10kW Prototype Kite Turbine Design Reasoning Report

General Release

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Summary

A report on Kite Turbine system design reasoning with suggested improvements and implications for scaled manufacture – With Particular regard to the 10kW MVP based upon kite turbines using static lift kites.

Windswept has documented the design reasoning for an MVP Kite Turbine concept with a static lift kite system.

Windswept was not able to develop a safe static lift kite system within our operating budget.

We can conclude that the safely practical scaling limit for simple kite turbine designs which use unmodified static KAP lift kites is less than 10kW.

Windswept is now searching for alternative, active lifting kite solutions to enable scaling the Kite Turbine concept beyond 10kW.

The Kite Turbines themselves still have world class airborne wind energy performance characteristics and good scaling potential.

The design reasoning of the alternative lift system we select will be captured in a future report.

Windswept intends to complete a new period of research and small-scale tests and component tests to inform design choices on suitable lift systems for a 10kW device.

Contents

1 Introduction

Windswept and Interesting Ltd (Windswept) have been working on scaling up and automating their existing 1.5kW kite turbine (Figure 1) to a 10kW kite turbine. The 10kW automated device is referred to as the Minimum Viable Product (MVP). 10kW and automation were the performance targets specified by Shell GameChanger at project initiation.

The 10kW MVP consists of 5 main subsystems;

- The Rotor
- Tensile Rotary Power Transmission (TRPT)
- The ground station
- A static lifting kite
- Backbot

In this report we will go over these subsystems and their interactions from a systems perspective, as well as dive into critical component level decisions within the subsystems.

Figure 1 – The existing 1.5kW Kite Turbine

1.1 MVP Prototype Objectives

The 10kW MVP prototype had the following objectives:

- Demonstrate the first automated operation of a kite turbine at 10kW
- Train our engineering model with detailed performance effects of increasing scale
- Assess automation methods across wide operating conditions
- Demonstrate operation to attract further investments

The MVP device was to be used to demonstrate the continuous procedure of launching – normal operation – landing, with the stretched target of repeating this procedure, without human intervention, except to signal the transition between stages. For the first iteration of the MVP prototype device, this continuous procedure would be demonstrated for a maximum of 30 minutes.

1.2 MVP Operational Wind Speeds

The operational wind speeds for the MVP device were defined as follows:

- The MVP had a rated power of 10kW at a rated wind speed of 11m/s.
- The MVP had an operation windspeed of 4 m/s to 15 m/s, and must withstand gusts up to 26 m/s. When the average and maximum wind speed goes outside of this range the MVP would initiate a landing procedure.

1.3 MVP Design Process

The MVP design process was done in three stages;

1. Requirements capture
2. Concept generation
3. Detailed design

1.3.1 Requirements Capture

The MVP device objectives were defined at the beginning of the design process, these are outlined in section 1.1 of this report. Once the high-level MVP objectives were documented, a series of requirement workshops were conducted. Initially, the workshops were focussed on detailing the high-level requirements which defined the top level design parameters, operational wind speeds, safety requirements, modes of operations, operating states and the launch, normal operation and landing procedures. These requirements were documented in a high-level requirements document.

The MVP design was split into the five subsystems and a design lead was allocated to each sub-system. Subsequent workshops were conducted, with a focus on defining the requirements for the individual subsystems. These subsystem requirements workshops were run by the relevant design lead and outcomes were documented in the subsystem design documentation.

The first iteration of the MVP was to be focussed on demonstrating autonomous operation. Further iterations of the MVP were intended to follow to implement additional features, and the requirements set to be updated with each iteration.

1.3.2 Concept Generation

The basic MVP concept is based on scaling the existing 1.5kW kite turbine. From a system overview perspective the concept and functionality of the subsystems does not change, with the notable exception of automation and launch land functionality. With scaling it is also expected that some design decisions from the 1.5kW system will need to change.

A series of concept generation workshops were required for the areas of new innovation; the launch and land procedure (executed by the BackBot system) and the ground station.

The ground station concept in the 1.5kW device was deemed too impractical for the MVP device and therefore a new ground station concept was generated. A wide variety of concepts were evaluated during the workshops and the team worked to down-select the options until a single concept was selected. The selected concepts were thought to be the most suitable for achieving the MVP device requirements within the allocated budget and timescales. Once the selected concepts had been documented by the relevant subsystem design lead, the subsystem moved onto the detailed design stage.

1.3.3 Detailed Design

Scaling and detailing of the MVP concept was completed for the rotor, TRPT and static lift kite subsystems. The BackBot and the ground station were designed from scratch. CAD models were generated for each of the subsystems and modelling and analysis work was conducted in order to size components to withstand the expected system forces. Where possible, off the shelf components were sourced. All design work completed was documented in a design documentation folder which was allocated to each subsystem. Manufacturing and assembly instructions were also an output from this design stage.

In parallel with the detailed design of each subsystem, a Failure Mode, Effects and Criticality Analysis (FMECA) was conducted. Once the FMECA process was established, a series of workshops were conducted to complete an analysis on each of the individual subsystems. The FMECA process was used to identify the failure modes and effects of each component within the subsystem. Subsequently, controls were identified which minimised the likelihood of the failure occurring, the consequence of the failure occurring, or implemented with an early detection method for the failure mode. Completion of this process resulted in a number of design changes to improve system safety and system reliability. The process also directly influenced the operating procedures adopted, such as the personal protective equipment (PPE) requirements, the spare parts inventory and the pre-flight tests and inspections. The test plan was also influenced by the outcomes of the FMECAs.

1.4 Report Structure

Section 2 of this report presents an overview of the MVP design with a static lift kite solution. Section 3 to Section 7 presents the selected concepts and the design reasoning for each of the major MVP sub-systems; the rotor, the ground station, the TRPT, the BackBot and the lift kite.

A scalability appraisal has been conducted on each sub-system to highlight the identified scalability compared with the current design. The scalability appraisal for each sub-system is also presented in Section 3 to Section 7.

2 10kW MVP Design Overview

The method of energy conversion works like a traditional wind turbine: We use an airborne rotor to convert movement of air into rotational power, which is transmitted via a short rotating line set, to be converted into electrical power in a ground-based generator.

The generated energy is stored locally and converted to heat when necessary.

The Tensile Rotary Power Transmission (TRPT) acts as a drive shaft between the ground-based generator and the rotor. The TRPT design concept is a very lightweight, yet wide and tensile driveshaft. This combination enables it to transfer more torque over a longer distance for very little mass penalty as compared to traditional driveshafts. It requires an axial force to keep its extended form, which is provided by the rotor kite line tension and the line tension provided by the lift kite. This mechanism is further expanded on in the TRPT section.

The lift kite flies above and downwind of the turbine system. Without any active control it holds the airborne components in the air, and makes sure the TRPT and rotor are directly aligned downwind.

The BackBot is used for fine tuning the TRPT and rotor elevation angle, as well as providing the infrastructure for the safe autonomous launching and landing operations of the lift kite, rotor and TRPT.

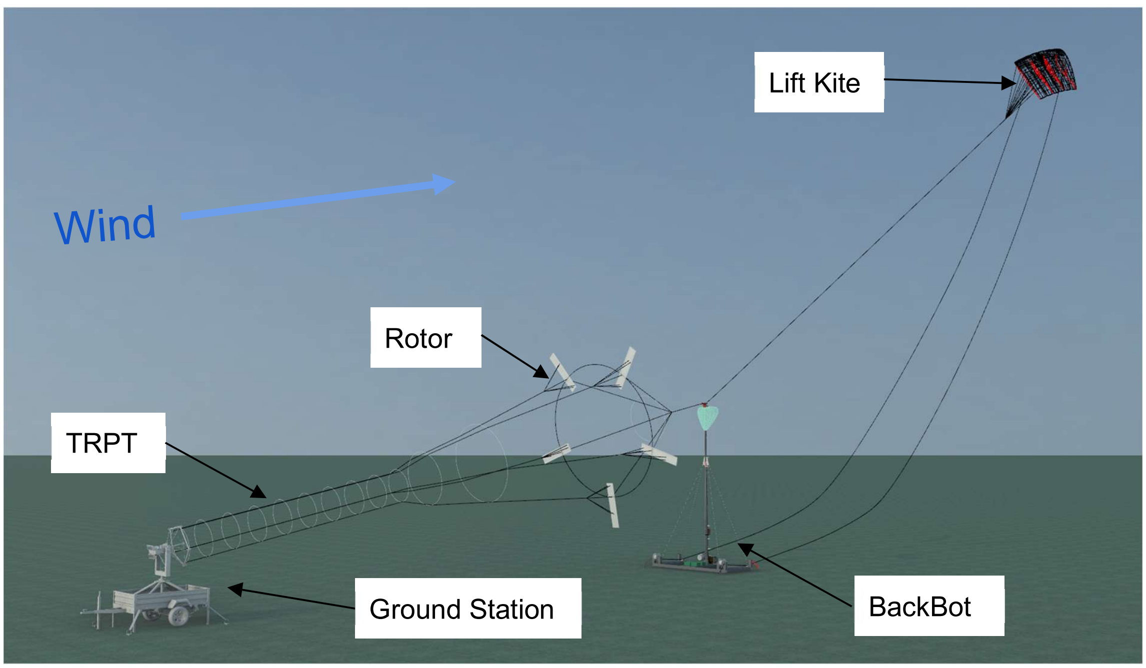


Figure 3 - MVP Device Schematic in landed position

2.1 Launch and landing procedure

All components of the system start on the ground. The subsystems are connected together and pre-launch system checks are done. The BackBot raises the TRPT and rotor, so they are suspended downwind. Once the TRPT and rotor are sufficiently tensioned and all on-board health checks are done, the system is ready to go to launch.

Launch

Once the signal has been given to launch by the operator, the lift kite is launched. Once stable flight has been achieved by the lift kite, the rotor and TRPT are released from the BackBot. Further raising of the lift kite line is used to pull the rotor and TRPT up to their operational altitude. Once this altitude is reached and the system is sufficiently tensioned, the normal operation stage is initiated.

Normal Operation

The rotor and TRPT will rotate, extracting energy from the wind and transmitting it down to the ground station. A large set of sensors is monitored to make sure all subsystems are operating within safe working limits. The generator control architecture will monitor and display a variety of state data from the rest of the system, including rotation lag, tension, position, speed trend, power and wind state data.

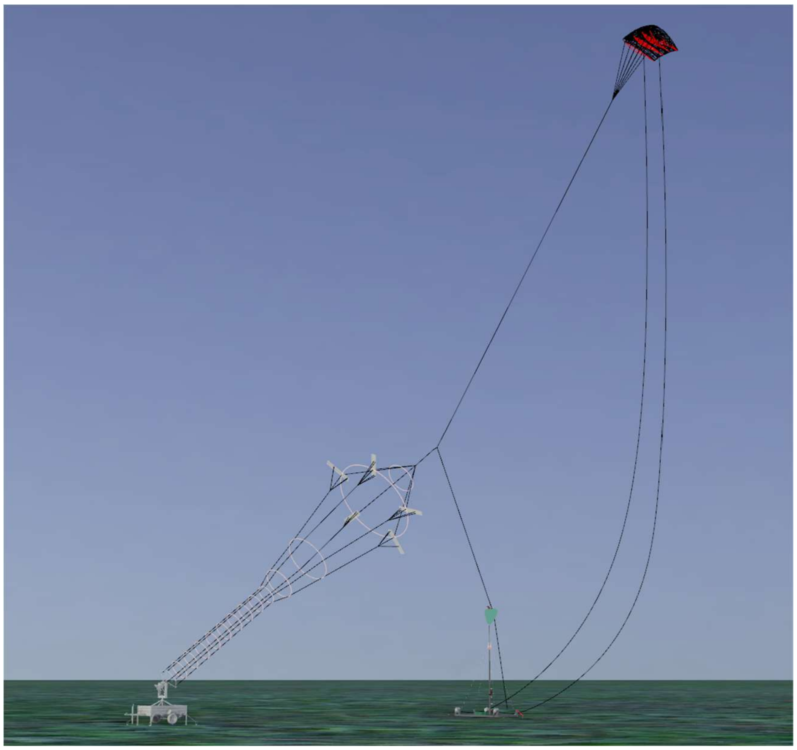
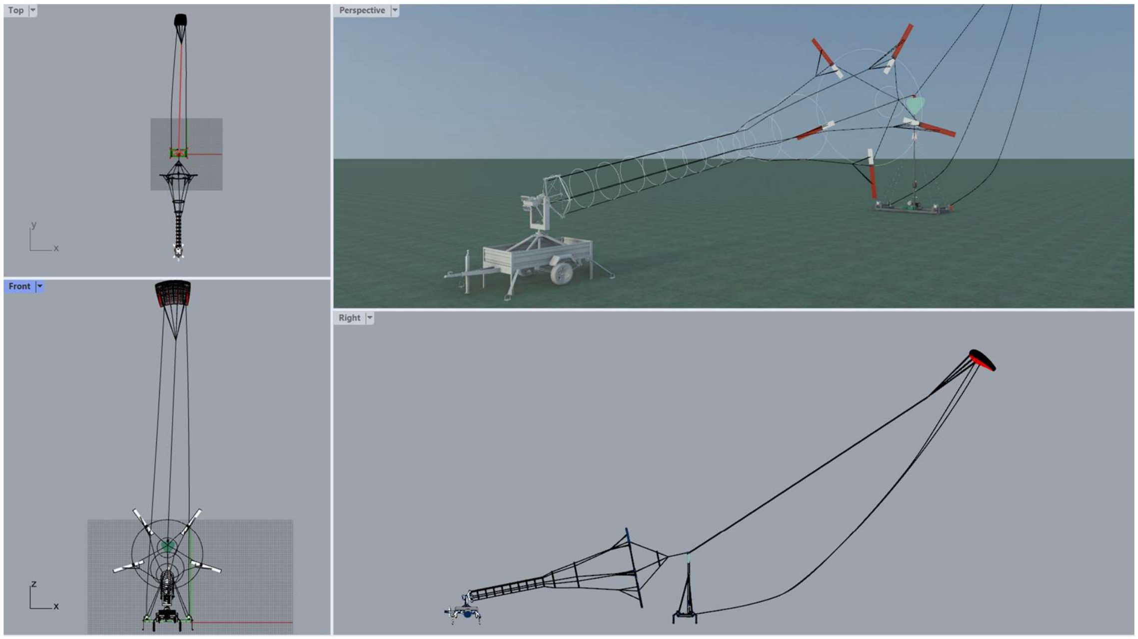


Figure 4 - MVP Device in generating position

Landing

When the device is operating outside of the set operational limits, or the signal has been given to land the system by the operator, the rotation of the rotor and TRPT is stopped and the set is returned to the prelaunch state. After the turbine and TRPT set is safely landed, the lift kite is brought fully down and returned to its prelaunch state.

