WINDHAWK SOLUTIONS

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1.0 Executive Summary

The University of Massachusetts Lowell's 2016 Collegiate Wind Competition team, *WindHawk Solutions*, has been collaborating with the U.S. Army, Natick Soldier Systems Center - Natick Soldier Research, Development and Engineering Center (NSSC-NSRDEC) and U.S. Army Belvoir Soldier Research, Development and Engineering Center (BSRDEC) to develop a wind energy system that supplements the use of diesel generators in austere environments. The U.S. Army consumed over 1.2 billion gallons of diesel fuel in 2011 of which 65% was used for electricity generation.

In order to supply the U.S. Army with renewable power, the system must be durable, deployable, and reliable. Our solution consists of a 6 kW Crosswind Aerial Wind System (C-AWS) and a 400 W truss tower-mounted wind turbine. The C-AWS is a kite system consisting of two small (45 cm diameter) turbines mounted on a hard-wing kite. The ground-based system is a 3 m diameter horizontal axis wind turbine (HAWT) mounted on a unique, 5-m tall truss tower.

The primary goal of these products is to provide a cost-effective, easy to use, reliable solution to capture and locally integrate available wind energy resources into the Army's off-grid power. A standard 3 kW generator weighs 375 lb. and requires six people to lift and move; subsequent usage requires soldier time to refuel the generator. The *WindHawk Solutions* are designed to run with minimal supervision and weigh less than 80 lbs., therefore requiring only two soldiers for deployment. The proposed solution will also (1) reduce diesel fuel expenditures and (2) increase personnel safety for the U.S. Army. Fuel convoys are high value targets for enemies, and as such fuel delivery represents a risk to personnel safety. The fully burdened cost (FBC) of fuel includes handling and transportation and can range from $15 to greater than $40 per gallon.

The C-AWS system is designed specifically for forward operating bases (FOBs) with two 45 cm diameter turbines, producing a total of 500 W of power in wind speeds of 3 m/s and 6 kW at wind speeds of 6 m/s. The ground system is designed for larger force provider bases with a 3.0 m rotor diameter, producing 128 W at a cut-in speed of 4 m/s and 400 W at a rated wind speed of 6 m/s. Both the C-AWS and ground turbine are equipped with blade pitching systems to achieve optimal power output and turbine load control. The blade pitching system is also used to control kite yaw during crosswind flight.

According to U.S. Army sources, the C-AWS system has the potential to replace 570 x 2 kW generators, 2,000 x 3 kW generators, and 1,000 x 5 kW generators for a total of 12.14 MW of power. The ground turbine will function as small networks of ten turbines each to provide power to 150 person Force Provider (FP) bases. During the Iraq and Afghanistan wars, approximately 125,000 soldiers were deployed. Using a ratio of one turbine per 20 soldiers creates a market for 6,250 ground turbines. *WindHawk Solutions* anticipates an initial $50 million market in order to pursue this opportunity to offset significant diesel costs, reduce pollution, and minimize risks to soldiers.

A wind tunnel prototype proof of concept has been developed for the mechanical and electrical design. Prototyping and testing has been divided into the following subsystem tasks:

1. Blade design and prototype fabrication using composite and 3D-printed materials
2. Hub design, prototyping and pitch control mechanisms
3. Generator selection, preliminary control electronics design and preliminary turbine testing

A MATLAB implementation of Blade Element Momentum Theory (BEMT) was used to design and optimize prototype blades. Multiple generators were researched and tested, with the Tiger-U8 100 KV motor selected for the wind tunnel prototype.

2.0 Introduction

WindHawk Solutions is a for-profit startup based in Lowell, Massachusetts that designs, engineers, and manufactures wind turbines to efficiently provide renewable energy for use in austere environments around the world. Extreme weather, remote locations, and rugged terrain characterize the austere environments targeted by *WindHawk Solutions*. These locations are primarily powered by diesel generators, which are reliable, yet loud, heavy, and inefficient. To date, unique market requirements have prevented existing renewable energy solutions from entering the market and competing against diesel generators: solar is too heavy, fragile, and inconsistent; bio-mass still requires expensive, dangerous, and wasteful transportation; and existing wind turbines lack mobility, efficiency, and require large diameter blades to produce even small amounts of power. The fundamental needs of reliability, durability, and consistent and efficient power production must be considered for any renewable energy design that intends to be a viable option for the austere environment market.

The *WindHawk Solutions* team has developed a unique and innovative solution designed to meet these unique market needs through extensive market research, interviews with end-users, and a relationship with the U.S. Army Natick Labs. The team has identified a number of potential customers within the market, yet the team's initial focus has been on renewable energy applications for the military, specifically U.S. Army Forward Operating Base's (FOB) and Force Provider base camps. The rationale for the U.S. Army as a customer is four-fold: an existing relationship with Natick Labs provided valuable and detailed market information and requirements; a design to military standards is rigorous and increases brand equity with future markets; a large potential market with energy needs in austere environments; and strong customer-oriented financial, environmental, and human benefits with the potential to save millions of taxpayer dollars, reduce fossil fuel-related emissions, and to improve and save the lives of soldiers.

Extensive and continued communication with U.S. Army Natick Labs has enabled *WindHawk Solutions* to outline critical system requirements and specifications. The main objective is to develop wind energy deployments specifically designed for FOB and Force Provider base camps. Small diesel-powered gensets are the power backbone of FOB's and Force Provider camps (FP). Each FOB uses a patchwork of 2 kW, 3 kW, and 5 kW gensets for a total of approximately 20 kW. Each Force Provider camp utilizes six 60 kW diesel generators tied into a micro-grid. The micro-grid system is designed to have one generator running at all times, with successive generators on standby. As power demand reaches 80% of the first generator's capacity, a second generator will kick in, and will cut out only once the demand for the first generator drops to below 60%. A renewable energy solution could dramatically reduce fuel consumption on these bases by decreasing the need for a second generator to come on, as well as reducing fuel consumption for gensets already generating electricity. Any renewable energy solution must be durable, reliable, and easy to transport and deploy.

