote monitoring sensors are a very sensibly effective method of executing predictive maintenance. Monitoring important parameters such as vibration and temperature will help you monitor possible problems before they lead to a fault and save money and unforeseen troubles. Finally, the original investment in the life of the components in the form of strong materials and finish and the use of standardized parts wherever possible, will result in the fact that the turbine will have fewer repairs during its life span and that its replacement parts will be not only cheap but also readily available. All these lead to the fact that the total cost of ownership is substantially reduced.

8. Do you think that the current design allows for modular upgrades or scalability in future iterations? If not, what changes would you suggest? *

Modularity is very evident in the current design, but size expansion is a serious problem. The design is also modular in nature since by using distinct components that can be attached to the generator, blades and the energy storage unit by bolts, it becomes easy to maintain and replace the parts. This implies that you can easily upgrade the generator or batteries when you need in the future without the need to reconstruct the entire turbine which is a major advantage. The one you have now, however, C-shaped and by having but one support in the vertical, would be a restriction had you to increase the size of the turbine. The increase in both axial and torsional loads would be significant with a larger turbine with larger blades, which is not a problem the present frame is made to counter. In order to have a design that can be scaled-up, there must be fundamental modifications to the structural framework. A stronger and two-sided frame, like an A-frame or a full tower, might be considered to support the additional loads. Instead, a stacked design, such as having several turbine modules stacked one upon the other on a common central axis, would be a highly effective and modular method of scaling up the power output in subsequent designs.

9. Are there any design elements that might hinder manufacturability or assembly at scale? Please specify. *

The existing design has a number of aspects that can cause problems during manufacturability and assembly on scale. A major bottleneck is the utilization of custom-cast N55 Neodymium magnets, because custom components are costly to manufacture, and they are hard to find in large quantities. Although the epoxy coating of the mild steel and the aluminum components is very efficient in terms of durability, it is a multi step process, consuming time and can cause the slacking of a high volume assembly line. Moreover, the C-shaped enclosure made of welded frame depends on the labor-intensive, precision-welding procedure that may be hard to standardize and recreate in the short term. Last, the jointing of the central axis and the magnetic bearing system are characterized by very high tolerances and specialized abilities that are not favorable to a quick and low-cost assembly procedure. A more standardized design with off-the-shelf components, a less elaborate bolted frame, and a more simplified process of assembling would be required to scale up.

10. Based on your domain expertise, what performance optimizations would you recommend to improve system efficiency or reduce energy loss? *

According to the existing design, a number of performance optimizations can enhance system efficiency and decrease the energy loss. You can optimise the profile of the blade to get the largest possible amount of lift-to-drag ratio so that the turbine can produce power at lower wind velocities. You have already removed a tremendous source of friction in the magnetic bearings, but to add to this, have the axial shaft perfectly aligned and balanced, so it does not wobble, which is a kind of parasitic power loss. In the case of the generator itself, it is important to have an efficient thermal control mechanism in place to ensure that the core and N55 magnets remain cool since the high temperatures are likely to lead to demagnetization and low efficiency. Maximum Power Point Tracking charge controller should be very efficient. This apparatus is able to adjust dynamically the electrical load on the generator such that it can run at its most efficient rotational speed in relation to the wind speed at any given moment ensuring that you are capturing and converting the maximum amount of power offered by the wind.

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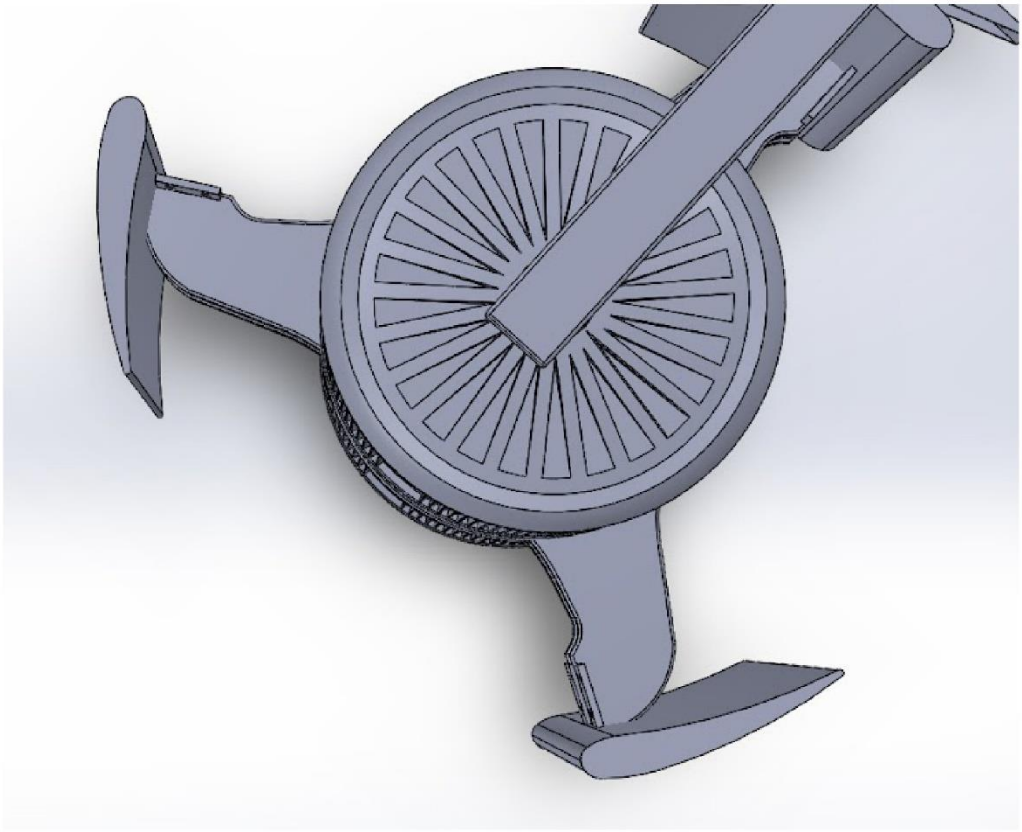
8.2.2 Delphi Questionnaire 2 - Participant Two Response

Delphi Technique Questionnaire 2: Advancing Urban Energy through Vertical Axis Wind Turbines and Microgrid Integration

The second-round survey will focus on obtaining more detailed expert research on the initial design concept and SolidWorks CAD model developed on a vertical axis wind turbine (VAWT) comprised of a microgrid system. The feedback will be directed directly to the next process of design refinement and will concentrate on the technical feasibility of the design, soundness of the structure, material selection and on the system optimization.
The discrete design elements that I would have you critically assess are the blade geometry, energy storage casting operating, generators choice and support structures and the points of integration of microgrids with their joints. This experience will help in enhancing functionality, serviceability, and cost-effectiveness of the proposed solution to urban energy resilience.
Please review the screenshots of the CAD model and answer the following questions in an informed way. Your knowledge will be very essential in the research process and development of realistic energy models that are practical in the urban setting.