3 Rotor System



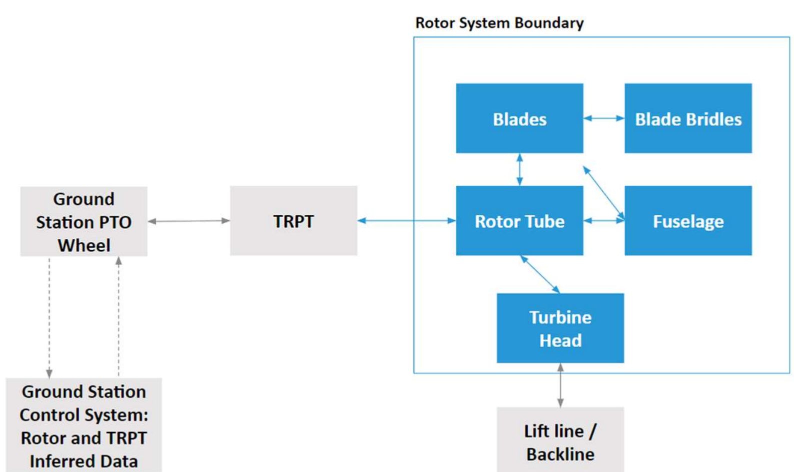
12kW rotor test design

3.1 System Functionality

The primary function of the rotor is to convert wind energy into torque and rotational speed. The rotor was designed to the operational wind speeds stated in section 1.2 of this report.

At rated wind speed, the rotor should output 12kW of mechanical rotational power to accommodate anticipated energy conversion losses in both the mechanical and electrical systems.

The rotor was designed to be as lightweight as possible, while keeping enough structural integrity to operate in all required conditions.

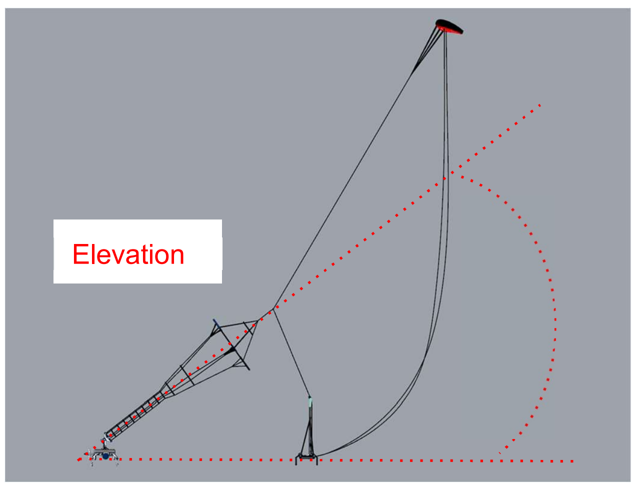


3.2 System Design

Where a traditional wind turbine rotor is mounted on a central horizontal axis, the kite turbine rotor is mounted on an airborne ring, with no part of the blades extending to the central axis, where blades are slower and less effective.

This hollow axis rotor structure is a notable difference from traditional wind turbines. This difference allows shorter blades to sweep a larger area. Due to this inherent property of our system, the rotor blades have a huge advantage in the material-to-power and power-to-weight ratios. The performance of the rotor is determined by several design parameters, such as blade geometry, blade bank angle, profile and flown elevation (angle between the Tensile Rotary Power Transmission (TRPT) and ground).

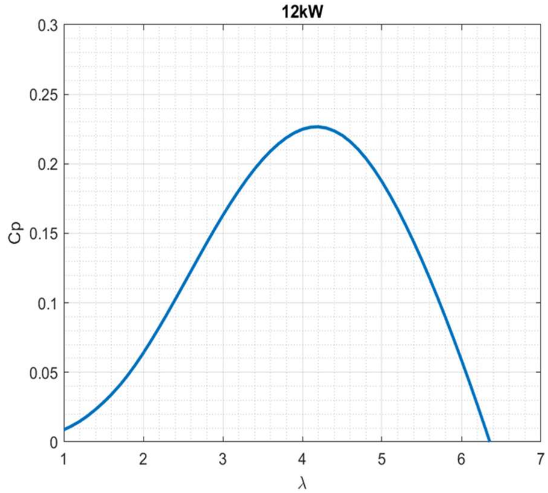
The rotor is assisted into its elevated operating position by using lift kite line tension connected to a thrust bearing in the turbine head.



A series of 5 bladed rotors were designed for testing in the MVP. The rotors were rated for 4,7 and 12kW. The rotor design needed to strike a balance between solidity (in terms of air flow blockage) and practicability (in terms of structural mass and rigidity). Fewer blades per rotor can enable higher tip speed ratios for more efficient flight with the trade off being a need for heavier structural elements connecting the blades. With our budget and manufacturing options, 5 blades were found to be the most feasible.

Similarly for speed & ease of analysis, operation and future development scope; we chose single rotor designs as opposed to stacked rotor kite turbine designs such as we had previously tested.

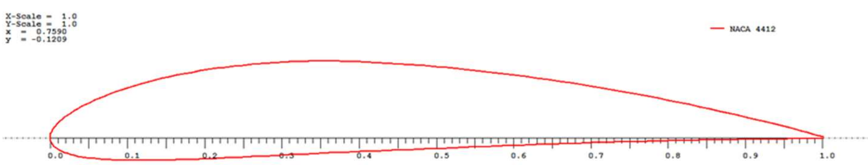
Our design process first evaluated rotor efficiency and swept area for a standard blade profile. We used custom Matlab scripts to query AeroDyn to evaluate efficient parameter choices for the rotor. Based on an 11m/s rated wind speed we found the optimal tip speed ratio to be 4.2.



By using legacy turbine analysis software, which assumes a three-blade setup, we only get an estimate of how a kite turbine will perform. To account for the expanded rotary diameter and higher blade count we decrease the chord of our blades proportionately. The actual performance was to be proven in operation.

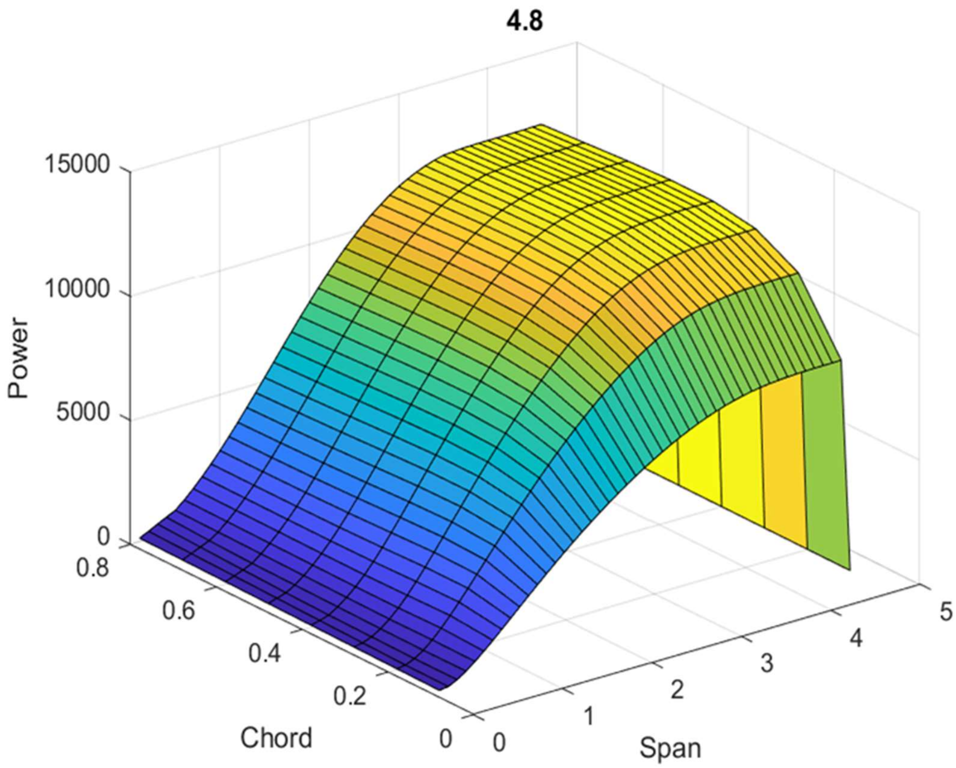
3.3 Blade profile

For the rotor the NACA4412 was selected again. This is a common wing profile for small wind turbines. It is generally low drag and works well within our operational wind speeds.

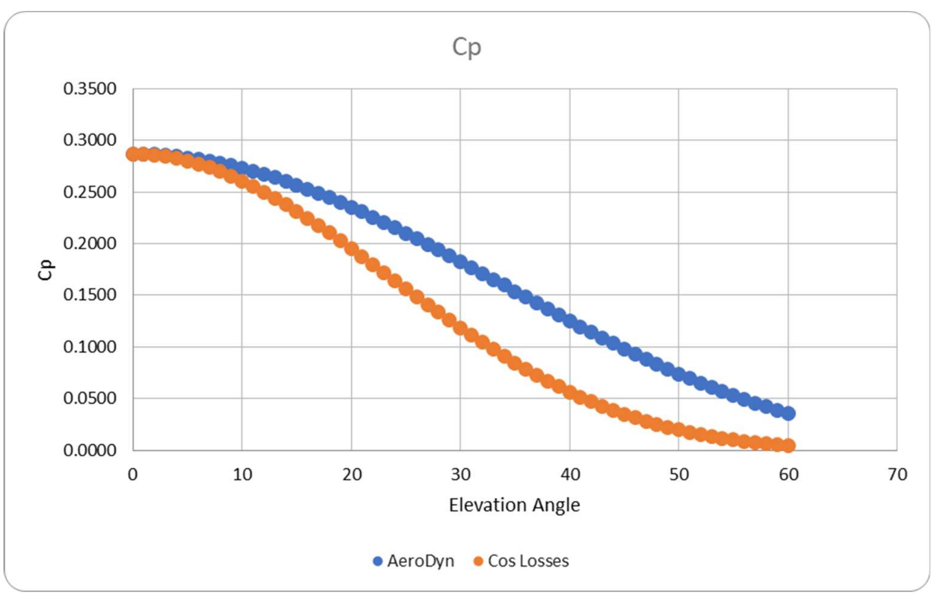


We adapted the rotor analysis results to maintain the same tip speed ratios for similar efficiency when using the blades in a kite turbine configuration, which has a larger radius for a given blade length. We experimented with calculations on blade length to rotor radius ratios to find an optimum. Then from the tip speed ratio we extrapolate angular velocity of the kite turbine rotor.

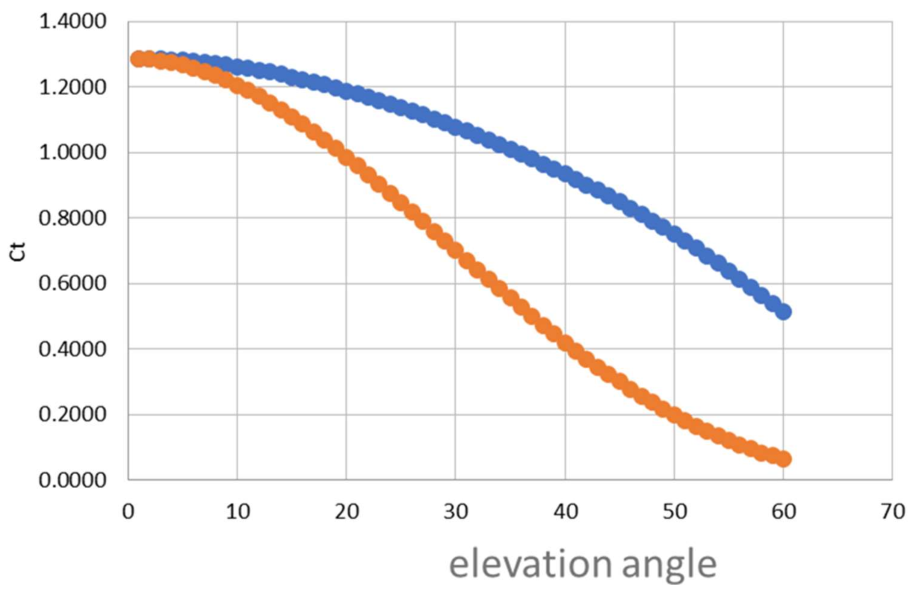
We fed custom Matlab scripts with radius, cord, span, speed and pitch data to get AeroDyn to output coefficients of power, torque and thrust data.