WindHawk's solution to these customer requirements is two-fold: a crosswind aerial wind system (C-AWS) – named the *WindHawk* C-AWS – to produce up to 6 kW for FOB's, and a truss-tower-based turbine capable of up to 400 W for Force Provider base camps. The design comprises a minimal number of components, and meets Army requirements for deployment by soldiers. The aerial C-AWS design solves the performance limitations associated with small wind turbines by accessing the stronger, more consistent winds at higher altitudes to substantially increase the energy production relative to the same turbine on a lower elevation tower. The aerial C-AWS system is thus capable of replacing 100% of the production output supplied by a 3 kW diesel genset in FOB's. The larger 3 m diameter, truss-tower-mounted wind turbine will be deployed as part of the FP system. The turbines will be placed around the camp perimeter, with each turbine providing up to 400 W to the camp micro-grid. The value of the tower-based turbines lies in their ability to extend the 80% usage capacity of the existing 60 kW generators used in these systems and to throttle fuel usage for operating generators even when not near the 80% capacity usage mark, thereby reducing excess diesel usage.

A reduction in fuel consumption rates will provide extensive benefits to the Army, most notably a dramatic reduction in direct fuel costs. Each diesel genset consumes between $18,000 – 26,000 of fuel per kW of rated capacity over its 25,000-hour lifespan; when this figure is multiplied by the Army's inventory of 45,000 diesel generators of >5 kW, there is substantial potential for large-scale savings. Moreover, the added costs of storing, transporting, and protecting fuel – termed the *fully burdened cost* – increases the fuel consumption costs on a per unit basis to a range of $315,000 – 450,000 per kW of rated capacity over a 25,000 hour lifespan. The Army will also benefit from extended mission length potential, reduced air and noise pollution, and increased operational effectiveness.

Even a small amount of renewable energy can strongly impact the morale and safety of the soldiers deployed in some of the most dangerous places on earth. During our business research, we discovered an article[i] from a former FOB Executive Officer, CPT. Chris O'Brian, detailing the real world challenges of building and operating an FOB in Afghanistan. *WindHawk Solutions* valued CPT. O'Brian's experience and reached out to him to secure an interview. Now a business strategy consultant in the U.K., Mr. O'Brian described the dramatic accounts of soldiers who had suffered gunshot wounds, lost limbs, and in some cases their lives, while transporting fuel to his camps. This sobering reality of energy production in austere environments greatly impacted our team's mission to impact not only the environment through reduced carbon dioxide emissions, but also to minimize energy-related risk to deployed soldiers.

2.1 Mission

The *WindHawk Solutions* company mission is the following:

"*WindHawk Solutions* aims to develop and produce innovative distributed wind turbine solutions that challenge the generally accepted limitations of wind via supplementing the power production of traditional diesel generators in austere environments."

2.2 Vision

The *WindHawk Solutions* company vision is the following:

"*WindHawk Solutions* aims to provide wind energy solutions that increase prosperity through economically viable renewable energy generation, enhance human health and safety, and sustainably protects the global environment."

3.0 Business Overview

3.1 Market Requirements

The market requirements have been carefully identified through a comprehensive evaluation of customer needs, strategic actions, and market analysis. The four market requirement topics relate to:

- **Performance**: In most cases, austere environments are completely cut off from utility infrastructures and are required to produce 100% of their own power. In order to efficiently augment diesel generators, a renewable energy system must consistently generate between 2-6 kW of rated power. For the military, as the first market targeted by WindHawk Solution, this power translates to 10-30% of total demand for a FOB and 4-13% for larger Force Provider base camps.
- **Reliability.** Austere environments are characterized by extreme temperatures, volatile weather, and rugged terrain. Each system requires a minimum downtime. Our customers are used to diesel generators that perform well in austere environments, and the customer will expect the same level of reliability from *WindHawk Solutions* products.

- **Ease of Use:** *WindHawk Solutions* features a C-AWS system and a traditional ground based turbine. Both systems deploy within 30 minutes and require minimal training. The *WindHawk Solution* must meet the same reliability standards of diesel generators in order to be competitive in this market.
- **Ease of Transport.** Each unit must ship as a self-contained unit and cannot exceed 80 lbs. The entire system conforms to dimensions of standard military Tricon® shipping containers. The ground turbine system has a steel truss tower. The structure of the C-AWS is comprised of airbeam technology which allows the system to be shipped at a mere three percent of deployed volume.

These market requirements were identified through meetings with the following industry experts:

- **Mr. Robert Nutter,** Designer and Integrator of Power Solutions, Project Manager-Expeditionary Energy & Sustainment Systems.
- **Mr. David Roy,** Project Director at Department of the Army, Product Directorate - Contingency Base Infrastructure.
- **Ms. Laura Biszko,** Engineer, U.S. Army Natick Soldier Research, Development & Engineering Center.
- **Mr. Fred Geurts**, Technical Director, Federal Fabrics and Fibers

3.2 Strategy

The long-term business strategy is to gain access to secondary markets (see section 5.2) within the larger austere environment market by meeting and exceeding the expectations and requirements of the U.S. Army, thus establishing *WindHawk Solutions* products as a "military grade". The C-AWS has the potential to have the biggest impact on secondary markets, and as such it is considered the core product for *WindHawk Solutions*. The ground-based system was added for a number of reasons:

- Added sales/increased production help achieve economies of scale faster and potential for higher production volume can help achieve manufacturing efficiency faster
- Turbine technology from kite is easily modified for use on ground
- Reduce the business risk associated with relying on the highly specialized C-AWS for as the only source of revenue

3.3 Execution Plan

In order to reach full-scale production, several goals and objectives must be met to secure a sustainable competitive advantage.