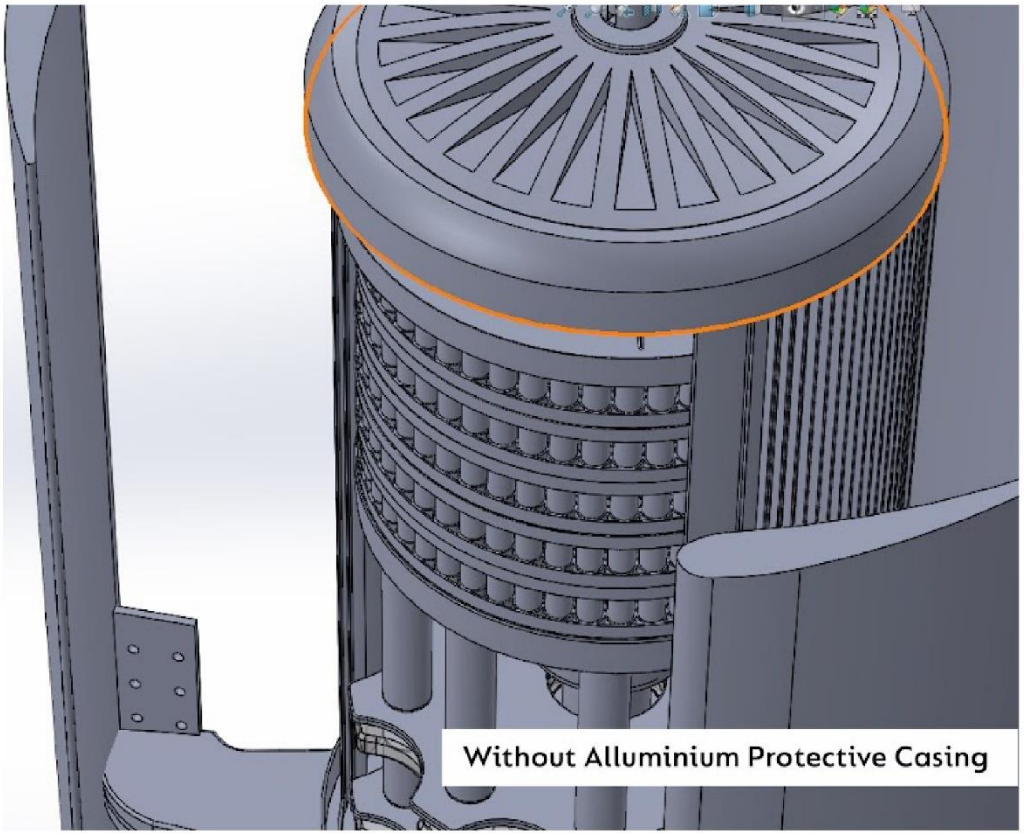
Owing to your time, wisdom and information. I can not overestimate your role in this project.

1. How effective is the current blade geometry in optimizing aerodynamic performance and structural integrity? *
(Refer to Screenshot 1: Blade geometry CAD view)



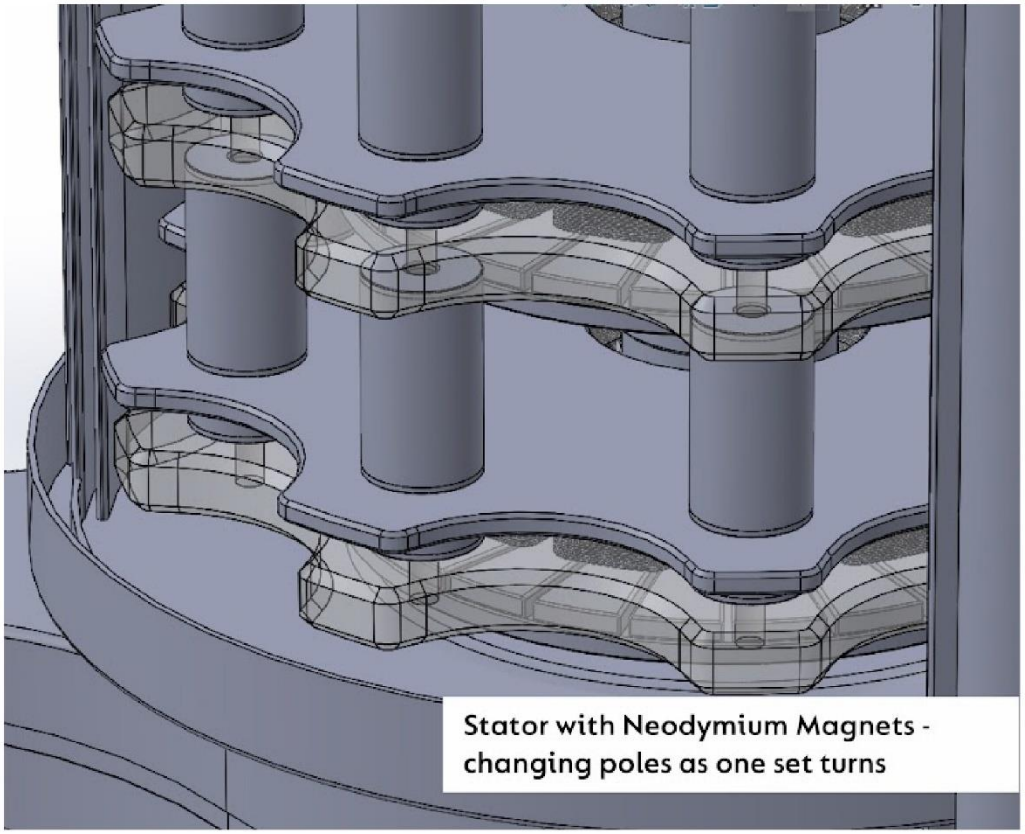
The simplicity and effectiveness of the design make it strong. With an airfoil that is symmetrical and curved, this has removed all the complexities of having a sophisticated yaw system to spin the turbine into the wind. This causes the turbine to become intrinsically dependable in that the turbine can harness energy generated by any direction of wind, which is a significant benefit with a vertical-axis wind turbine. It is also designed in a form that distributes stress on both sides of the blade naturally and this is excellent in structural integrity.