We then analysed the area effects on the coefficient of power and coefficient of torque for a set of given elevation angles to provide expected operational characteristics of the rotors.



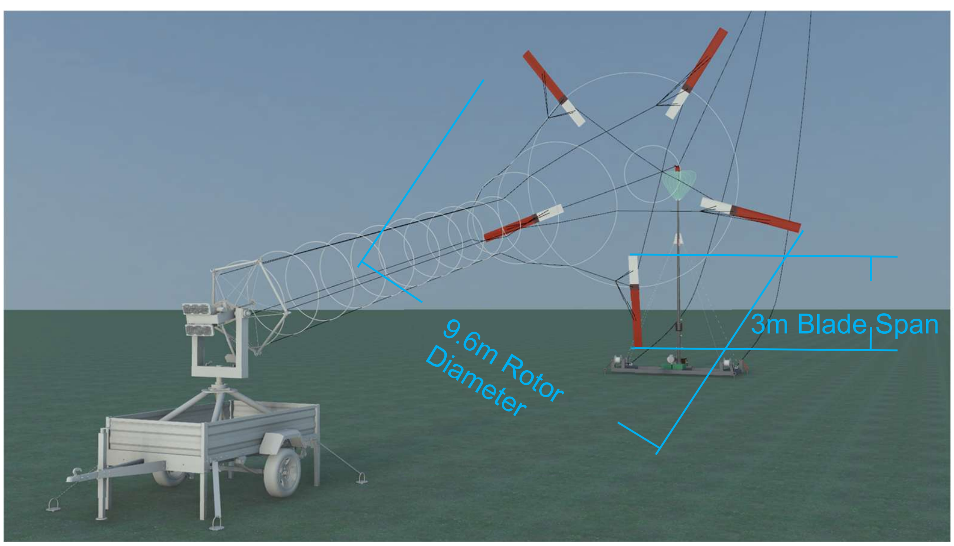
Although the coefficient of power drops significantly with elevation beyond 20 degrees, when we analysed the ground area energy density, we found that an angle of 40 degrees gave a higher energy output per ground area.

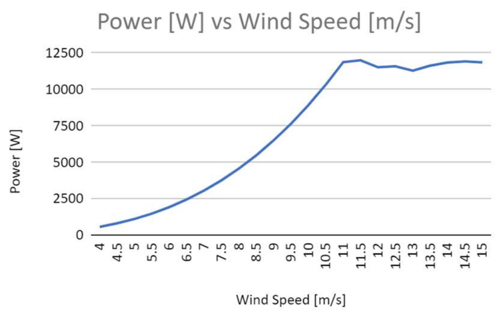


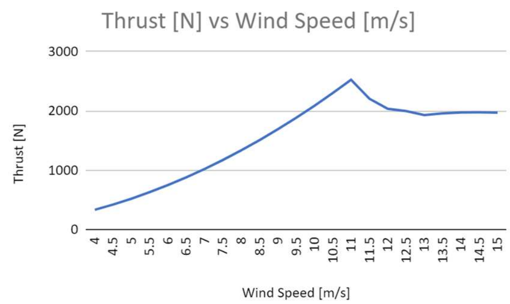
3.4 12kW Rotor dimensions

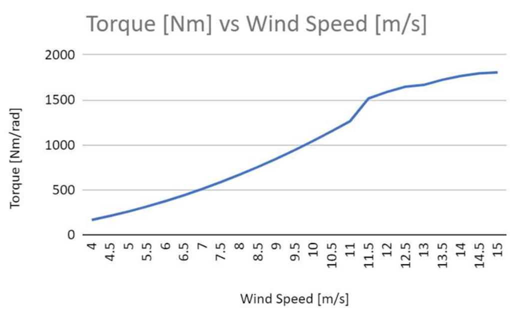
The 5-bladed rotor has a 9.6m outer diameter. This gives the rotor a swept area of (pi*(4.8^2-1.8^2) 62m^2.

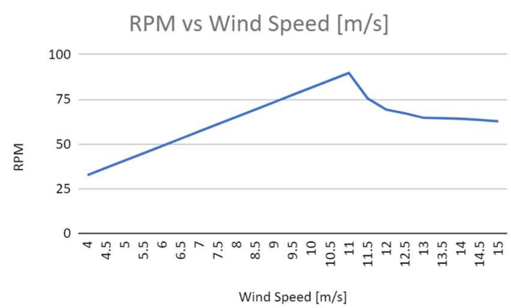
The individual rotor blades are 3 m long, have a 30 cm chord and are approximately 25 mm thick.





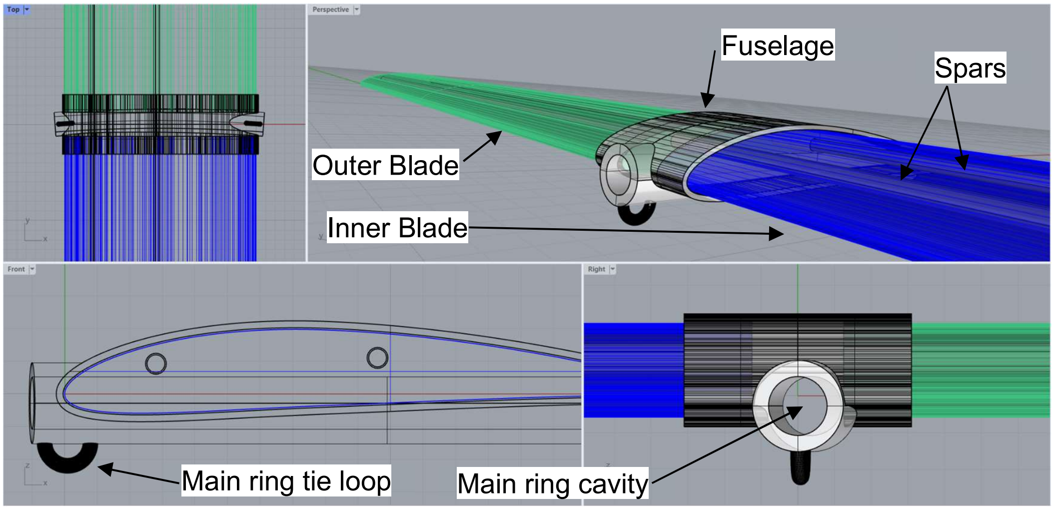


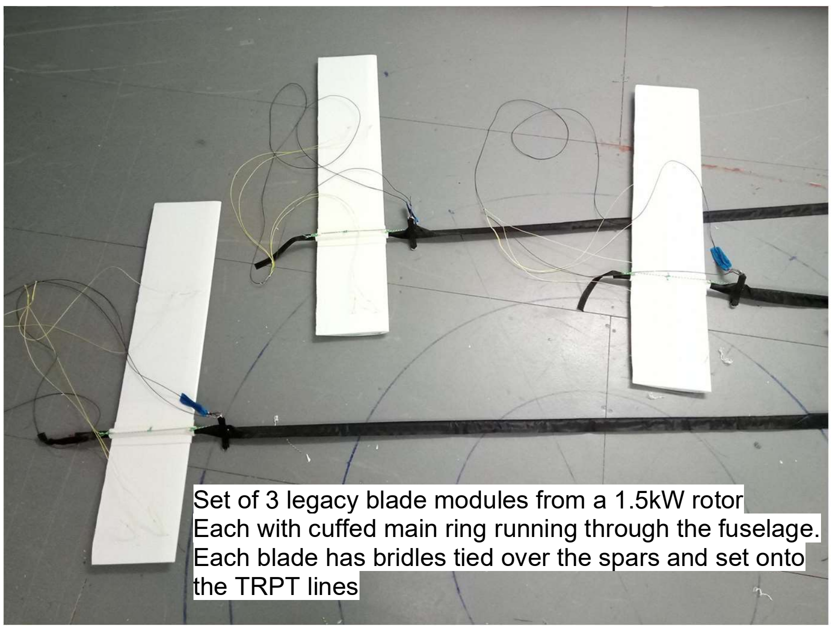




3.5 Blade construction and weight

The 12kW rotor designs were based on our legacy 1.5kW rotors. They were to be made from light-weight closed cell foam weighing 33 kg/m3. They were to be covered in carbon fibre weave with a weight of 300g/m2 and equal amount of epoxy resin. The 12kW rotor blades have dimensions of 3m x 30cm x ~2.5cm. This means each blade has 742 grams of foam and 1.08kg in carbon composites. 5 blades bring it up to a total of 9.11kg.
Accounting for spars, cuffs, rings, bridling and other hardware, the rotor has a realistic minimum weight of 11kg.





3.6 Rotor System Design Scalability Appraisal

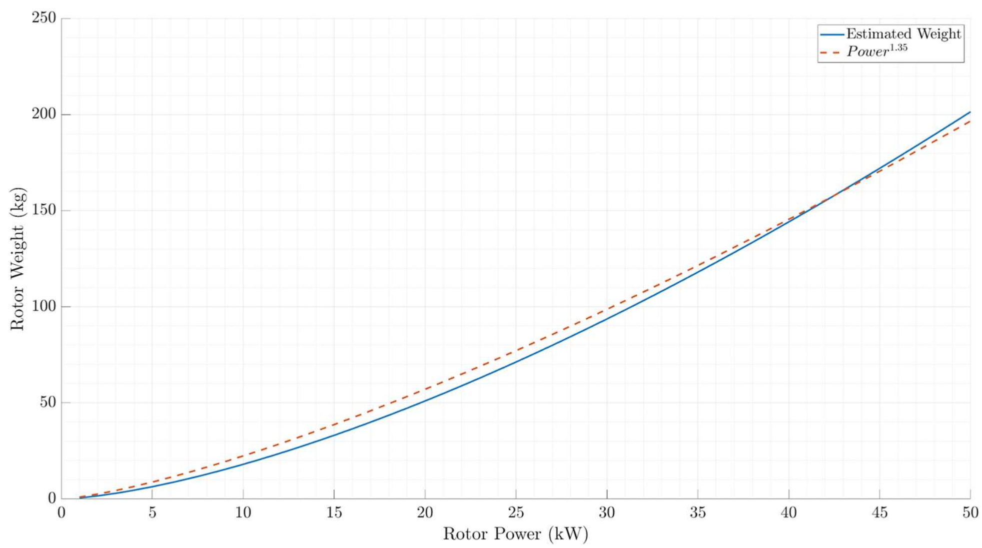
For increasing power, the swept area of the rotor scales linearly with the power that can be generated. This means the rotor length scales with the square root of the power. In other words, if the blades are twice as long, there is four times the power that can be generated.

Increasing the rotor diameter for a given blade span will increase swept area and power, but this will also decrease rotor rigidity and increase launch complexity, so our analysis did not consider variations of this parameter.

When power increases the ideal number of blades will change, the length/chord and chord/thickness ratios change, and the method of construction will vary.

Following development and evaluation of rotor designs across a range of sizes, we can approximate that the mass of these simple single rotor configurations escalates exponentially relative to the rotor's rated power, with a power coefficient of 1.35. This means that for a system with twice the power, the rotor weight increases by a factor of 2^1.35=2.55. An increase of 27% with respect to a linearly scaling system.

The rotor needs to be kept in the air by the lift kite during launch. For a larger system the force the lift kite needs to pull to keep the rotor airborne in low wind is affected by this scaling power coefficient. The effect to the overall scaling of the system will be covered in the lift kite section.



4 Ground Station System

4.1 System Functionality

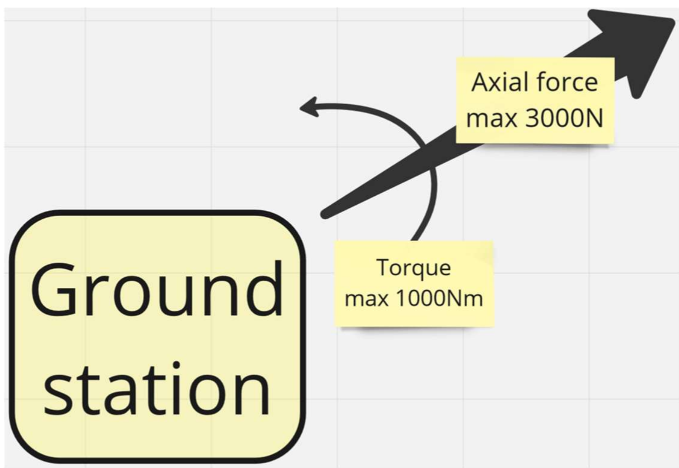
The ground station's main function is to govern and convert the torque from the Tensile Rotary Power Transmission (TRPT) to 10kW of electrical power with fine control across the entire range of operating conditions. The system needs to be able to do this without relying on a local electrical grid connection, as this is assumed to not always be accessible. Additionally, the ground station must resist the axial force generated by the lift kite and the rotor, it must be transportable and should be possible to be set up by a single person within three hours.