- Produce working prototype
- Obtain funding
- Reach production stage
- Increase efficiency
- Enter secondary markets

The C-AWS will reach prototype stage in one year. *WindHawk Solutions* will apply for a D.O.D. Technical Readiness Assessment (TRA) for preliminary testing and development funding. A minimum Technical Readiness Level (TRL) of six is required to obtain D.O.D. funding and assistance. TRL six requires that a representative model or prototype system is tested in a relevant environment. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment[ii].

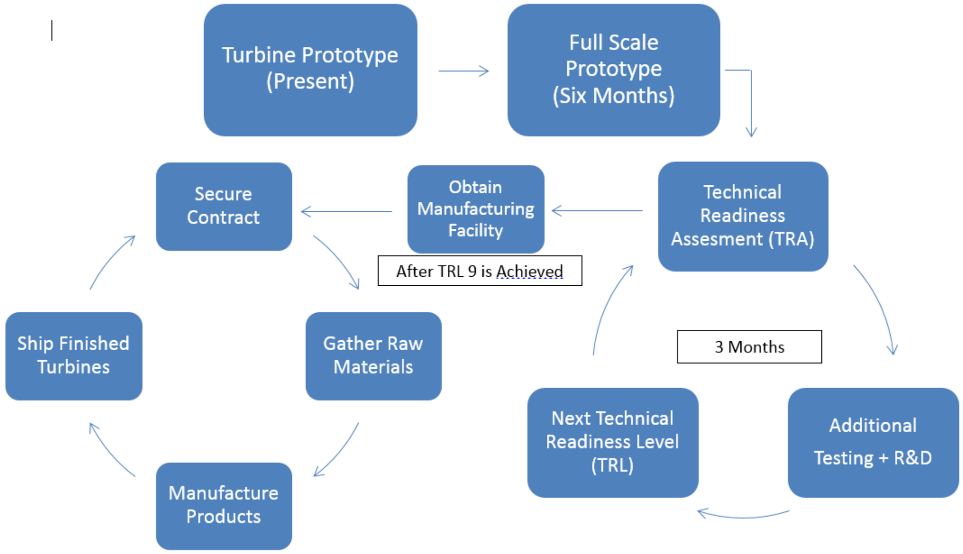


Figure B-3.1 - Execution Plan

Production stage will be reached through a cycle of development and TRA until a TRL 9 is reached. TRL 9 requires application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E).[iii] The execution plan (Figure B-3.1) illustrates the business development process and the steps needed

4.0 Products

WindHawk Solutions offers two wind turbine systems, the C-AWS and a network of ground based turbines. The C-AWS will be sourced to austere locations to reduce the fuel consumption of diesel generators, while the ground based system will be used to supplement the load of larger generators in a microgrid that will minimize the number of times another generator will be needed when the running generators reach the threshold power usage.

4.1 C-AWS

The 6 kW, Crosswind Aerial Wind System (C-AWS) (Figure B-4.1) is an inflatable, kite based system that uses two, kite mounted turbines to produce power. The C-AWS exploits higher altitude winds and faster relative velocities to substantially increase the wind power generation capacity. The kite is controlled autonomously and the power is transferred to the ground via a 500 m tether that will connect into a diesel generator and offset fuel usage.

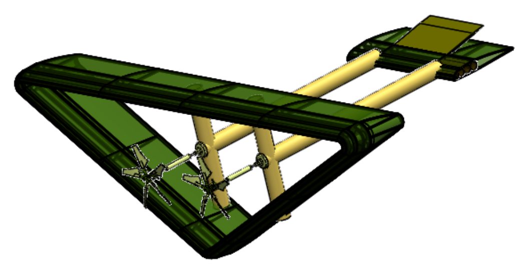


Figure B-4.1 - Engineering Model of C-AWS

This system will be put in place as a redundancy system to extend the use of diesel generators used on forward operating bases and other austere environments. The C-AWS will be packaged in two Pelican® cases and transported by Tricon® containers. The C-AWS system will only require two personnel with limited technical knowledge to set up in a time span of 30 minutes.

4.2 Ground Based Turbine System

The 400 W ground based turbine (Figure B-4.2) will be set up in series of 10, with the goal of offsetting peak power usage in a micro-grid. The system is intended to be used at larger encampments such as force provider camps or other large establishments with pre-existing infrastructure. The ground turbines will be placed 60 m apart around the perimeter of the camp to avoid interference with internal operations and other turbines, while also being accessible. The system will boost the capacity of 60 kW gensets from 48 kW (80%) to 52 kW, effectively increasing the rated capacity to 86.7%. The system of turbines is shipped using military standard Tricon® shipping containers, which will include the blades and tower assembly separately. These larger systems will require more time to set up as well as a more experienced technical staff.

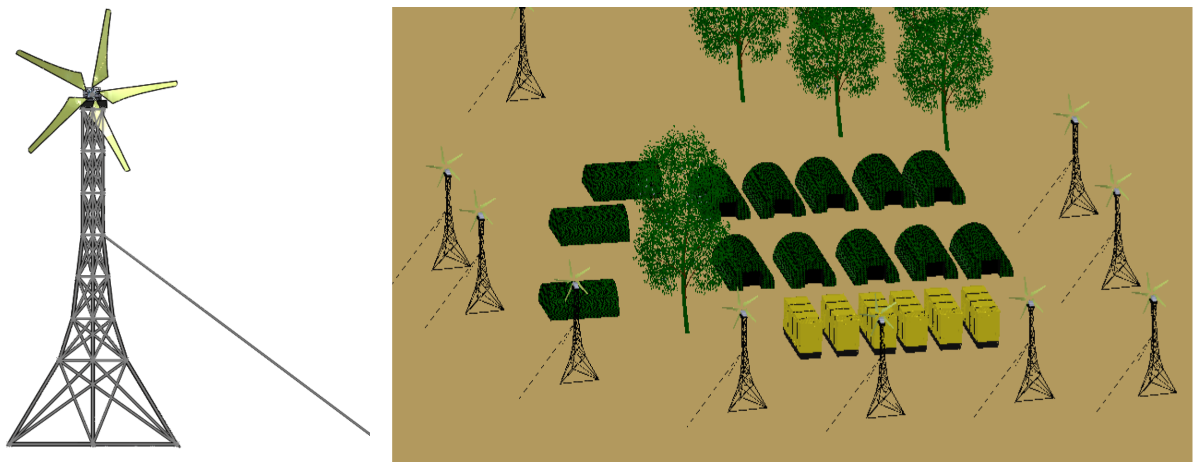


Figure B-4.2 – (left) Ground Turbine System and (left) Deployment in a Force Provider Camp