2. Does the proposed casing mechanism for the energy storage system present * any foreseeable manufacturing or operational challenges? *(Refer to Screenshot 2: Energy storage system layout)*



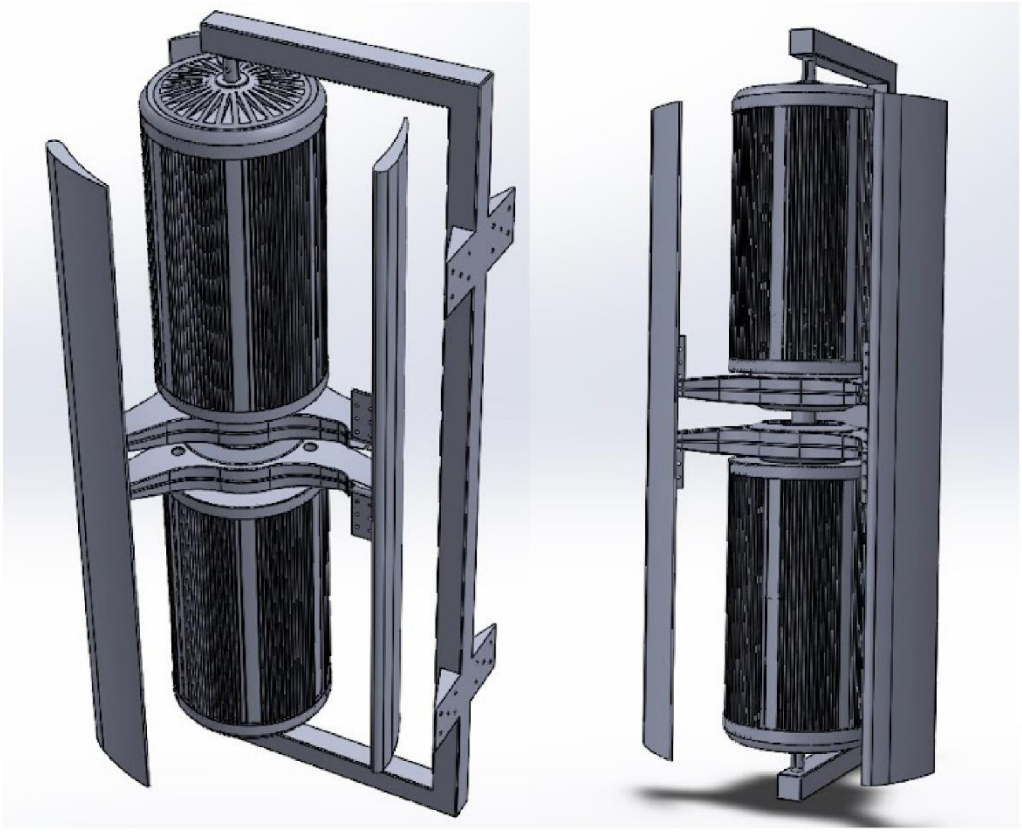
I believe that the emphasis on thermal management is the excellent beginning. The casing is not just a shell, it is a very important safety feature. Not only should its design safeguard the elements against the components but it should also be designed to hold any possible failures such as a thermal runaway event to stop a fire. The problem, here, is striking a compromise between that protective shield and a design, which yet need not be a big pain to service.

3. Is the selected generator type appropriate for the intended energy output and environmental conditions? Please elaborate. *(Refer to Screenshot 3: Generator integration model)* *



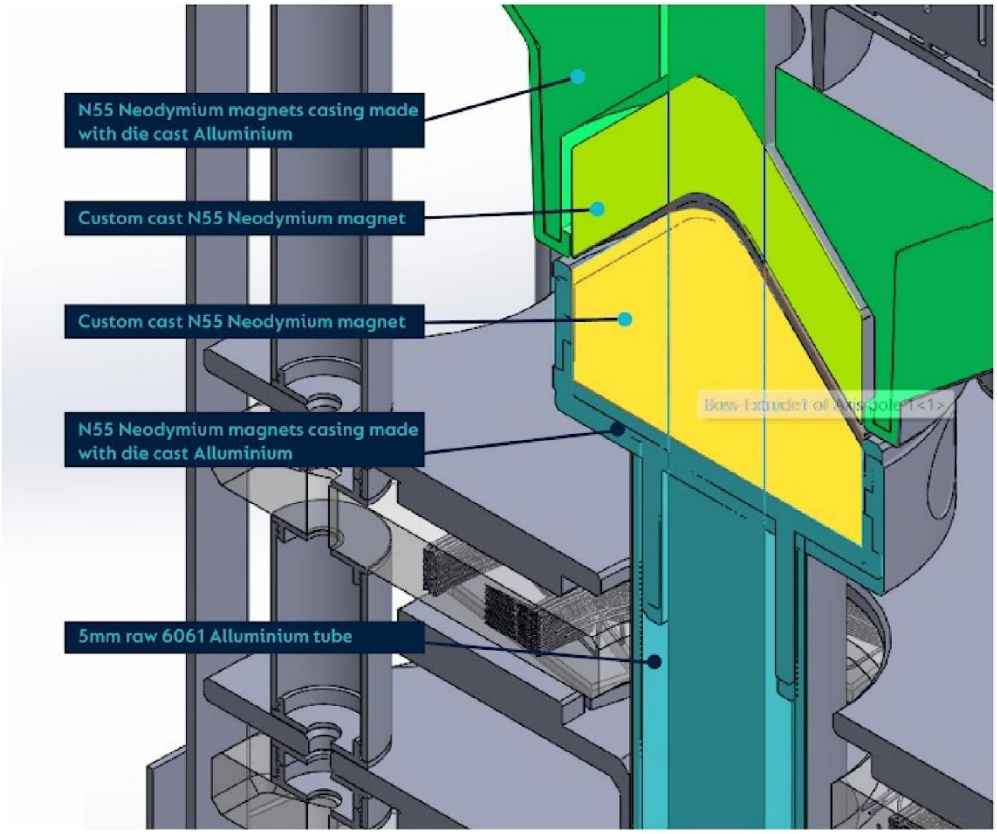
That's a solid choice. I would also say that although a PM generator is incredibly simple, the fact that it has variable voltage and variable frequency output implies that you need to be very careful with your power electronics in order to supply the power to the batteries. This further complicates the system as a whole, however the benefits of the high torque density of the generator are certainly worth it.