The ground station also houses the oversight control and battery systems.

4.2 System Design

The ground station is exposed to two dominant vectors from the airborne systems:

- An axial force vector up to 3000 N in line with the TRPT, generated by the lift kite and rotor thrust. This force is upward at the same angle as the TRPT.
- A torque vector around the TRPT, up to 1000 Nm at 120 RPM, generated by the wind on the rotor, to be converted into electrical power by the generator in the ground station.



Additionally the ground station has the following requirements:

- The ground station needs to be self-sufficient in terms of power generation and storage, and needs to work continuously without any external infrastructure, such as a power grid.
- The ground station needs to automatically align to the TRPT and rotor in all expected directions without human intervention.
- The ground station must stay in place without external infrastructure, such as a concrete foundation. It may use its own weight as well as ground anchors to transfer the resultant forces to the ground to ensure a safe installation.
- The ground station needs to be transportable with a regular car with a trailer hook, and deployable without anything other than hand tools.

4.3 Drivetrain

The ground station resists a precisely controlled amount of torque by electrical regenerative braking, i.e. converting the mechanical power into electrical power. Two components are connected in-line to accomplish this; a gearbox and an electrical generator. The following components were selected:

Generator

For the generator, the water-cooled high power synchronous motor ME1616 from MotEnergy was selected. The motor is rated up to 20kW continuous, so it meets the power requirements. The motor has two big water-cooling ports to make sure that the heat from the inherent power losses from generation can be transported to an external radiator. Considering a modest efficiency of 80%, up to 2kW of heat is generated which can damage the motor without cooling. The actual efficiency for regen is not known for this motor and will follow from testing. The motor is rated up to 6000 RPM, but a safe operating range of ~4000 RPM is preferred.

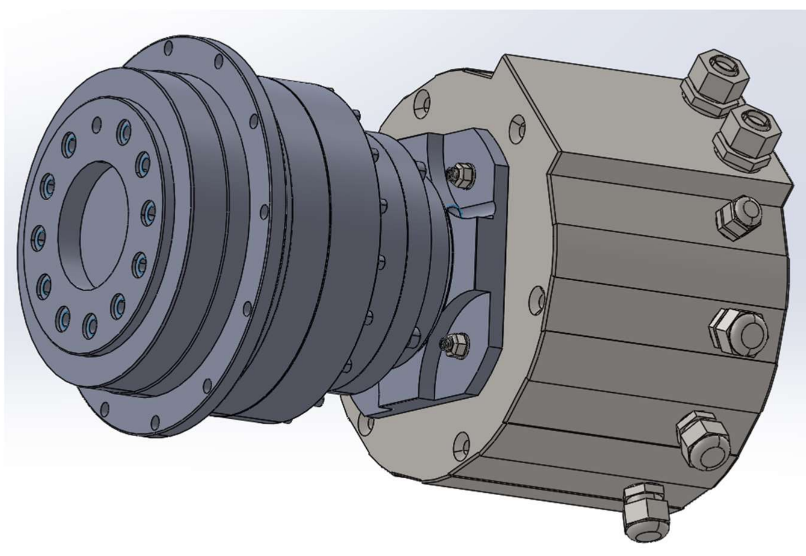
https://www.electricmotorsport.com/me1616-brushless-65hp-liquid-cooled-ipm-motor-24-120v.html

Gearbox

A gearbox is required to speed up the TRPT RPM to a speed that is in the usable range for the generator. The AD200 35:1 planetary gearbox from MotionControlProducts was selected. This gearbox is made with a custom flange to mate directly with our generator. Both the gearbox and the generator have a maximum speed of 6000 RPM. The 35:1 ratio ensures a speed in a favourable RPM (~4200 RPM) range whilst maintaining enough of a safety margin to stay below the maximum.

The AD200 can resist up to 1100 Nm of input torque and 16kN of axial force, so it meets the force and torque requirements. The PTO can be mounted straight to the front plate, minimising the component count in the drivetrain.

https://motioncontrolproducts.com/ad200-planetary-gearbox.html



Assembly with adaptor flange

Yaw and elevation tracking

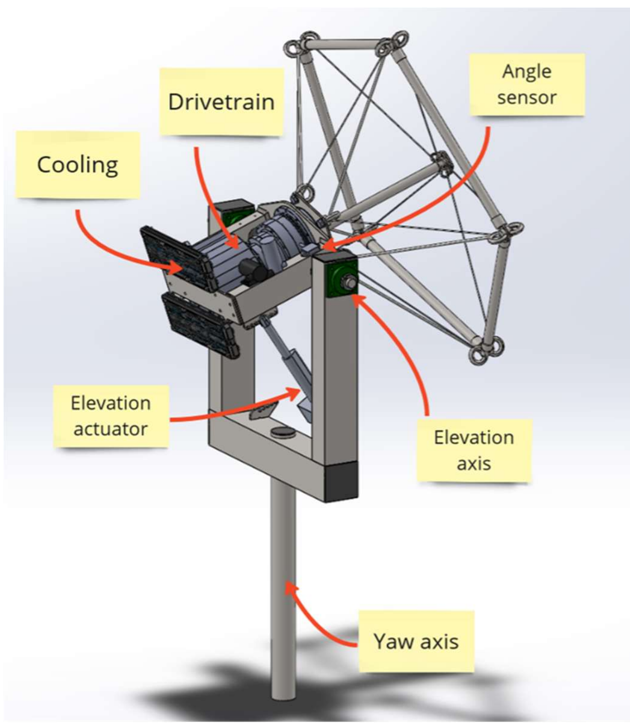
The drivetrain needs to be aligned to the TRPT and rotor in conditions with varying wind speeds and direction. A gyroscope yoke type mounting frame was selected where the generator, gearbox and PTO are mounted in a subframe. The subframe has an axle right through the centre of gravity, which allows it to move without significant force and helps eliminate the effects of gyroscopic precession.

The subframe houses the following components:

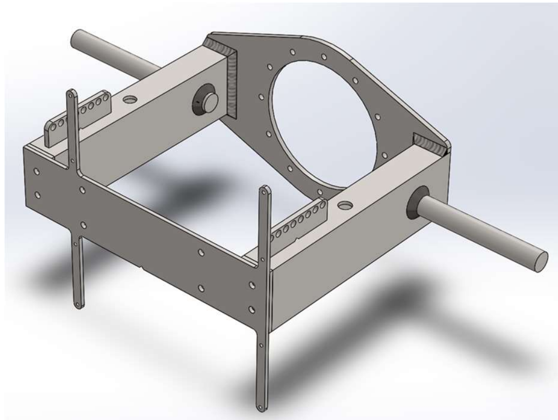
- generator
- gearbox
- cooling system (radiator, pump and coolant reservoir)
- angle sensor

The subframe is suspended in the wishbone shaped vertical frame with 4 industrial bearings. Between these two frames is a 12V linear actuator to change the elevation angle. Elevation angles ranging from -10 degrees to +70 degrees can be achieved.

The wishbone frame is mounted with 2 additional industrial bearings (not shown) and is driven with a 12V rotary actuator (not shown), to allow for continuous yaw rotation.



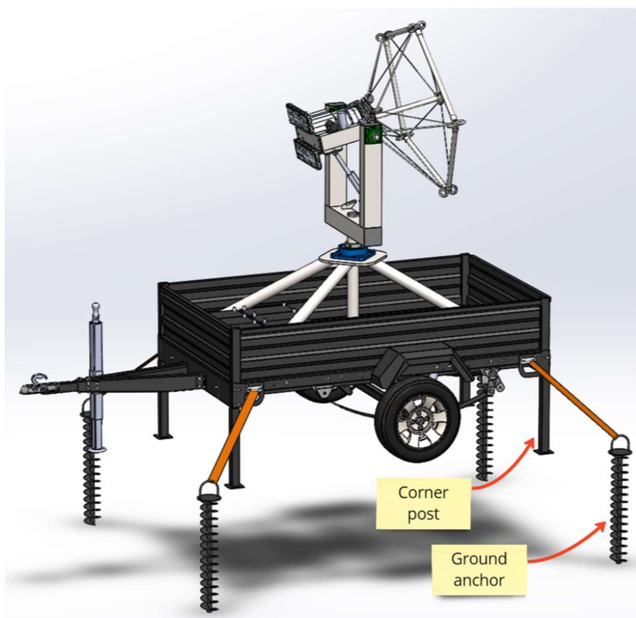
The drivetrain mount and support frame are made from standard box sections of steel, round bar and water-jet cut flat steel, welded and bolted together. The mount is fully symmetrical to avoid any human error production issues.

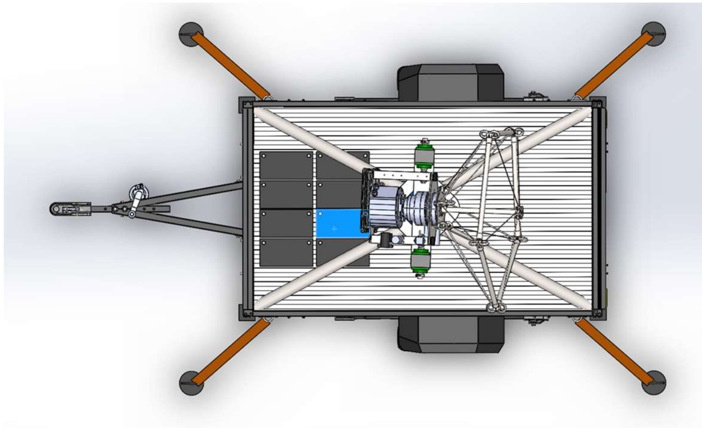


Frame and transport

The drivetrain is mounted on a standard trailer to allow for easy transport to demonstration sites and events.

Two industrial bearings allow the yaw axis to spin around 360 degrees. The horizontal force is transmitted to the corners of the trailer with round steel tubes. In the corners the force is transferred to the ground with four removable corner posts for compression and four ground anchors and straps for tension.





Electronics

To allow for autonomous operation, suitable for on-site demonstrations, the ground station electronics are fully self-contained. Power generation, control, sensing and dissipation is all done locally.

The ground station has a 200Ah 48V lithium-iron battery pack. It can take 400A in, so it has a maximum power input of about 19kW, which is above the rated 10kW minimum.

The generator three-phase output is run through an array of active rectifiers and DC/DC converters. The final DC/DC stage has precise current control. The torque the generator puts on the gearbox and TRPT is directly proportional to the current that is drawn, so in this way precise control of TRPT twist and optimal production can be achieved within safe working limits for the whole turbine.

If it proves necessary for rotor startup or overtwist prevention, a BLDC motor driver can be installed in parallel with the power generation electronics.

To burn off excess power, two 5kW inverters and an array of space heaters are installed.

A series of tests involving sensors on the power-take-off (PTO) wheel will be conducted in order to determine the best control algorithm for governing torque and power generation.

Power Take Off

The Power-Take-Off (PTO) wheel is a tensegrity structure which allows the TRPT to be connected to the ground station. It is bolted directly to the gearbox with 12 M10 bolts. It is made from all steel tubing, plates and cables. A central pole keeps the ring from touching the ground station when it is not tensioned by the TRPT.

Five attachment rings allow the TRPT to easily be connected and disconnected. Optional load cells can be connected in between the TRPT and PTO for analysis purposes.

4.4 Ground Station System Design Scalability Appraisal

The Ground Station drivetrain is somewhat comparable to the drivetrain of regular HAWTs, with the notable exception of the elevation axis pitching. The assumption is that if yawing is possible for >12MW HAWTs, it should be possible to do both yawing and pitching up to the same scale also.

The current powertrain setup of a low voltage generator, rectifiers and low voltage battery bank is not going to scale much further. When scaling the system further the drivetrain either needs to switch to a 600V automotive system, which should work up to 200kW, or an AC grid-tied system. Both options have standard parts available on the market.

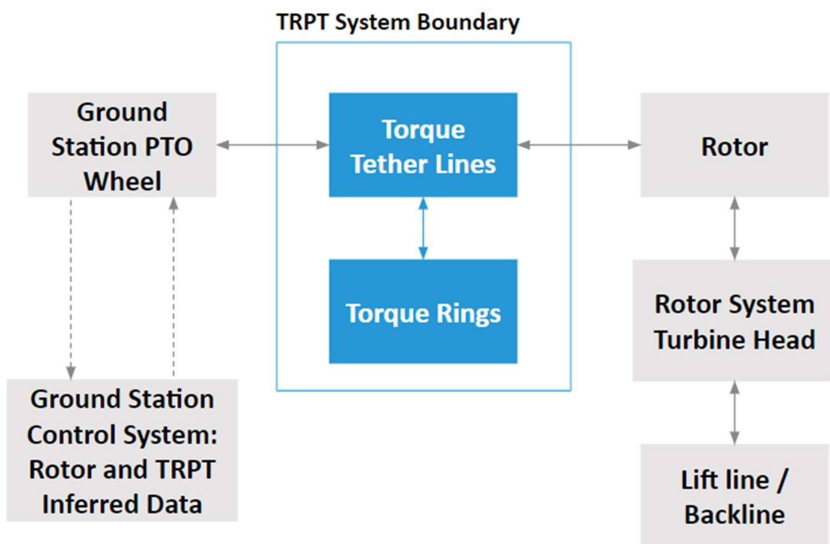
A trailer-based foundation for the Ground Station is also not going to scale much further, though there are definitely larger trailers in existence, the width ultimately is limited for regular roads. Outriggers might help up to a certain point, but ultimately the Ground Station will need to be fixed to concrete plate or foundation. Compared to regular HAWTs this foundation will be considerably smaller, due to the lack of overturning moment from the tower.