5.0 Market Opportunity

5.1 Primary/Preliminary Market.

The need for an affordable renewable energy option for austere environments is evident given the astronomically high FBC, the overreliance on diesel generators, and global shift towards cleaner energy. Both of *WindHawk Solutions'* products will be priced using a value-based pricing model, meaning the cost of the unit will be justified by the benefits it provides. The $25,000 C-AWS and $12,000 ground based turbine are priced according to the value added to the military. The "value" created by the *WindHawk Solutions* products was determined using the following factors relevant to the U.S. Army.

- **Reduced Fuel Costs:** The Army's true fuel cost includes the base cost of the fuel (e.g., pump price of $2.50 per gallon), the availability of the fuel (urban vs. rural deployment), as well as all related handling and transportation costs. The aggregate of these costs is termed the *fully burdened cost (FBC)* of fuel. The fully burdened cost of diesel is highly dependent on the final destination of the fuel and can range between $15 for traditional convoy transport to $40 or more if aerial delivery is required (GAO 2012). In extreme cases, the per gallon FBC can skyrocket to $400[iv].
    - **C-AWS:** Potential to supplement 30% of total power needs on small FOB or other austere environments, equating to 14.8 gallons of diesel during a 24 hour period, or between $220-$600.
    - **Ground Turbine**: A network of ten 400 W turbines on a single Force Provider camp increases the capacity of a 60 kW generator from 48 kW (80% of rated power) to 52 kW before a successive generator is needed. The turbines would only have to delay the need for a second generator by less than one hour for Army to recoup the $200,000 expense in three years.

- **Reduced Risks to Soldiers:** Each diesel fuel delivery to a forward operating base requires U.S. army personnel to traverse contested terrain and puts those personnel at increased risk of injury or death. *WindHawk Solutions* systems will reduce diesel fuel consumption on bases, thereby directly reducing the number of fuel delivery missions required. This safety and security is not measurable in dollars alone, but must be considered; figures estimate the value of a single human life at $6-9.1 million[v].
- **Increased Operational Effectiveness:** Operational effectiveness is broadly defined as the "analysis, selection, and development of institutional concepts or doctrines for employing major forces to achieve strategic objectives within a theater of war" (Millett *et al*., 1986). Operational effectiveness is directly correlated to the army's agility and autonomy. The C-AWS provides a 6 kW boost to total available power with no increase in fuel consumption.
- **Reduced Pollution:** The primary environmental benefits provided by *WindHawk Solutions* system will be reduced noise pollution and reduced carbon emissions. Diesel generators are extremely loud; therefore a reduction in usage will reduce unwanted noise on FOB's and Force Provider base camps. The improved local air quality and reduced global carbon emissions will reduce the health and environmental burden of military operations.

5.2 Secondary Markets

The primary market guides the possible secondary market opportunities. The need for durable, and consistent power to global austere environments across various industries holds. The *Windhawk Solution* addresses these needs to other industries that consume comparable amounts of diesel fuel. Secondary markets with an ideal need for augmentation of diesel generators include (i) agriculture along with the Department of Agriculture (DOA) and (ii) telecommunication towers. These main markets use the ground system of the *Windhawk Solution* to harness rated power to prevent the consumption of diesel fuel.

After preliminary research, the DOA has 3.7 million acres of organic farmland[vi] in which *Windhawk Solutions* can place one ground turbine system for every ten acres of land, thus giving an estimated market value of 370,000 ground turbines. Additionally, the wireless telecommunication industry has 298,055 cellular towers online as of 2015.[vii] A market penetration of 20% allows for 59,611 ground turbines to be erected adjacent to a telecommunication tower.

5.3 Potential Market Size

Data from NSSC-NSRDEC suggests the Army is looking to replace a number of small power diesel gensets with renewable power. While the WindHawk systems will not be replacing diesel gensets on a per unit basis, they will reduce the need for extra gensets on each base. The estimation from NSSC-NSRDEC represents the potential first year sales. Future year sales are addressed in Table B-5.1. Success in the preliminary market could lead to more widespread military use as well as expansion into secondary markets. To provide sustainable power to Force Provider camps, the total number of troops deployed to Iraq and Afghanistan from 2001-2009 was 125,000 troops. This was based on 1.5 million troop-years[viii]. If one ground turbine was installed for every 20 troops, 6,250 turbines would be necessary to augment diesel fuel consumption. Table B-5.1 displays the potential market penetration based on interviews with contacts from NSSC-NSRDEC.

Table B-5.1 - Potential Market

Year	Preliminary Demand	Total kW Demand	C-AWS Unit Equivalent	Potential Revenue
1-4	3,570 <5 kW gensets	12,140 kW	~ 2,000	$50 million
Total Market	**Total Army Inventory**	**Total Power**	**Full C-AWS implementation** (1 system/20 kW)	**Potential Revenue**
5+	45,000 <5 kW gensets	90,000 - 225,000 kW	4,500 – 11,250 units	$112 -280 million

5.4 Competitive Advantage

The C-AWS is unique in the way that it can be considered a viable power option in areas where renewables have not been integrated yet because of reliability and efficiency issues. Below is a table comparing the most popular renewable energy options and diesel to the C-AWS in terms of the aforementioned market requirements for the industry and our initial customer.