4. Evaluate the soundness and stability of the supporting structures under expected load conditions. Are there any areas of concern? *(Refer to Screenshot 4: Structural framework)* *



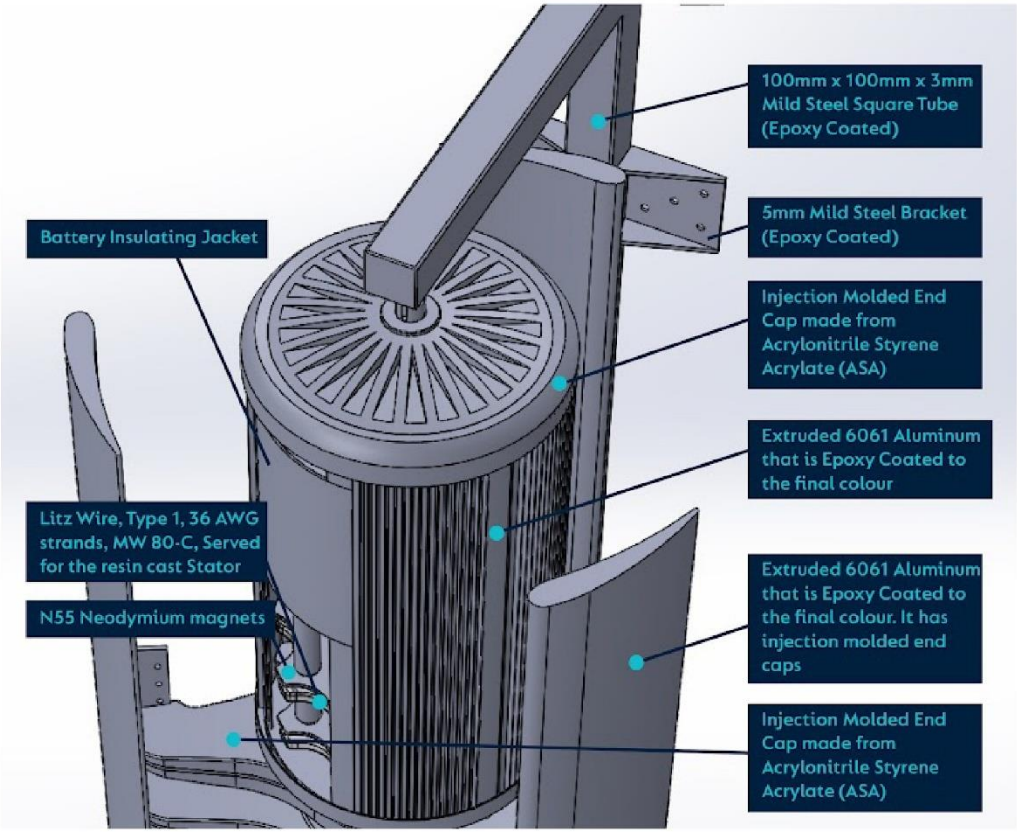
The C-frame appears to be quite robust, although I would say its rigidity is a two-sided sword in the long term as far as vibration is concerned. One that is too rigid may perhaps pass the vibration up to the base which still may eventually lead to a fatigued material especially at the points of connection. I believe that the secret of durability lies not only in its static strength but also in a strategy of how the structure will cope with the dynamic constant loads. It is a great beginning, but it is something that is to be closely followed.

5. How effective is the integration of floating magnetic bearings within the axis tube in minimizing friction, enhancing rotational stability, and extending the operational lifespan of the vertical axis wind turbine? Please refer to the figure below for a visual representation of the bearing placement and axis configuration, and comment on any potential limitations or suggested improvements. *



I'm also a huge fan of this idea. I would highlight that the absence of contact is very efficient, but the precision of the need of the alignment of the magnets is impossible to be over-emphasized. Any small lack of fit would result in a wobble which would be more energy-losing than an ordinary mechanical bearing. I would also suggest considering the possibility of magnetic impact on the possibility of magnetic interaction with any surrounding electronic parts or sensors, which can also need some sort of shielding.

6. Are the proposed materials suitable for long-term durability, cost efficiency, and environmental resilience? *(Refer to Screenshot 6: Material specification overlay)* *



The material selections are evidently selecting more performance over cost, which is a good aspect to a high standard product. Epoxy materials and ASA plastic used are excellent. I would ask whether the N55 Neodymium magnets were a total requirement or not. They are very strong, however, a slightly less strong grade of magnet could be a better cost to performance ratio in this application, especially when the intended market is where cost is a significant factor in the turbine. Cost of the Litz wire is also high, which should be taken into consideration in terms of production.