5 Tensile Rotary Power Transmission (TRPT) System

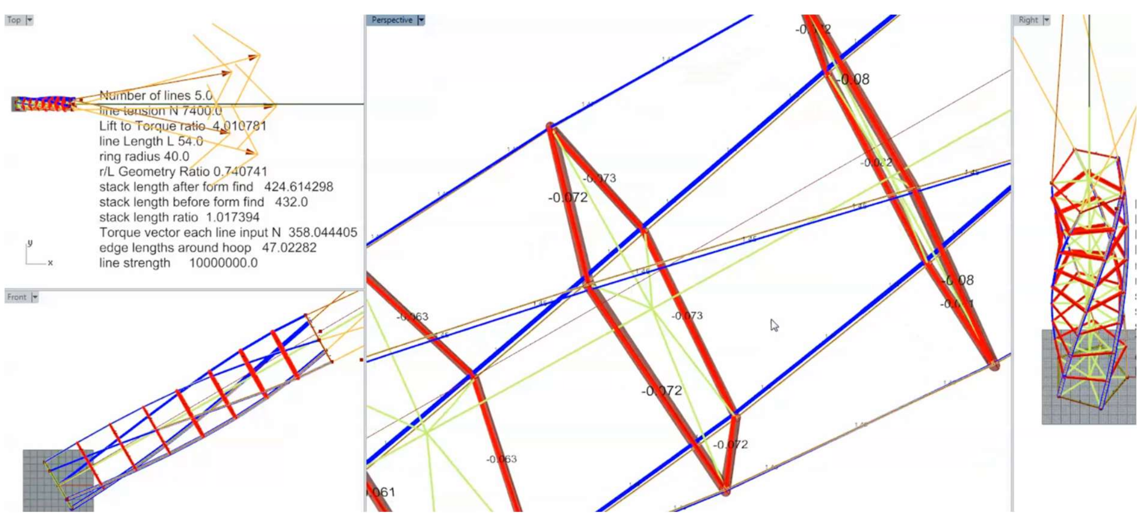
5.1 System Functionality

The TRPTs main function is to transfer the torque from the rotor to the PTO wheel on the ground station. The TRPT must also tether the rotor to resist the axial force from the rotor and lift kite. The TRPT should be as lightweight as practically possible.

5.2 System Design



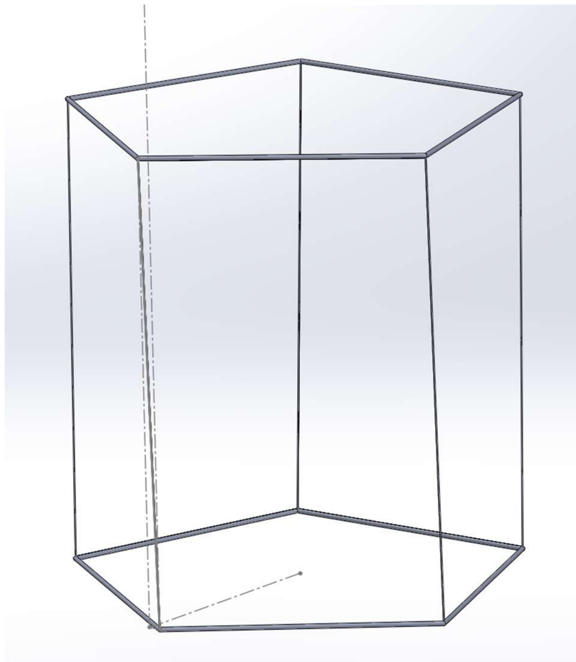
The TRPT consists of 5 tethers along the length, which are kept in shape by several pentagonal torque rings. The TRPT is like a tensegrity structure, with a notable difference that it relies on axial force to keep its shape, without sufficient axial tension the TRPT will deform significantly. This allows for the structure to be incredibly lightweight for the amount of torque it can handle.



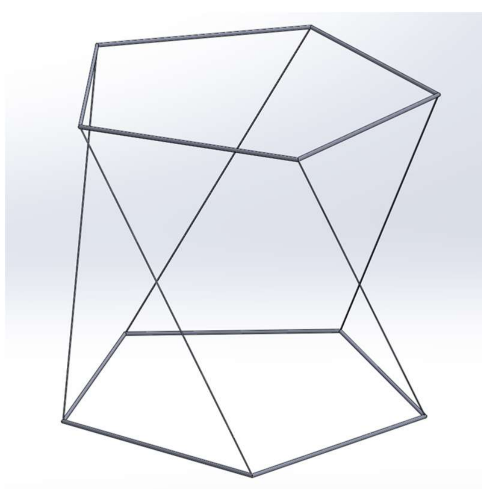
TRPT torsional compression analysis showing beams in compression (Red) Lines in tension (Blue)

Forces

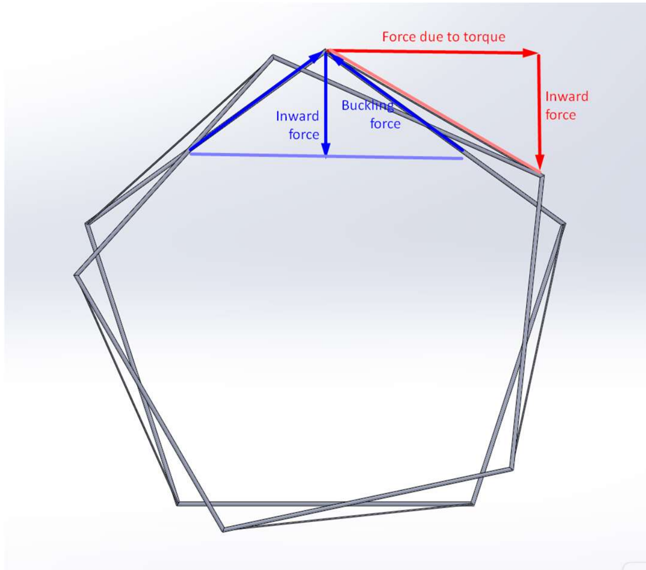
During rated operation the expected force on the tether wires is about (9000N/5) 1800N and the torque on the entire TRPT is about 1200Nm. Under these conditions the TRPT is only expected to twist 3 degrees per section, with an almost negligible inward force of 7N.



In transients however, this inward force can increase significantly and quickly. With a 30 degree twist the inward force goes up to 625N and right before crushing (60 degrees) the force even increases up to 2600N. It can be seen that the TRPT needs to be designed with great safety margins in mind.



This inward force is counteracted by the tubes in the rings. Due to the geometry of the TRPT, a 7N inward force results in a 12N compressive force. The main failure mode in the tubes due to this force is buckling and can be calculated using Eulers Critical Load calculation.



$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

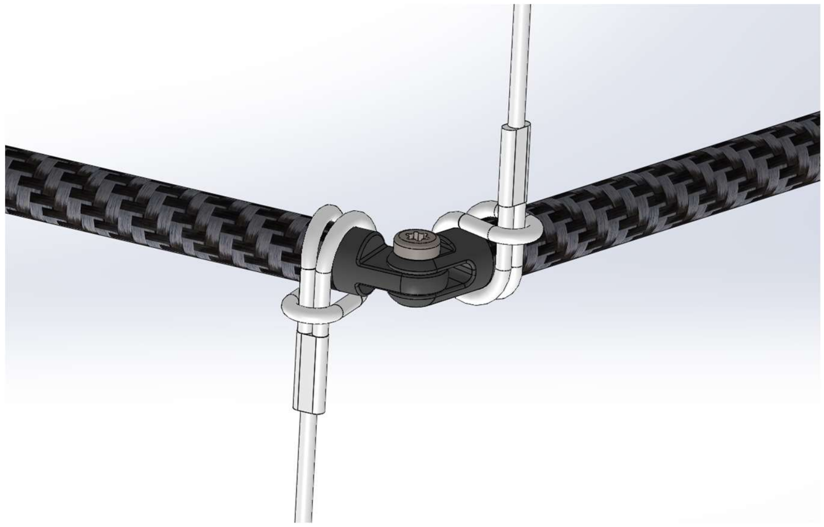
Tether lines

For the 5 tether lines we selected a 3mm type 01505 Dyneema rope. This rope has a typical breaking strength of 950 kg and weighs 6 gr/m. Dyneema is UV resistant and keeps its strength over a long time, making it very suitable for continuous outdoor usage. For a 30m TRPT the weight of the tether lines is 1kg total, excluding the extra weight of knots and splicing.

Torque rings

The torque rings are made from 12mm carbon fibre tubes with 1mm wall thickness. The TRPT uses 1m standard sections of carbon fibre tubes to minimise assembly steps, as well as minimise the risk of microcracks from cutting operations.

The tubes are connected with aluminium clevis tube connectors from Dragonplate. They are pressed into the tubes from either end. The TRPT rings are only subjected to compression forces, so the tube connectors are always pressed into the tubes.



The carbon fibre tubes weigh 58 grams each, the clevis pins are 10 grams each, and the connecting bolt 2 grams. This means a single TRPT ring has a weight of ~ 400 grams.

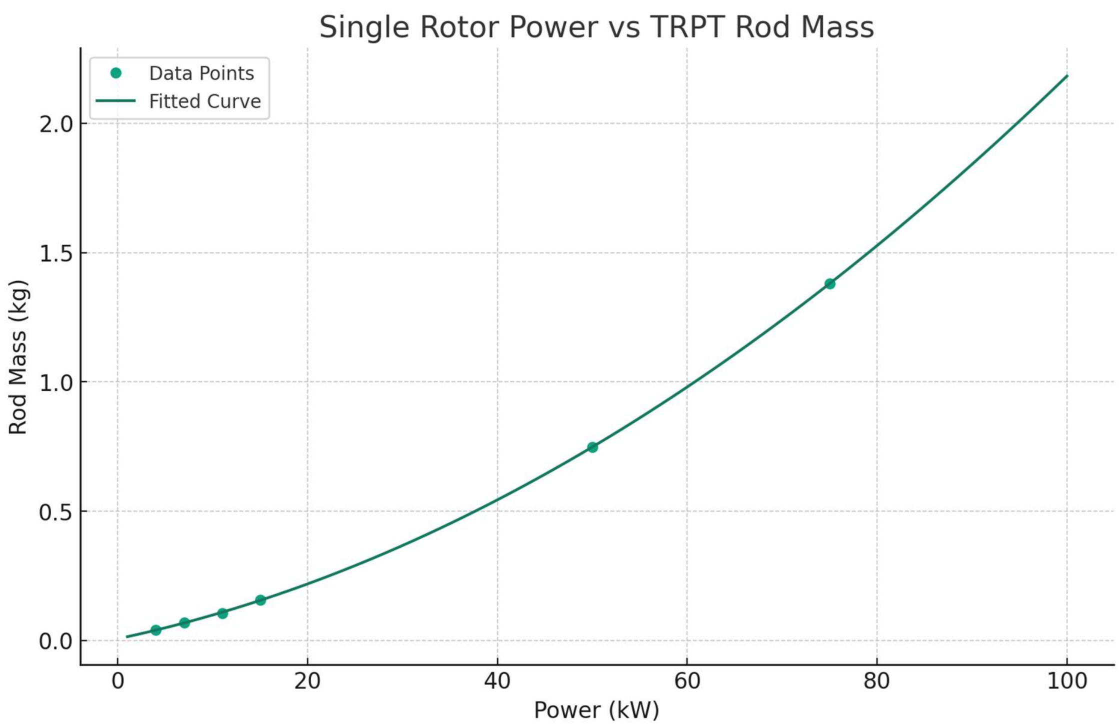
With a 30m TRPT and rings every 2m, the TRPT is expected to weigh ~ 6.6 kg.