Table B-5.2 highlights the unique combination of features that makes the C-AWS a compelling option within the market. Most notable is the fact that the C-AWS is the only system engineered to be rated for 6 kW of power while still remaining lightweight and compact.

Table B-5.2 - Industry Comparison for Energy Production

Market Needs	Solar	Diesel	Biodiesel	Wind	C-AWS
Performance (2-6 kW)	√ 400 sq. ft. for 5 kW	√ 0.35-0.5 gal/hr for 5 kW	√ Comparable energy density to diesel	√ 46 ft diameter blades	√ 6 kW rated output
Ease of Transport. (<80 lbs.)	X Requires large heavy panels	X 3 kW gensets is 375 lbs.	X 375 lb diesel genset	X Tower, 46 ft diameter blades	√ Ships in two 80 lb. Pelican containers
Reliable (25,000 hour)	X Fragile construction	√ 25,000 hour lifespan	—	√	√ 25,000 hour lifespan
Environmental (Renewable, quiet)	√	X	√ Renewable, pollutants	√ Loud	√ Quiet

6.0 Management and Design Team

The company leadership is divided into three teams, product research, design, and development; business development; and strategic advisors. The roles and responsibilities of the team members are listed below.

6.1 Product Research, Design, and Development

- **Linda Pratto, Mechanical Engineering Team Lead**
  - Responsible for turbine blade and aircraft design

- **Dana Pierce, Mechanical Engineering Team**
  - Lead engineer on pitching mechanism, overseer of preliminary wind tunnel testing
- **Christopher Illsley, Mechanical Engineering Team**
  - Responsible for turbine blade and aircraft design
- **William Hallissey, Electrical Engineering Team Lead**
  - Manager of electrical engineering operations, designed codes for WindHawk safety and operational protocols
- **Maxwell McCabe, Plastics Engineering Team Lead**
  - Manager of the plastics and prototyping division

6.2 Business Development

- **Christian Bain, Business Team Lead –** Responsible for leading the business team in preliminary market analysis, the drafting of the business plan, and coordination with engineering teams in order to maintaining a cohesive vision.
- **Noah Meunier, Business Team/Technical Liaison –** Responsible for communications and coordination of cross-functional teams, and compilation of the business plan and market analysis.
- **Sarah Sirois, Business Team and Graphic Artist**
  Responsible for team branding, concept art, and marketing materials.

6.3 Strategic Advisors

- **Michael Darish, Electrical Engineering Advisor –** Primary electrical engineering advisor.
- **Stephen Johnston, Plastics Engineering Advisor –** Primary plastics engineering team advisor.
- **Christopher Hansen, Composites Manufacturing Advisor –** Project overview advisor, providing objective insight to all engineering and business obstacles.
- **Thomas O'Donnell, Business Advisor –** Primary advisor to the business team.
- **David Willis, Mechanical Engineering Advisor –** Primary mechanical engineering team advisor.

7.0 Financial Analysis

The first year of operation will be devoted to development and funding to reach a production stage in year two. The funding for the prototype and development of the C-AWS is discussed in section 2.3. Once the manufacturing stage is reached, projected sales represent four years of production at full capacity. A $300,000 rent expense represents the majority of the capital requirements needed for production, with another $200,000 needed for equipment.

Projected sales for the first year are $46 million, remaining constant over subsequent years due to production limitations. The potential for expansion is acknowledged but was not included in projections.

The Revenue model for *WindHawk Solutions* is consists of direct sales on a per unit basis, with sale prices of $12,000 for the ground turbine and $25,000 for the C-AWS. After sales product service and consulting services will serve as secondary revenue streams.

Detailed financial analyses can be found in section 8, appendix A1-A9.

8.0 Appendix

A-1, Team UML-WindHawk (from left to right): D. Willis, T. O'Donnell, P. Anderson, E. Copeland, C. Hansen, S.Johnston, M. Darish, N. Patel, S. Dabney, A. Lay, M. Siopes, M. McCabe, L. Pratto, W. Hallissey, Z. Anderson, M. Barre, S. San, C. Bain, K. Stuart, N. Meunier, D. Pierce, C. Illsley.

A-2: 1st Year Sales Forecast

Product Lines	Units	Sales Price Per Unit	COGS Per Unit	Margin Per Unit
C-AWS	400	$ 25,000.00	$ 13,158.00	$ 11,842.00
Tower Turbine	2510	$ 12,000.00	$ 4,142.00	$ 7,858.00

Product Line	January	February	March	April	May	June	July	August	September	October	November	December	Annual Totals	Category Breakdown	Category Total
C-AWS															
400 Sold	40	40	40	40	40	40	40	40	40	40	40	40	480		14.3%
Total Sales	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	$12,000,000	100.0%	25.8%
Total COGS	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	$ 6,315,840	52.6%	34.6%
Total Margin	473,680	473,680	473,680	473,680	473,680	473,680	473,680	473,680	473,680	473,680	473,680	473,680	$ 5,684,160	47.4%	20.1%
Product Line	January	February	March	April	May	June	July	August	September	October	November	December	Annual Totals	Category Breakdown	Category Total
Tower Turbine															
2510 Sold	240	240	240	240	240	240	240	240	240	240	240	240	2,880		85.7%
Total Sales	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	$34,560,000	100.0%	74.2%
Total COGS	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	$11,928,960	34.5%	65.4%
Margin	1,885,920	1,885,920	1,885,920	1,885,920	1,885,920	1,885,920	1,885,920	1,885,920	1,885,920	1,885,920	1,885,920	1,885,920	$22,631,040	65.5%	79.9%
Total Units Sold	280	280	280	280	280	280	280	280	280	280	280	280	3,360		
Total Sales	$3,880,000	$ 3,880,000	$ 3,880,000	$ 3,880,000	$3,880,000	$3,880,000	$3,880,000	$3,880,000	$3,880,000	$3,880,000	$3,880,000	$3,880,000	$46,560,000		
Total Cost of Goods Sold	$1,520,400	$ 1,520,400	$ 1,520,400	$ 1,520,400	$1,520,400	$1,520,400	$1,520,400	$1,520,400	$1,520,400	$1,520,400	$1,520,400	$1,520,400	$18,244,800		
Total Margin	$2,359,600	$ 2,359,600	$ 2,359,600	$ 2,359,600	$2,359,600	$2,359,600	$2,359,600	$2,359,600	$2,359,600	$2,359,600	$2,359,600	$2,359,600	$28,315,200		