7. What technical forethoughts should be considered to enhance maintainability and reduce lifecycle costs? *

Modularity and accessibility is a critical issue. I would also mention that one of the factors that can help in lowering the cost of lifecycle is the creation of a detailed maintenance plan at the earliest stage. This involves the development of a digital logbook of the turbine, recording all the service procedures, and making use of universal tools and fasteners of all components. It is the surrounding process which will eventually dictate the cost such a design will be to own and run throughout its lifetime.

8. Do you think that the current design allows for modular upgrades or scalability in future iterations? If not, what changes would you suggest? *

I would say that the design is scalable, but there is a very narrow scope. The C-frame might be slightly expanded and reinforced in terms of thicker walls or other bracing. But to have a really large-scale one, a radical change of transition to a more stable form, such as a full tower with bracing on both sides, would be necessary to support the added forces. The thought of a modular and scalable power generation stackable design is a brilliant idea that does not require a single and massive building.

9. Are there any design elements that might hinder manufacturability or assembly at scale? Please specify. *

I have to admit that mass production would be greatly hampered by the custom magnets and welded frame. On top of that, a multi-material assembly line can hardly be underestimated in terms of its complexity. Supply managerial control over extruded aluminum, injection-molded plastic, steel tube and custom-cast magnets introduces an additional supply chain complexity that does not scale easily. A single-material design would be far easier to produce and construct.

10. Based on your domain expertise, what performance optimizations would you recommend to improve system efficiency or reduce energy loss? *

I would add that another optimization which was not covered above but which is important is taking the aerodynamics of the whole system rather than the blades. The body of the turbine with its blocky shape may produce large amount of drag and turbulence. I would suggest investigating a less parasitic conical or teardrop shape of the casing to minimize that parasitic drag. A highly-calibrated MPPT controller specially adjusted into the performance curve of the generator would also prove to be the most efficient method of extracting the absolute maximum power out of the wind.

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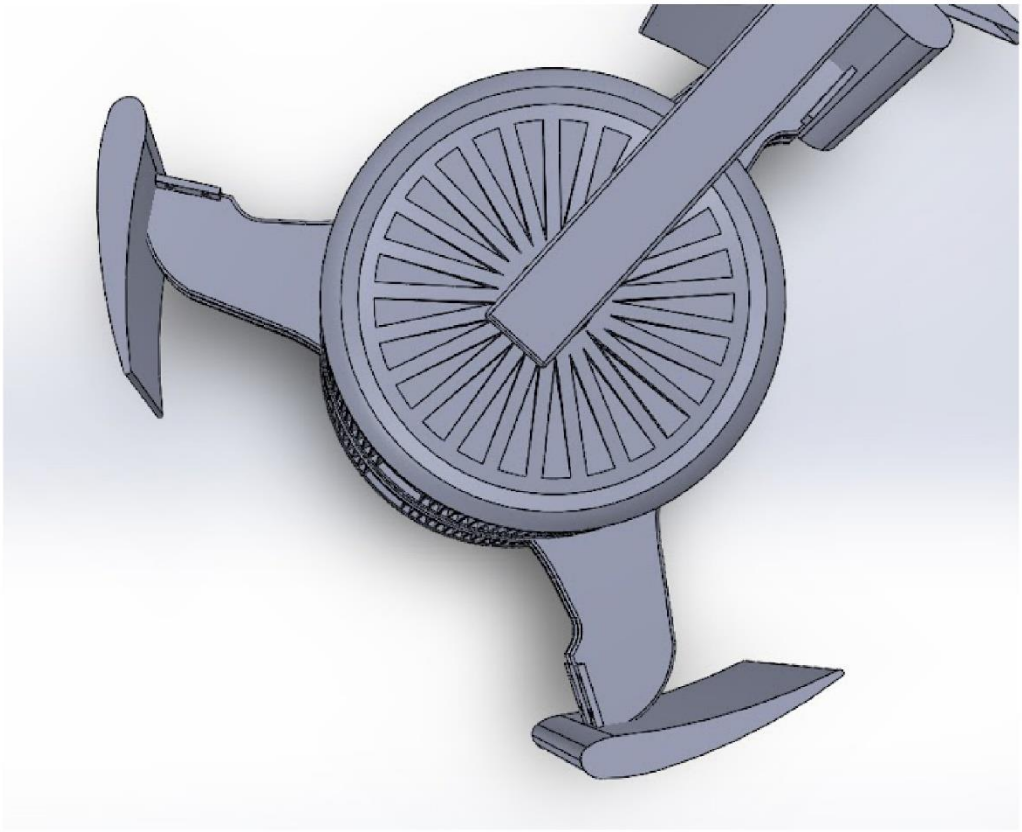
8.2.3 Delphi Questionnaire 2 - Participant Three Response

Delphi Technique Questionnaire 2: Advancing Urban Energy through Vertical Axis Wind Turbines and Microgrid Integration

The second-round survey will focus on obtaining more detailed expert research on the initial design concept and SolidWorks CAD model developed on a vertical axis wind turbine (VAWT) comprised of a microgrid system. The feedback will be directed directly to the next process of design refinement and will concentrate on the technical feasibility of the design, soundness of the structure, material selection and on the system optimization.
The discrete design elements that I would have you critically assess are the blade geometry, energy storage casting operating, generators choice and support structures and the points of integration of microgrids with their joints. This experience will help in enhancing functionality, serviceability, and cost-effectiveness of the proposed solution to urban energy resilience.
Please review the screenshots of the CAD model and answer the following questions in an informed way. Your knowledge will be very essential in the research process and development of realistic energy models that are practical in the urban setting.