((30/2)-1 * 0.4kg + 30*5*0.0024kg = 5.6kg + 1kg ~= 6.6kg)

5.3 Tensile Rotary Power Transmission Design Scalability Appraisal

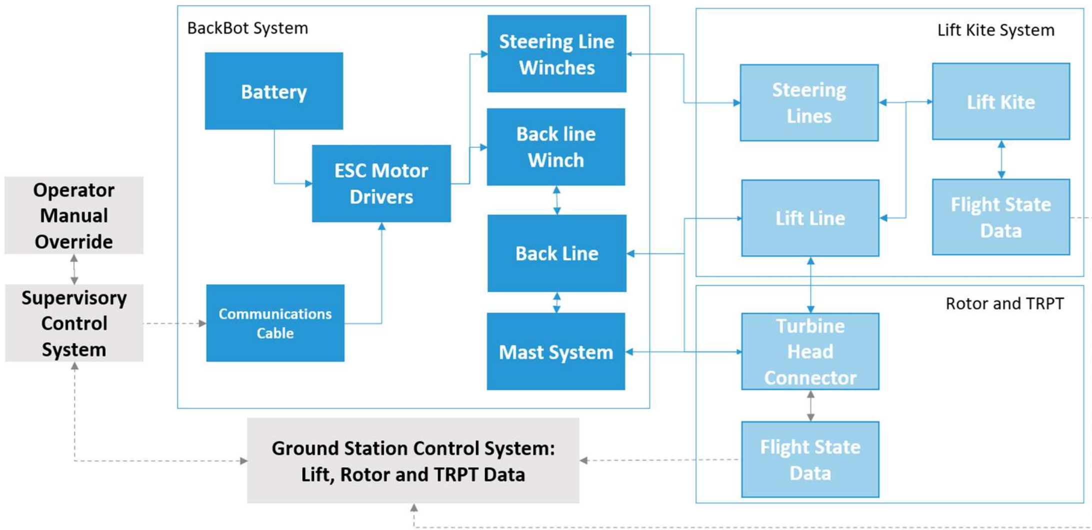
Using a range of the thrust and torque values we expect from single rotor scaling calculations we assessed mass scaling implication on the TRPT.

The results show that as the power capacity of the turbine increases, the weight of the TRPT increases only slightly more than proportionally. Therefore we do not expect TRPT mass scaling to be problematic in Kite Turbine scaling.



6 BackBot System

The 10kW system will automate Kite Turbine launch, operation and landing procedures. To implement these new features, a backline handling subsystem has been added to the MVP. The system is referred to as the BackBot.



6.1 System Functionality

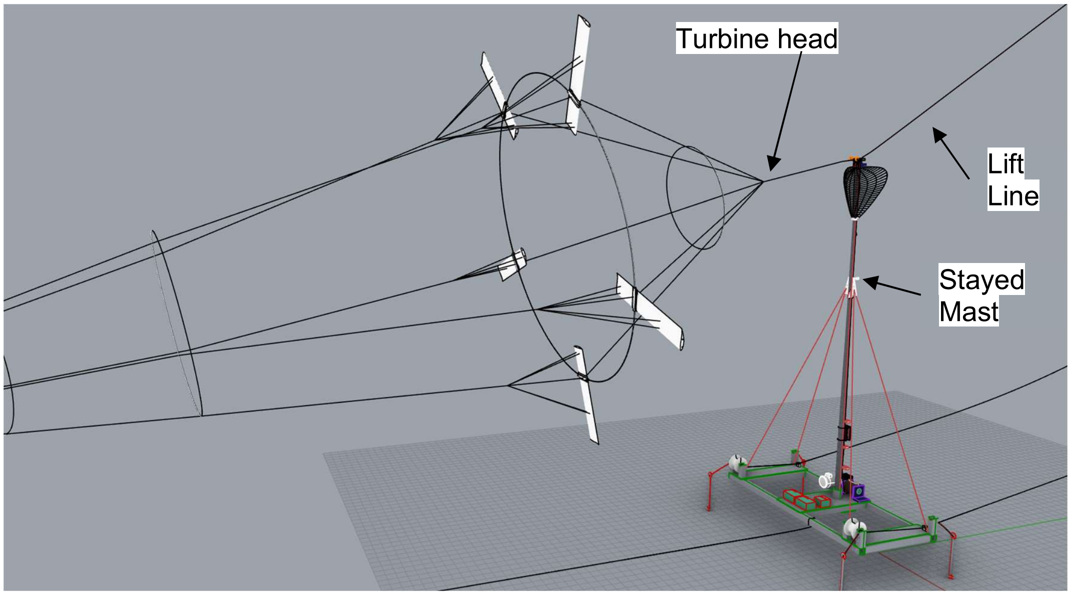
The functional requirements of the BackBot system are:

1. Safely control the launch and land of the lift kite system, the rotor and the Tensile Rotary Power Transmission (TRPT) using a repeatable and reversible method which prevents component damage and can operate with and without human intervention.
2. Capable of setting the elevation angle of the rotor and TRPT, from 0° to the natural maximum elevation angle set by the lift kite, during normal operation, based on external commands.
3. Ability to attach/detach the rotor to/from the backline.
4. Capable of working over soft, rough uneven ground with up to 35 degree slopes.
5. The system must have appropriate safety measures in place to execute the emergency shutdown procedures.
6. Communicates sufficient health state data to the central controller for safe automation.
7. Capable of operating within the operational wind speed envelope of the rotor.

6.2 BackBot System Design

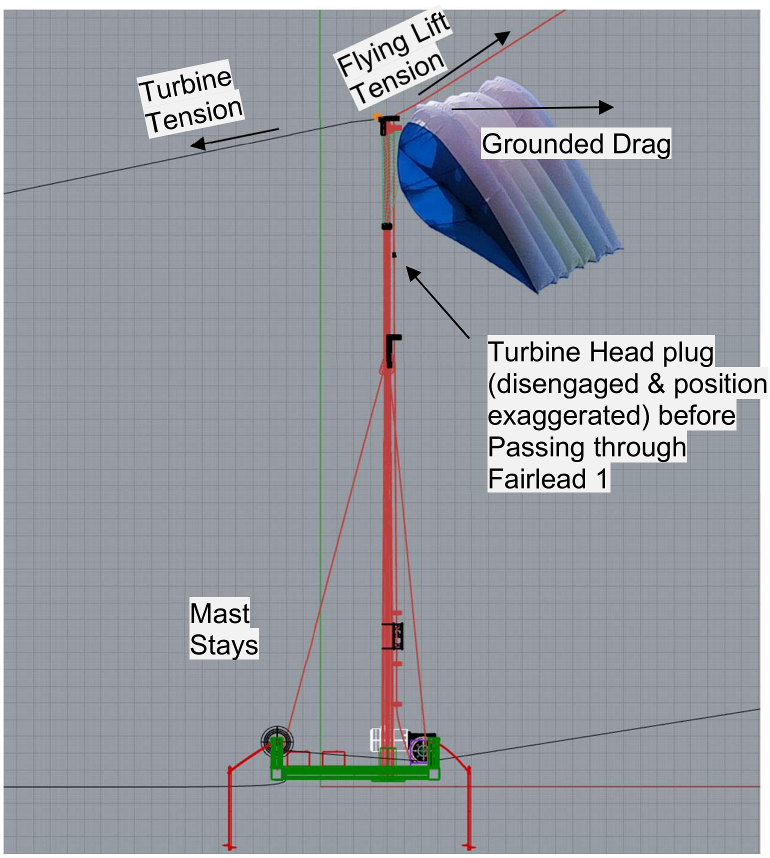
After assessing concepts for the BackBot system, the concept we selected was backline handling with mast hoisting. This concept was the most robust and adaptable platform for automation testing. A description and schematic of the selected concept is shown.

The simple operation to connect the turbine and lift kite relies on a plug fixed to the lift line. The plug passes through a masthead fairlead but engages in a smaller fairlead on the turbine head line.



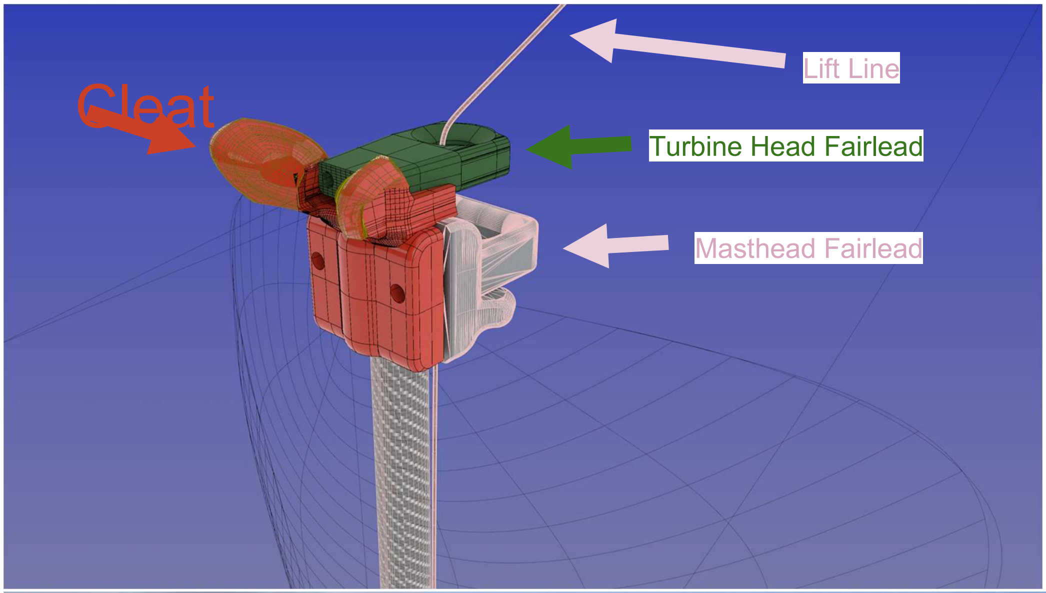
Backbot with lifter launched before engaging the turbine to the lift line to allow turbine launch.

In the pre-launch state, the lift kite, is held with it's bridles choked inside a fairlead at the top of the mast.



Examples of masthead force changes from landed to launching states.

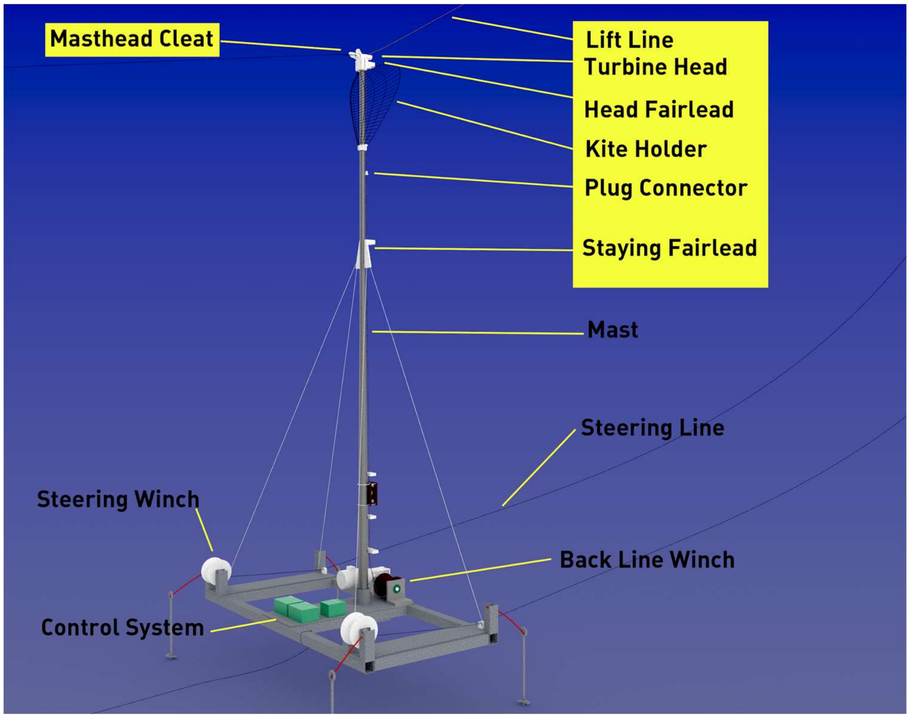
The turbine head fairlead is also held at the top of the mast in a cleat device. The turbine head fairlead is lifted from the mast when a plug on the lift line engages into a smaller fairlead on the turbine head.




Lift Kite masthead holder


Lift Line Plug and Turbine Head Fairlead in the Masthead cleat

When the launch control signal is received, the back line winch is used to reel out the lift line slowly. This allows the lift kite parafoil pockets to fill with air and take full shape as the bridles are pulled through the choke hold of the fairlead. Simultaneously, the 2x steering winches will reel out the lift kite steering lines at a similar rate to the lift/back line winch. Once the bridles on the lift kite have cleared the masthead, the winch reel out speeds can increase.



At a set distance along the lift line there is a turbine head connector (plug connector). The plug connector passes through the masthead fairlead but is sized to fit inside and pick up the turbine head fairlead, thus providing a connection between the lift line and the turbine head.

The turbine head is connected to the rotor and TRPT, therefore, once connected, further reeling out of the lift line/back line will cause the rotor and TRPT to rise. The back line (the portion of lift line below the plug connector) is continued to be reeled out until the desired operational elevation angle is reached.

The reverse of this procedure is performed when landing the device.

The thrust bearing in the turbine head allows the turbine and TRPT to rotate without twisting the backline/lifting line set.

Adjusting the set point of the winches will be used to control the elevation and yaw alignment of the rotor and TRPT during operation.

The Masthead arrangement provided a simple way for the lift line to automate catching and lifting the kite turbine head away from the masthead cleat.

The reverse launch and recovery mechanisms were tested to work when the lift kite is aligned within +/-15 deg of downwind.

The steering winches and lines were chosen to be able to maintain lift kite alignment for reliable launch and land.

In an emergency situation, the steering winches could be used to pull the steering lines with sufficient force to cause the lift kite to be steered into the ground. This will result in the landing of all airborne components as quickly as possible.

The selected concept succeeded in meeting the functional requirements outlined in section 6.1 and the concept was selected as it offered a simple, robust and adaptable platform for testing.