A-3: Years 1-3 Sales Forecast

Product Lines	Year 1 Totals	Year 2 Totals	Year 3 Totals
Product Lines			
400 Sold	**480**	**480**	**480**
Total Sales	**$12,000,000**	**$ 12,000,000**	**$ 12,000,000**
Total COGS	**$ -**	**$ 6,315,840**	**$ 6,315,840**
Total Margin	**$ -**	**$ 5,684,160**	**$ 5,684,160**
Sold	**2880**	**2,880**	**2,880**
Total Sales	**$34,560,000**	**$ 34,560,000**	**$ 34,560,000**
Total COGS	**$ -**	**$ 11,928,960**	**$ 11,928,960**
Margin	**$ 480**	**$ 22,631,040**	**$ 22,631,040**
Total Units Sold	**3360**	**3,360**	**3,360**
Total Sales	**$46,560,000**	**$ 46,560,000**	**$ 46,560,000**
Total Cost of Goods Sold	**$18,244,800**	**$ 18,244,800**	**$ 18,244,800**
Total Margin	**$28,315,200**	**$ 28,315,200**	**$ 28,315,200**

A-4: 1st Year Cash Flow

	January	February	March	April	May	June	July	August	September	October	November	December	Totals
Beginning Balance	$ -	$1,101,540	$1,846,679	$2,766,217	$5,063,357	$7,360,497	$ 8,280,017	$10,577,157	$12,874,296	$13,793,799	$16,090,939	$18,388,079	
Cash Inflows													
Cash Sales	1,164,000	1,164,000	1,164,000	1,164,000	1,164,000	1,164,000	1,164,000	1,164,000	1,164,000	1,164,000	1,164,000	1,164,000	$13,968,000
Accounts Receivable	-	1,164,000	2,716,000	2,716,000	2,716,000	2,716,000	2,716,000	2,716,000	2,716,000	2,716,000	2,716,000	2,716,000	$28,324,000
Total Cash Inflows	$1,164,000	$2,328,000	$3,880,000	$3,880,000	$3,880,000	$3,880,000	$ 3,880,000	$ 3,880,000	$ 3,880,000	$ 3,880,000	$ 3,880,000	$ 3,880,000	$42,292,000
Cash Outflows													
Investing Activities													
New Fixed Asset Purchases	-	-	-	-	-	-	-	-	-	-	-	-	$ -
Additional Inventory													$ -
Cost of Goods Sold	-	1,520,400	1,520,400	1,520,400	1,520,400	1,520,400	1,520,400	1,520,400	1,520,400	1,520,400	1,520,400	1,520,400	$16,724,400
Operating Activities													
Operating Expenses	4,583	4,583	4,583	4,583	4,583	4,583	4,583	4,583	4,583	4,583	4,583	4,583	$ 54,996
Payroll	55,489	55,489	55,489	55,489	55,489	55,489	55,489	55,489	55,489	55,489	55,489	55,489	$ 665,863
Taxes	-	-	1,377,601	-	-	1,377,619	-	-	1,377,637	-	-	1,377,655	$ 5,510,511
Financing Activities													
Loan Payments	2,389	2,389	2,389	2,389	2,389	2,389	2,389	2,389	2,389	2,389	2,389	2,389	$ 28,666
Owners Distribution													$ -
Line of Credit Interest		-	-	-	-	-	-	-	-	-	-	-	$ -
Line of Credit Repayments													$ -
Dividends Paid													$ -
Total Cash Outflows	$ 62,460	$1,582,860	$2,960,462	$1,582,860	$1,582,860	$2,960,479	$ 1,582,860	$ 1,582,860	$ 2,960,497	$ 1,582,860	$ 1,582,860	$ 2,960,515	$22,984,437
Net Cash Flows	$1,101,540	$ 745,140	$ 919,538	$2,297,140	$2,297,140	$ 919,521	$ 2,297,140	$ 2,297,140	$ 919,503	$ 2,297,140	$ 2,297,140	$ 919,485	$19,307,563
Operating Cash Balance	$1,101,540	$1,846,679	$2,766,217	$5,063,357	$7,360,497	$8,280,017	$10,577,157	$12,874,296	$13,793,799	$16,090,939	$18,388,079	$19,307,563	
Line of Credit Drawdown	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ending Cash Balance	$1,101,540	$1,846,679	$2,766,217	$5,063,357	$7,360,497	$8,280,017	$10,577,157	$12,874,296	$13,793,799	$16,090,939	$18,388,079	$19,307,563	

A-5: Years 1-3 Cash Flow

	Year 1 Totals	Year 2 Totals	Year 3 Totals
Beginning Balance			
Cash Inflows			
Cash Sales	**$ 13,968,000**	**$ 13,968,000**	**$ 13,968,000**
Accounts Receivable	**$ 28,324,000**	**$ 32,592,000**	**$ 32,592,000**
Total Cash Inflows	**$ 42,292,000**	**$ 46,560,000**	**$ 46,560,000**
Cash Outflows			
Investing Activities			
New Fixed Asset Purchases	**$ -**	**$ -**	**$ -**
Additional Inventory	**$ -**	**$ -**	**$ -**
Cost of Goods Sold	**$ 16,724,400**	**$ 18,244,800**	**$ 18,244,800**
Operating Activities			
Operating Expenses	**$ 54,996**	**$ 57,146**	**$ 59,385**
Payroll	**$ 665,863**	**$ 716,466**	**$ 800,997**
Taxes	**$ 5,510,511**		**$ 5,483,233**
Financing Activities			
Loan Payments	**$ 28,666**	**$ 28,666**	**$ 28,666**
Owners Distribution	**$ -**	**$ -**	**$ -**
Line of Credit Interest	**$ -**	**$ -**	**$ -**
Line of Credit Repayments	**$ -**	**$ -**	**$ -**
Dividends Paid	**$ -**	**$ -**	**$ -**
Total Cash Outflows	**$ 22,984,437**	**$ 19,047,078**	**$ 24,617,082**
Net Cash Flows	**$ 19,307,563**	**$ 27,512,922**	**$ 21,942,918**
Operating Cash Balance			
Line of Credit Drawdown	**$ -**	**$ -**	**$ -**