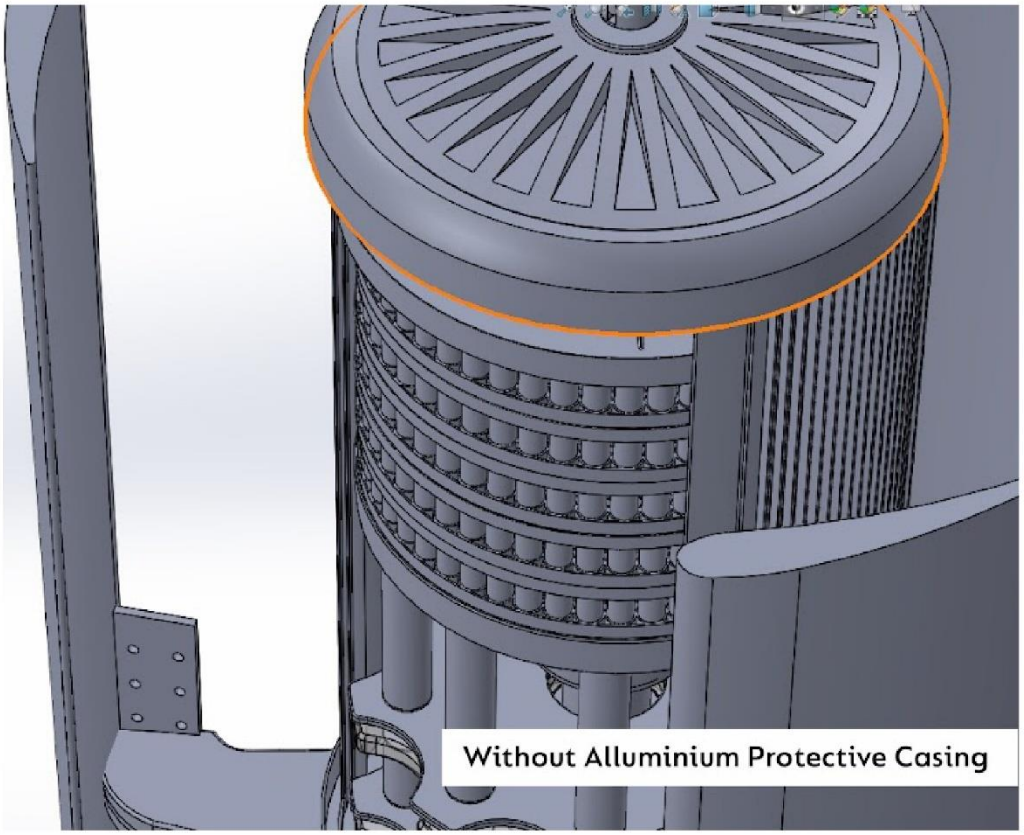
Owing to your time, wisdom and information. I can not overestimate your role in this project.

1. How effective is the current blade geometry in optimizing aerodynamic performance and structural integrity? *
(Refer to Screenshot 1: Blade geometry CAD view)



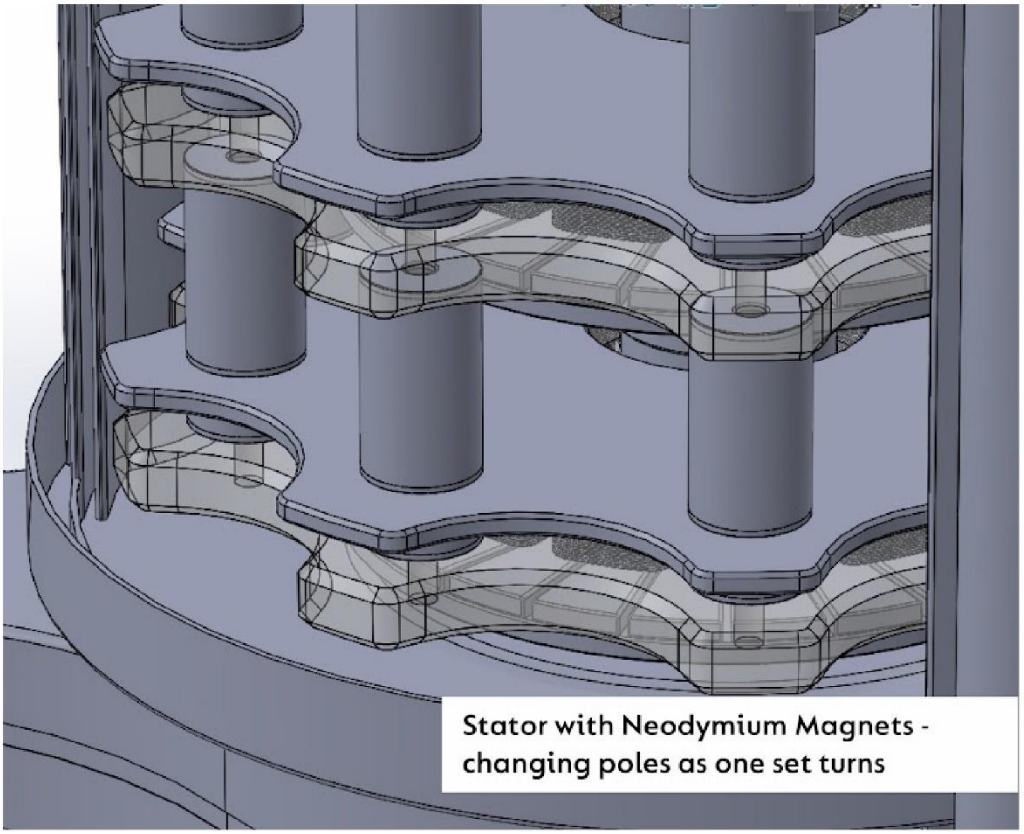
The conception is superb in its simplicity. You have taken the operational simplicity and reliability of operation over optimal aerodynamics performance by selecting a symmetrical airfoil. You lose a small margin of lift-to-drag ratio at certain wind angles to an asymmetric blade, whereas you can obtain energy at all directions at once, which makes the turbine very versatile and robust.