Earlier practical tests demonstrated that deployment of the turbine set can avoid damage by lifting the turbine head vertically off the ground and walking the turbine downwind until the kite turbine and TRPT are stretched out and supported above the ground. Our selected concept allows the rotor to be held suspended off the ground in the pre-launch state, thereby eliminating the risk of rotor damage from impact with the ground.

Several versions of mast supported articulation were considered for the MVP. For example, a jacked mast, a telescoping mast or converted plant machinery. We decided that the most cost effective and simple method for the 10kW scale MVP system was a stayed mast Backbot which would be tipped up from lying on its side prior to the first launch.

Note that the 10kW MVP prototype device is only intended to operate as a demonstrator for periods of 30 minutes or less. Therefore extreme changes in wind direction are not anticipated. The BackBot concept selected for the first iteration of the device would not be able to operate over extreme changes of wind direction. Once autonomous operation had been demonstrated using the first iteration of the MVP device, Windswept intended to further develop the BackBot concept to allow for wind direction changes during operation.

We calculated the braking force available on the ground station would be sufficient to safely stall the kite turbine rotor prior to landing in all wind conditions. This negated the requirement of a portable backbot to facilitate a side-field yaw based stalling method.

The backbot frame was designed to be augmented with motor driven wheels, so that side-field yaw stalling could be tested later. For the final build it was determined that a suitable frame could be constructed using a locally available rigid inflatable boat trailer frame. This frame would more naturally satisfy the yaw-stall via portability tests.

A 24V 600W motor and worm gear combination were sourced from Motion Dynamics to drive the lift line winch drum. Bafang wheelbarrow wheels with VESC Speed Controllers were sourced for the steering winching.

The only parts of the Backbot which needed custom manufacture were the masthead cleat, the turbine head connector, and the staying fairlead. All other components were standard and available off the shelf with some interfacing and mounting arrangements.

6.3 BackBot System Design Scalability Appraisal

The backbot system selected for the first iteration of the MVP device is static. It is therefore unsuited to changes in wind direction >30 degrees during operation. As the first iteration of the MVP device will only operate for periods of 30 minutes or less, extreme changes in wind direction during operation were avoidable and not anticipated. Therefore, a static backbot system was deemed to be acceptable. However, to accommodate for longer periods of operation and therefore changes in wind direction, the backbot frame was been designed to be augmented with motor driven wheels. These frame driving wheels were intended to be implemented during later phases of testing. A roaming backbot was thought to be an acceptable solution for a 10kW product.

However, as the design scales into larger systems with single rotors and longer TRPT sections, the ground footprint required for a roaming backbot would become increasingly unacceptable. Similarly, the mast height required to suspend larger rotors off the ground is not expected to scale favourably. The principles of the automation will not change substantially as the system scales, however the backbot concept for executing the automation is expected to require significant alterations for larger systems. Windswept expect that the backbot system would ultimately end up being integrated into the ground station design. In doing this, the ground station would need to house the rotor and TRPT. This would lead to the exploration of new design concepts such as folding rotor blades or line attachment systems for this transition to be implemented.

7 Lift Kite System

7.1 Lift Kite System Design

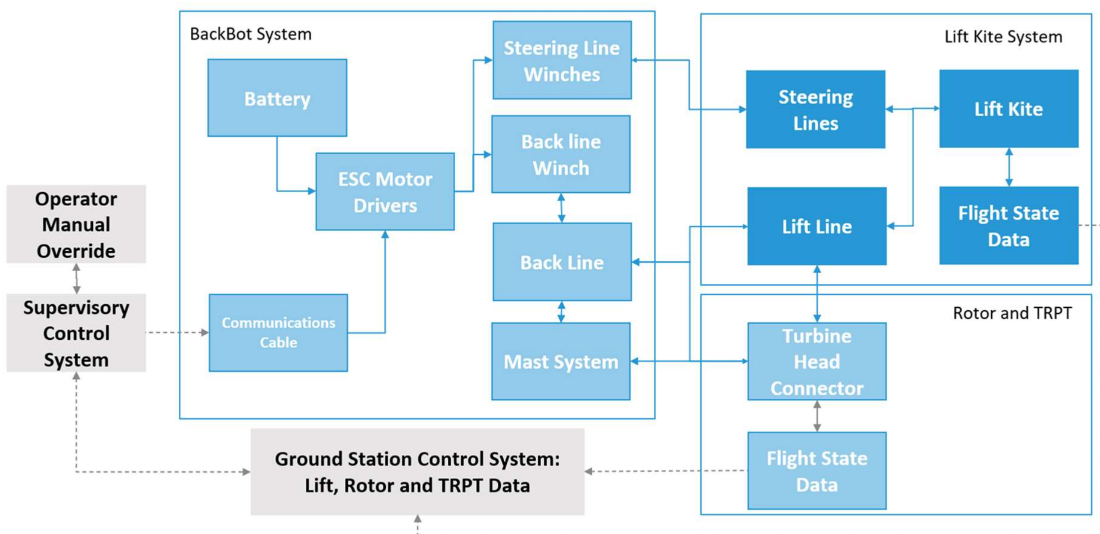
The lift kite system is used for 3 main purposes

1) Lifting the rotor and Tensile Rotary Power Transmission (TRPT) up into the air.

2) Providing additional tensile axial force, to enhance torque transmission capability in the TRPT.

3) Keeping the rotor and TRPT aligned with the wind, downwind in the "Kite Power Zone".

After testing several lift steering options and running FMECA on the lift system, we were able to reduce the complexity of the MVP lift kite, to a classic Kite Aerial Photography (KAP) lift kite platform, which would be augmented with 2 steering lines and a flight state data monitoring system. All line control to be handled on the Backline Robot. The flight state data monitoring to be relayed live to inform the winching controls.



For the MVP off-the-shelf KAP lift kites by HQ were chosen as they would provide the easiest launch and most stable lift solution. Windswept had previously successfully used the 1.6m² and 3m² HQ KAP Foils with smaller Kite Turbines in winds from 8 to 15m/s.

KAP design has evolved over the last century into stable ram air foil kites. They have proven reliable for stable support of camera equipment over 15kg. Windswept had previously tested that 1.6m² and 3m² HQ KAP kites are capable of reliable operation in a wide wind range. We knew that we would have to increase size used, likely to the 5m² model, we chose to also test the 8m² just in case more lift was needed in low winds.

Windswept had also previously tested that these kites are able to be launched from a simple fairlead at the top of a mast. This launch method effectively mimics, with the fairlead, how a human kite operator controls the kite bridles in launch and land with their hand. The tether and bridles pass through a fairlead (a smooth toroidal ring) as the kite is raised and lowered. At the lowest position, the kite ribs touch the fairlead where the bridles are sewn on. With all of the ribs held together the kite is "doused" or "choked." The kite has a minimally inflated volume in this state and causes little lift or drag. By slowly releasing the lines out from the fairlead, the lift kite inflates ready for launch. The reverse is similar, pulling the bridles back into the fairlead douses the kite again.

We used the following set of top level functional requirements.

1. Capable of operating within the operational wind speed envelope of the rotor.

2. Safety Compliant with EASA CAA Our own SORA and SAIL Standard with a Soft fail - e.g. Must fall from sky as required

3. Capable of pulling the rotor through the wind window to a yaw angle of >30deg with lift force of 190N based on external commands

4. Operation should not be limited by local topography.

5. No external Power Requirement Tethers OK - Cables Bad.

6. Must support Kite turbine with sufficient tensile Lift forces to achieve a lift angle of 40 deg for winds >4m/s.

7. Communicates sufficient data to the ground station to monitor health state

These top level requirements were identified as the highest priority requirements derived from the Lift Kite FMECA.

Prior experience and the standard kite line tension model formulae suggested that the 8m2 lifter should be more than sufficient.

$$F_L = \frac{1}{2}\rho A C_L v_a^2,$$

where ρ is the density of the air, A the airfoil area, and C_L the lift coefficient which depends on the geometry of the airfoil.

Test plan

The Lift kite is the first part of the Kite Turbine to be launched. It is the most standard kite element used in the Kite turbine system design. The MVP test series plan reflected this by having the lift kite as the first system in the MVP to be tested.

Windswept have now run initial testing to assess the performance of several lift kite types and models across a range of wind speeds. The most significant test result is that the new larger static lift kites are providing far less lift than we reasonably expected in low winds.

Each kite was tested on a 30m line for ease of airspace compliance and for easier and safer manual launching before the full Backbot was built.

In our initial test series the most important data we measured came from line angle, line tension and wind data sensors.

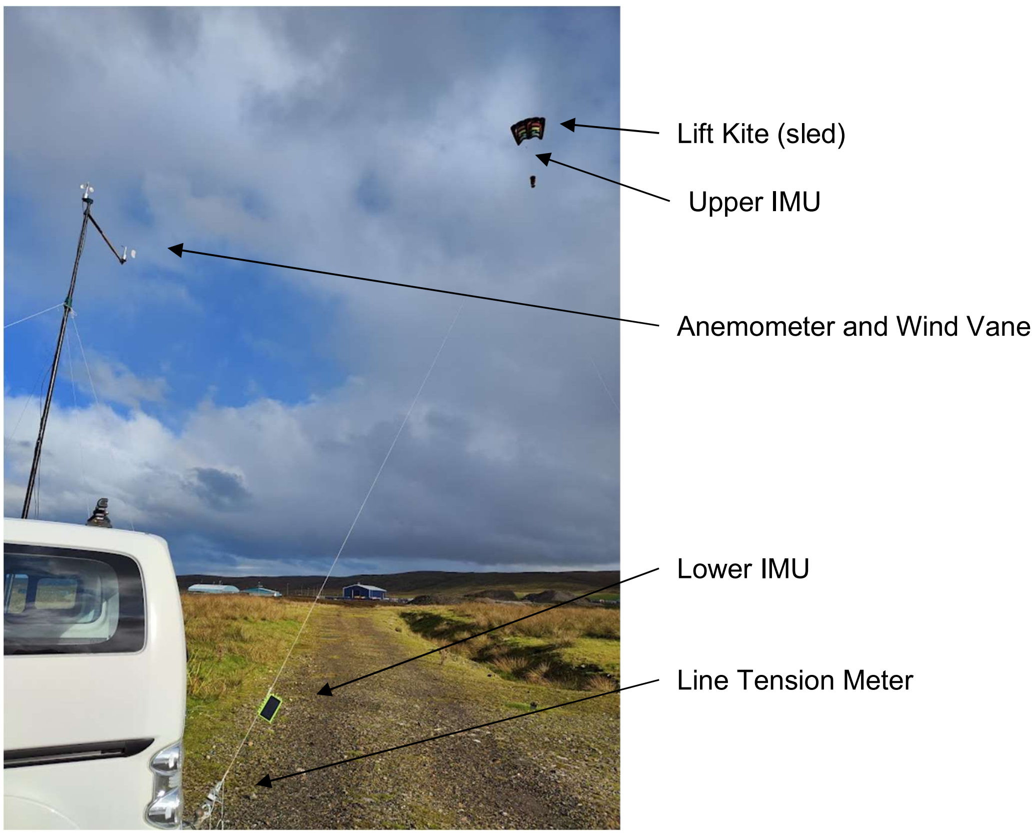
Line angle was measured both by using an MPU9250 Inertial Motion Unit (IMU) connected to an ESP32 microcontroller and by a repurposed smartphone in a custom line holding case using an

IMU data logging app. The ESP32 used our customised flight control software to data log attitude to a pc. MPU-9250/6500 Digital Gyroscope Sensor ±3% SSFT @ 25C

Line tension data was from a TAS501 load cell attached to the tether, data logged via an HX711 load cell amplifier and Arduino to PC. HT Sensor Technology TAS501 Load Cell Accuracy ±.02% max 400kg with a HX711 amplifier CMRR 100dB & max .4mV drift.

Our anemometer was mounted on top of a 5.5m mast, with a wind vane mounted 1m to the side. An arduino was used to read the speed and direction data which was then logged on a PC inside our van on the test field. The anemometer gives ±1% accuracy for 20-110kts with 0.4% nonlinearity. Wind Vane gives ±3° @ >5m/s = ±0.83%

Each test was launched, stabilised, calibrated and then run for 12 minutes with readings being taken every 0.5 seconds.



Typical testing setup with kite type and sensor arrangement.

Lift requirements

With the 10kW MVP having a TRPT of minimum 6kg and a Rotor of minimum 11kg, the Lift Kite needs to be able to lift 17kg vertically off the ground to get the system airborne.
The vertical lift force is a combination of the line tension and the line angle. For instance a lift kite with a line angle of 30 degrees needs to pull with 34kg to lift a 17kg system.

It can be seen in the results section that the KAP lift kites performed well below this requirement.

Assuming a cut-in windspeed of 4 m/s, it can be seen that the 8 m2 lifter generates a line tension of 80N to 150N.

With the required 340N line tension, the 80N is woefully insufficient. Therefore an alternative lifting kite solution is required.

If we opt for a larger KAP lift kite (Which doesn't exist readily on the market) and assuming kite lift force scales linearly with the surface area. A Lift Kite of (340/80*8=) 34m^2 minimum is needed to lift the Rotor and TRPT off the ground at 4m/s.