A-6: 1st Year Income Statement

	January	February	March	April	May	June	July	August	September	October	November	December	Annual Totals
Revenue													
C-AWS	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	**$ 12,000,000**
Tower Turbine	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	2,880,000	**$ 34,560,000**
Total Revenue	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 3,880,000**	**$ 46,560,000**
Cost of Goods Sold													
C-AWS	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	526,320	**$ 6,315,840**
Tower Turbine	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	994,080	**$ 11,928,960**
Total Cost of Goods Sold	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 1,520,400**	**$ 18,244,800**
Gross Margin	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 2,359,600**	**$ 28,315,200**
Payroll	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 55,489**	**$ 665,863**
Operating Expenses													
Repairs and Maintenance	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	**$ 24,996**
Utilities	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	**$ 30,000**
Total Operating Expenses	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 4,583**	**$ 54,996**
Income (Before Other Expenses)	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 2,299,528**	**$ 27,594,341**
Other Expenses													
Amortized Start-up Expenses	694	694	694	694	694	694	694	694	694	694	694	694	**$ 8,333**
Depreciation	2,422	2,422	2,422	2,422	2,422	2,422	2,422	2,422	2,422	2,422	2,422	2,422	**$ 29,068**
Interest													
Commercial Loan	1,114	1,104	1,094	1,085	1,075	1,065	1,055	1,045	1,035	1,025	1,015	1,004	**$ 12,716**
Bad Debt Expense	-	-	-	-	-	-	-	-	-	-	-	-	**$ -**
Total Other Expenses	4,230	4,221	4,211	4,201	4,192	4,182	4,172	4,162	4,152	4,142	4,131	4,121	**$ 50,117**
Net Income Before Income Tax	**$ 2,295,298**	**$ 2,295,308**	**$ 2,295,317**	**$ 2,295,327**	**$ 2,295,337**	**$ 2,295,347**	**$ 2,295,357**	**$ 2,295,367**	**$ 2,295,377**	**$ 2,295,387**	**$ 2,295,397**	**$ 2,295,407**	**$ 27,544,224**
Income Tax	$ 459,198	$ 459,200	$ 459,202	$ 459,204	$ 459,206	$ 459,208	$ 459,210	$ 459,212	$ 459,214	$ 459,216	$ 459,218	$ 459,220	**$ 5,510,511**
Net Profit/Loss	**$ 1,836,100**	**$ 1,836,107**	**$ 1,836,115**	**$ 1,836,123**	**$ 1,836,130**	**$ 1,836,138**	**$ 1,836,146**	**$ 1,836,154**	**$ 1,836,162**	**$ 1,836,171**	**$ 1,836,179**	**$ 1,836,187**	**$ 22,033,712**

A-7: Years 1-3 Income Statement

Revenue	2017		2018		2019	
C-AWS	12,000,000		12,000,000		12,000,000	
Tower Turbine	34,560,000		34,560,000		34,560,000	
Total Revenue	**$ 46,560,000**	**100%**	**$ 46,560,000**	**100%**	**$ 46,560,000**	**100%**
Cost of Goods Sold						
C-AWS	6,315,840		6,315,840		6,315,840	
Tower Turbine	11,928,960		11,928,960		11,928,960	
Total Cost of Goods Sold	**18,244,800**	**39%**	**18,244,800**	**39%**	**18,244,800**	**39%**
Gross Margin	28,315,200	**61%**	28,315,200	**61%**	28,315,200	**61%**
Payroll	665,863		716,466		800,997	
Operating Expenses						
Repairs and Maintenance	24,996		26,246		27,558	
Utilities	30,000		30,900		31,827	
Total Operating Expenses	**$ 54,996**	**0%**	**$ 57,146**	**0%**	**$ 59,385**	**0%**
Income (Before Other Expenses)	**$ 27,594,341**	**59%**	**$ 27,541,589**	**59%**	**$ 27,454,818**	**59%**
Other Expenses						
Amortized Start-up Expenses	8,333		8,333		8,333	
Depreciation	29,068		29,068		29,068	
Commercial Loan	12,716		11,219		9,583	
Total Other Expenses	**$ 50,117**	**0%**	**$ 48,621**	**0%**	**$ 46,984**	**0%**
Net Income Before Income Tax	**$ 27,544,224**		**$ 27,492,968**		**$ 27,407,833**	
Income Tax	$ 5,510,511		$ 5,500,260		$ 5,483,233	
Net Income/Loss	**$ 22,033,712**	**47%**	**$ 21,992,707**	**47%**	**$ 21,924,600**	**47%**