2. Does the proposed casing mechanism for the energy storage system present any foreseeable manufacturing or operational challenges? *(Refer to Screenshot 2: Energy storage system layout)* *



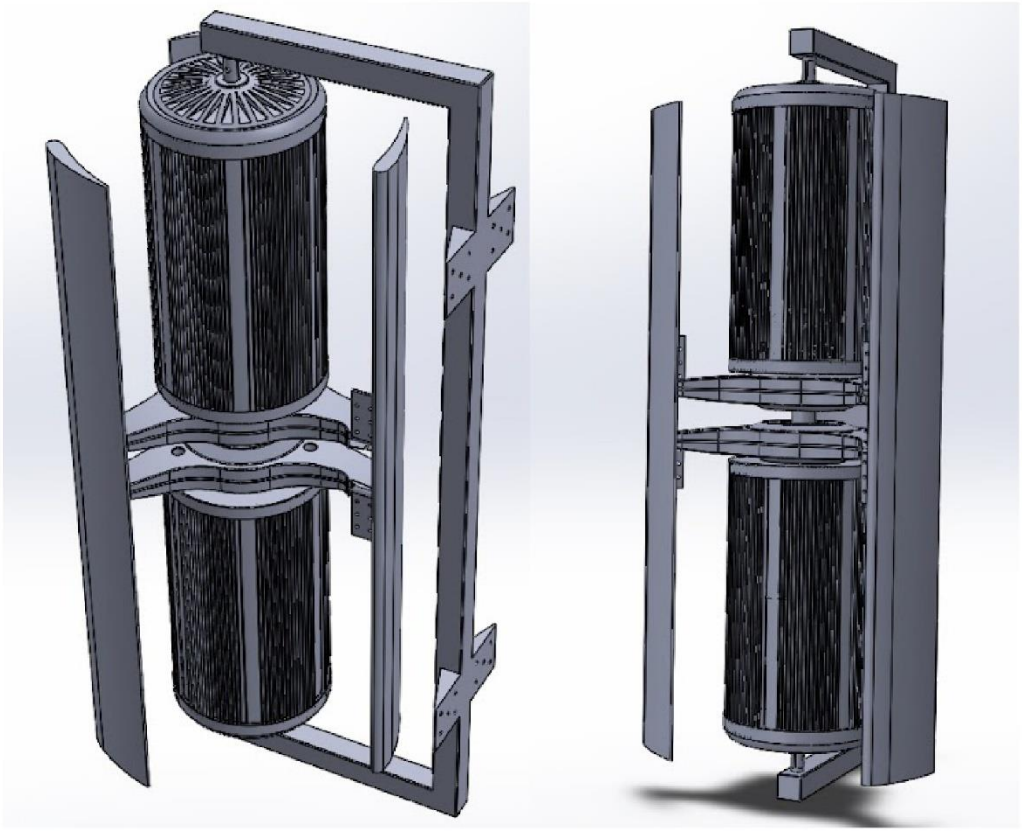
I think the casing's primary challenge is not just what's inside, but how it's made. The combination of die-cast and extruded aluminum and other materials requires complex manufacturing and assembly processes. The casing's ability to protect from the elements and contain internal issues is critical, and a simple, single-piece casing with integrated cooling might have been more cost-effective to produce at scale.

3. Is the selected generator type appropriate for the intended energy output and environmental conditions? Please elaborate. *(Refer to Screenshot 3: Generator integration model)* *



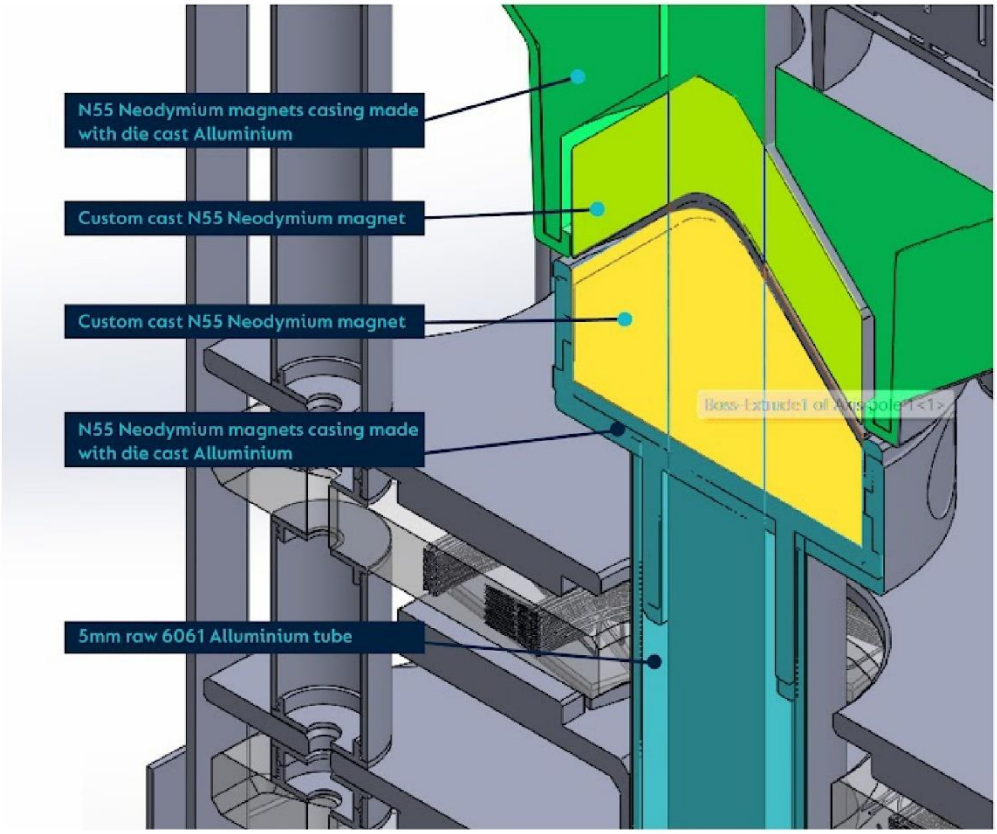
That's a solid choice. The emphasis on robustness and low-RPM capability is important. I would also mention that although the simplicity of a PM generator is a massive advantage, that its variable voltage and frequency output implies that you must be very specific with your power electronics in order to rectify the power available to the batteries. This introduces some complexity to the entire system, however, the efficiency benefits of a high torque density of the generator are well worth it.