A kite of 34m^2 would significantly increase the sizes specified in our Backbot systems. Such a large kite would also demand extremely capable ground control systems at higher wind speeds.

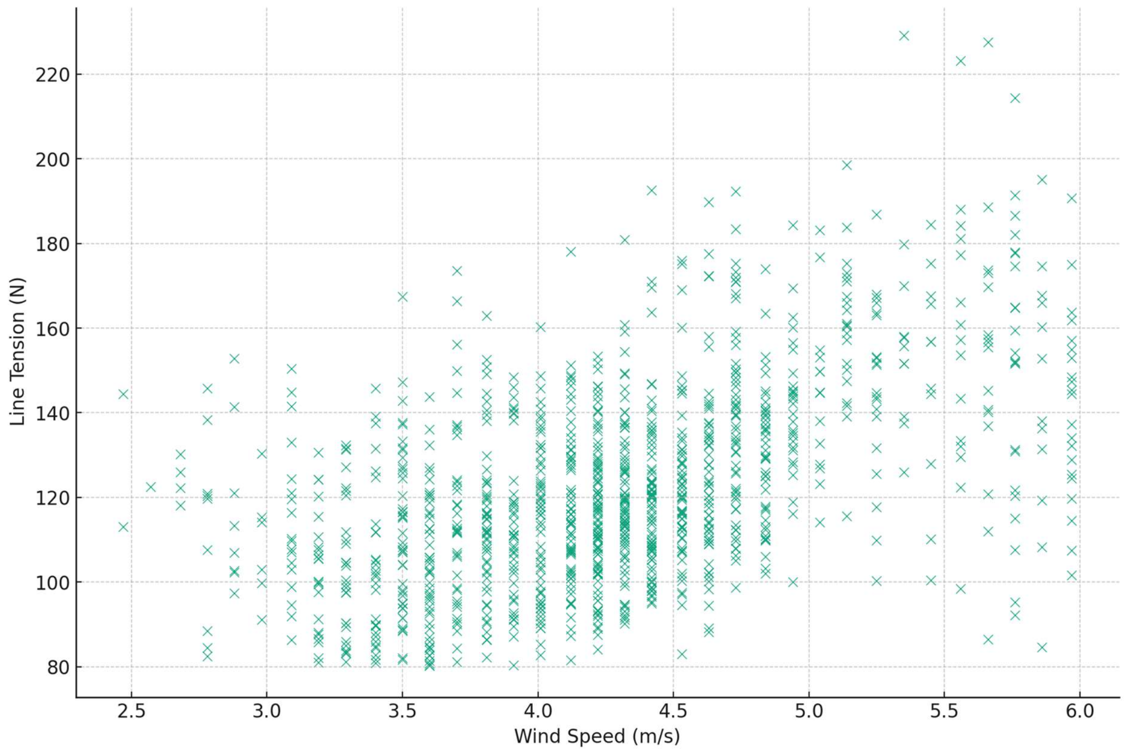
Any weight increase in the TRPT, Rotor, Lift Kite, bridling etc will also linearly increase this surface area. So scaling by using static lifting kites now seems too problematic to continue investigating.

Windswept are now actively investigating multiple alternatives to static lifting KAP solutions.

Results

The HQ KAP foil kites all inflated and launched as expected. They all exhibited stable flight as expected. Launch and retraction cycles were cleanly demonstrated safely.

Tension in the low end of the wind range however has proven disappointingly low.



Typical 8m² KAP foil Line tension vs wind speed test result chart (filtering has been applied to remove the downwind lag time effects of gusts arriving at the lift kite after arriving at the anemometer)

The low lift line tension problem disappears as the wind increases. Our maximum recorded tension to date was 540N in a ~20m/s gust on the 5m² lifter.

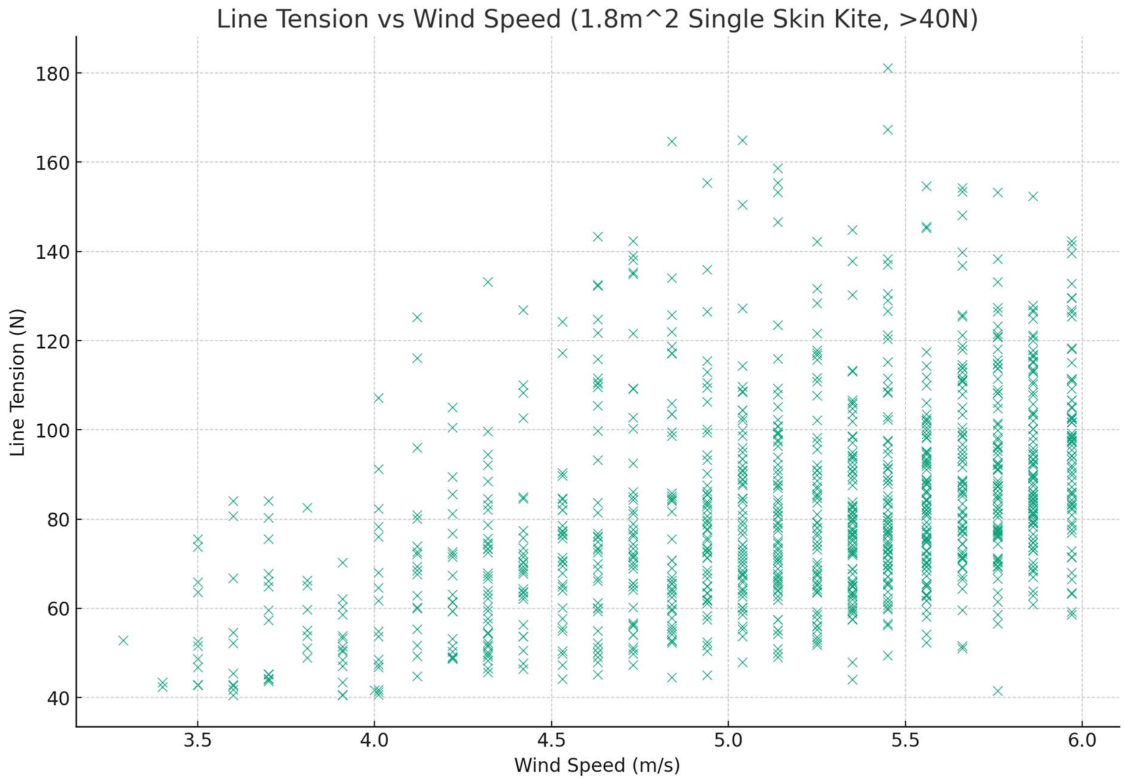
Wind Turbine systems however require to be able to operate from 4m/s to be economically viable.

Expectation vs Reality

The lift tension performance expectations were based on results of our earlier airborne system modelling and published lift kite performance data and model calculations from prior works within the Airborne Wind Energy community.

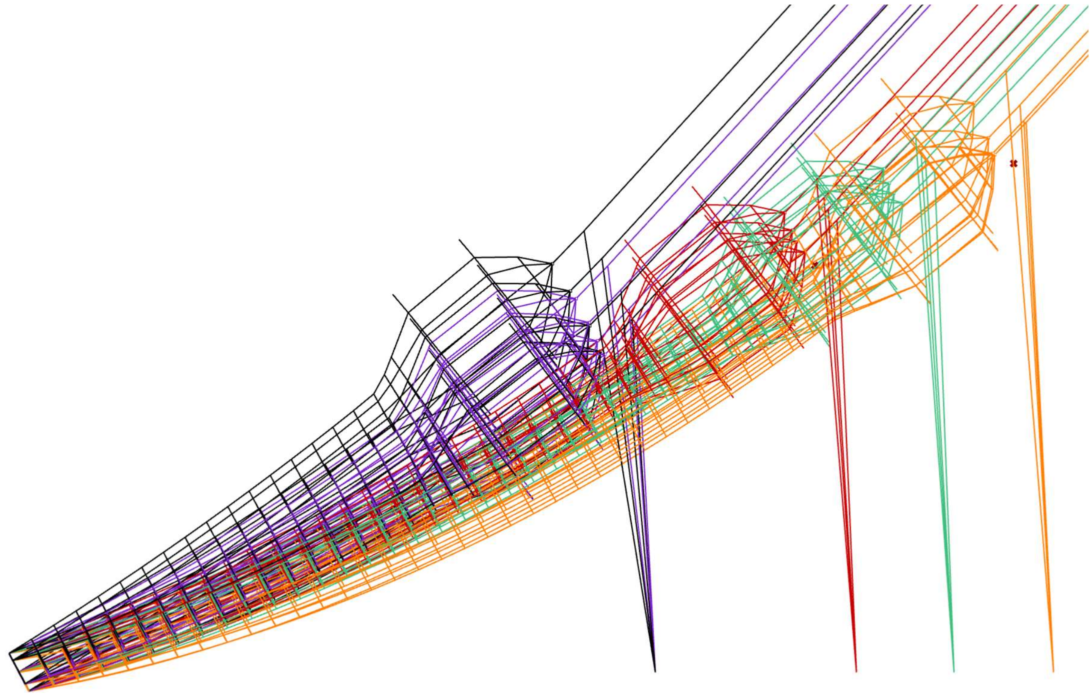
Windswept had successfully used a 3m² KAP foil lift kite on our 1.5kW system so we did expect this series of 5m² and 8m² lifters to be more than capable.

Using the same test gear we also assessed our old 1.8m^2 custom sewn single skin lift kite. (Chart below) This was the lifter most used during the 1.5kW tests. The line tension per area from this small lifter greatly exceeds that demonstrated by the large foil lifters. Our assumption on performance has likely also been biassed by this prior experience.



Sag result from Low Lift

Kite turbine system masses and forces were modelled in a physics solver to compare the expected flown form state of a variety of Turbine network designs (colours) with a set range of lift line tension vector profiles



The resultant positions of the turbine heads can be compared to the ideal (fully stretched) form to systematically assess whether a given system sag is sufficiently low for operation. All of the above would be suitably taut to initiate the next stage - rotation and generation.

None of the static lifters we tested would be able to achieve these taut forms at 4m/s with a 10kW Kite Turbine.

7.2 Lift Kite System Design Scalability Appraisal

The static 5m² and 8m² KAP lift kites were very disappointing in their low wind tension performance. In higher winds their tension is sufficient and they perform well enough overall for operation of systems up to potentially 6kW starting in moderate winds. This static lift method obviously falls below our requirements however and does not lend itself to marketing the value of a scaled product.

Where they offered ease of access to small scale tests. The simplistic static kite deployment method will not suit scaled kite turbine deployments without significant advancement.

Windswept have begun to assess the merits of several furthering concepts which overcome this scaling limitation.

Some examples of deployment options being considered at Windswept are

- Using a more standard AWES approach of crosswind lifting, where active kite apparent wind is enhanced resulting in significant tether tension increases. This method requires more active lifter steering than we currently have available.

- Cyclic pitch control of Rotors for self-supporting turbines. Similar systems are being studied in other AWES organisations.
- Cyclic bank angle control of Rotors for self-supporting turbines.
- Active lift kite parameter adjustments. E.g. Angle of Attack, profile depth. Simple adjustments however, seem unlikely to yield large enough impacts on performance.
- Kite Turbine suspension using a tensioned net suspension across a valley. Not strictly Airborne and more limited in deployment
- Kite turbine rotor stacking for higher power to mass ratios.
- Lifter stacking to reduce mass per swept area.
- Lift array and stacking multiple lifter attachment designs for combined lift tension.

The main lesson for using lift kites in larger scale AWES (even kite turbines), they need to exploit the V^2 Velocity Squared relationship with apparent wind and line tension to operate effectively in low winds.

8 Conclusion

Our seemingly reasonable plan to test automation at 10kW was thwarted by an unexpected deficiency of line tension in larger scale lift kites in low winds. This blind spot came from a lack of published data on static lift kite line tension and our experience using an exceptionally efficient lifter. Windswept intend to address this deficiency by openly publishing further test data on lift kite performances.

The tension scaling observed suggests that very large and expensive static lift kites would be needed, if we were to keep using static lift kites for kite turbine lifting as we scale. These kites can be problematic but not impossible to handle in high winds. This method would increase operational risk which suggests a long development path at best.

Much of that work has been achieved in other Airborne wind energy companies. Reports of tension data from AWES companies deploying active kites suggests their systems could easily support kite turbines with higher generating outputs than they currently attain from pumping cycle operation.

Windswept are as committed as ever to our core purpose of Increasing access to clean, low-cost, airborne wind energy - We did not see a match with that purpose in the 10kW automated design with using static lift kites.

Windswept are now searching for more marketable alternatives to the 10kW static lift kite designs. Windswept strategy was to get an MVP to market as quickly as possible to build investment and maintain independent financial sustainability. We expected our MVP to be capable of a carbon cost of energy at 0.7gCO2e/kWh but the low wind performance would have significantly lowered yields. Our decision to alter course made our development costs more challenging to maintain. The difficult decision was made to reduce staffing at Windswept and focus on small parts and components testing while we try and regroup efforts on more capable kite turbine systems.

It should be noted that:

Windswept engineers on this project were all just the best in the world.

Our scaling calculations included assumptions and interdependent multi variable optimisations; Significant testing is still required to validate these calculations.

Many AWES design variations are still to be tested.

Lifting larger rotors and stacks of rotors is still feasible.