4. Evaluate the soundness and stability of the supporting structures under expected load conditions. Are there any areas of concern? *(Refer to Screenshot 4: Structural framework)* *



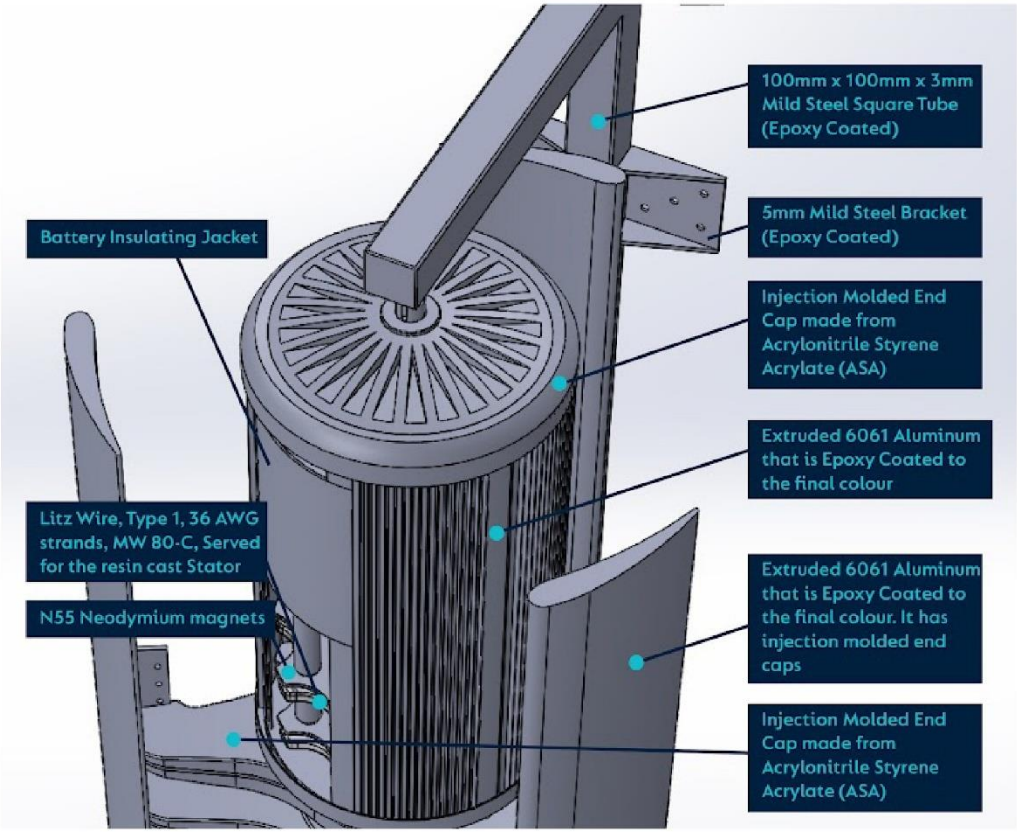
The C-frame appears incredibly robust, however, I would rate its rigidity as a two-sided sword in the long term vibration. An over-rigid structure may pass the vibrations all the way to the base and even then may result in material fatigue with the passage of time particularly at the connection points. I believe that, durability may not only lie in the statical strength of the structure but a scheme of how the structure will accommodate the dynamic loads that are always present. It is a good beginning, yet it is an issue that needs to be followed up on.

5. How effective is the integration of floating magnetic bearings within the axis tube in minimizing friction, enhancing rotational stability, and extending the operational lifespan of the vertical axis wind turbine? Please refer to the figure below for a visual representation of the bearing placement and axis configuration, and comment on any potential limitations or suggested improvements. *



I'm also a huge fan of this idea. I would stress the fact that even though it is very efficient with the lack of contact, the accuracy in the alignment of the magnets cannot be overrated. Any minor misalignment may lead to a wobble which may result in more energy loss than an ordinary mechanical bearing. I would also suggest that it is possible to consider the possibility of magnetic interference of any electronic components or sensors present in the vicinity, which might have to be shielded in some way.

6. Are the proposed materials suitable for long-term durability, cost efficiency, and environmental resilience? *(Refer to Screenshot 6: Material specification overlay)* *



The choice of materials is evidently based heavily on performance over cost and this is good when it comes to a high quality product. The metals and ASA plastic that are covered with epoxy are superior. I would question the requirement of the N55 Neodymium magnets as being a necessity. Although they are ultra power-strong, a moderately less quality of magnet may provide a higher cost; performance ratio to the present use, especially when the turbine is to be used in markets where price is a significant consideration. Another production aspect to consider is the Litz wire is also very expensive.

7. What technical forethoughts should be considered to enhance maintainability and reduce lifecycle costs? *

The significance of modularity and accessibility is a key factor. I would also include that one of the most important aspects in the minimization of lifecycle costs is the determination of a detailed maintenance plan at the earliest stage. These involve development of a digital logbook of the turbine, recording all the service operation, and common tools and fasteners of all parts. The surrounding of the design is what will eventually define its cheapness to own and run throughout its existence.

8. Do you think that the current design allows for modular upgrades or scalability in future iterations? If not, what changes would you suggest? *

I would say that the design is scalable, though to a very limited extent. The C-frame would be slightly enlarged with reinforcements such as use of thicker walls or more bracing. But to achieve a real full scale one, a radical redesign to a more stable form, such as a full tower with bracing on either side would be necessary to cope with the added forces. The concept of a stackable design is an ingenious method in modular scalable power generation without having to use one large structure.

9. Are there any design elements that might hinder manufacturability or assembly at scale? Please specify. *

I concur that the handmade magnets and welded frame would be a significant bottleneck in the process of mass production. To top it all the complexity of a multi-material assembly line can not be undermined. The extrusion aluminum, injection-molded plastic, steel tubing and custom-cast magnets suppliers are another source of supply chain complexity that is hard to simplify at scale. A single material design would be a lot easier to produce and construct.

10. Based on your domain expertise, what performance optimizations would you recommend to improve system efficiency or reduce energy loss? *

I would say one of the main optimization in addition to those mentioned is dwelling on the aerodynamics of the whole system rather than the blades. The turbine blocky shape offers a lot of drag and turbulence to the main body of the turbine. I would suggest a more streamlined, conical or teardrop shape to accomplish that reduction of the parasitic drag by the casing. Besides, an MPPT controller, particularly adjusted to the performance curve of the generator, would be the best method of extracting the last ounce of power out of the wind.

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