A-8: Balance Sheet

ASSETS	2017	2018	2019
Current Assets			
Cash	19,307,563	41,320,225	63,263,143
Accounts Receivable	4,268,000	4,268,000	4,268,000
Inventory	-	-	-
Prepaid Expenses	16,667	8,333	-
Other Initial Costs	-	-	-
Total Current Assets	**$ 23,592,230**	**$ 45,596,558**	**$ 67,531,143**
Fixed Assets			
Real Estate -- Land	-	-	-
Real Estate -- Buildings	-	-	-
Leasehold Improvements	-	-	-
Equipment	203,478	203,478	203,478
Furniture and Fixtures	-	-	-
Vehicles	-	-	-
Other	-	-	-
Total Fixed Assets	**$ 203,478**	**$ 203,478**	**$ 203,478**
(Less Accumulated Depreciation)	$ 29,068	$ 58,137	$ 87,205
Total Assets	$ 23,766,639	$ 45,741,899	$ 67,647,416
LIABILITIES & EQUITY			
Liabilities			
Accounts Payable	1,520,400	1,520,400	1,520,400
Commercial Loan Balance	132,527	115,080	95,996
Commercial Mortgage Balance	-	-	-
Credit Card Debt Balance	-	-	-
Vehicle Loans Balance	-	-	-
Other Bank Debt Balance	-	-	-
Line of Credit Balance	-	-	-
Total Liabilities	**$ 1,652,927**	**$ 1,635,480**	**$ 1,616,396**
Equity			
Common Stock	80,000	80,000	80,000
Retained Earnings	22,033,712	44,026,420	65,951,020
Dividends Dispersed/Owners Draw	-	-	-
Total Equity	**$ 22,113,712**	**$ 44,106,420**	**$ 66,031,020**
Total Liabilities and Equity	$ 23,766,639	$ 45,741,899	$ 67,647,416
Balance sheet in or out of balance?	$ - Balanced!	$ - Balanced!	$ - Balanced!

A-9: Breakeven Analysis

Gross Margin % of Sales		
Gross Margin	$	28,315,200
Total Sales	$	46,560,000
Gross Margin/Total Sales		**60.8%**
Total Fixed Expenses		
Payroll	$	665,862.84
Operating Expenses	$	96,779.99
Operating + Payroll	**$**	**762,643**
Breakeven Sales in Dollars (Annual)		
Gross Margin % of Sales		60.8%
Total Fixed Expenses	$	762,643
Yearly Breakeven Amount	**$**	**1,254,049**
Monthly Breakeven Amount	**$**	**104,504**

UML Team Technical Report

9.0 Design Objective

The U.S. Army is one of the largest consumers of off-grid energy in the world. In 2014, the Department of Defense (DoD) consumed over 87 million barrels of fuel, costing an estimated $14 billion. Operational energy, defined as "energy required for training, moving, and sustaining military forces and weapons platforms for military operations" accounted for nearly 70% of this fuel consumption[ix]. The DoD is actively examining and deploying renewable energy alternatives to fossil fuel generation due to (1) the risks posed to personnel and equipment associated with refueling Army deployments, (2) the high "fully burdened cost" of diesel fuel, estimated to be $15-$40+ per gallon as shown in Table B-4.1 and (3) the environmental impact associated with fossil fuels. The DoD's 2016 budget proposal included $150 million allocated towards the Energy Conservation Investment Program (ECIP)[x]. Specifically, $37 million is budgeted for the Operational Energy Capability Improvement Fund (OECIF), which supports operational energy technology innovations with the mission to improve the DoD's operational effectiveness[xi].

The Army has a clear need for renewable energy; however, the army presents non-traditional operational and technical challenges. The Army's energy requirement varies depending on the deployment type. A typical large-scale deployment will include large bases (>150 people), force provider camps (50-150 person capacity) and forward operating bases (<50 people). The Army currently uses diesel generators for the majority of their overseas operating bases and camps.

The University of Massachusetts Lowell (UML) 2016 Collegiate Wind Competition team, *WindHawk Solutions*, is collaborating with the *U.S. Army Natick Soldier Systems Center-Natick Soldier Research Development and Engineering Center (NSSC-NSRDEC)*[xii] and the *Belvoir Soldier Research Development and Engineering Center (BSRDEC)* to design a relevant user-centric product that directly addresses the Army's needs. *WindHawk Solutions* is a specialty wind turbine design and manufacturing company that designs durable, off-grid, renewable energy solutions to supplement and reduce diesel fuel consumption anywhere in the world. The products, depicted in **Figure B-4.1** and Figure B-4.2, include a unique 6 kW aerial wind turbine system and a more traditional 400 W ground based, transportable wind turbine. The *WindHawk Solutions* technology is targeted towards two deployment types:

1. **Forward Operating Bases (FOBs), Figure B-4.1**, FOBs are often located in hostile environments with adverse terrain as well as limited access to fuel and other resources, employ a series of individual 2–

5 kW diesel generators for power generation. Due to FOB isolation, the fully burdened cost of diesel can exceed $40/gal. The primary *WindHawk Solutions* product is a 4 m wingspan, inflatable, Cross-wind Aerial Wind System (C-AWS) that can generate 6 kW at rated wind speeds while transmitting power through a conductive tether that also serves to anchor the system to the ground. The C-AWS is a kite-gen system, inspired by Google's Makani®[xiii], comprises two 45 cm diameter, 5-bladed wind turbines mounted to an inflatable kite. By contrast, a terrestrial wind turbine that generates 6 kW in 4 m/s ground wind speeds would require 9 m blades, an 18 m diameter (see Figure **T-9.2**). The high velocity kite amplifies the power extraction by covering a significant swept area in a figure-eight flight path. Due to the higher flight altitudes of 200 m to 300 m, the system also exploits the more consistent and higher energy density winds not accessible to traditional small tower-based wind turbines.

2. **Force Provider Camps,** Figure B-4.2, use 60 kW diesel generators to generate electrical power. To ensure sufficient power is always available, successive generators come into service when 80% of present capacity is reached and remain in service until the power demand is less than 60% of the reduced system[xiv]. *WindHawk Solutions'* secondary product is a traditional 3 m diameter ground-based, downwind configuration, five-bladed wind turbine system that leverages the technology and manufacturing processes developed for the C-AWS. One of the unique features of this system is the lightweight, transportable guy-wire supported truss tower[xv]. These turbines cut in at low wind speeds and produce 400 W of rated power at wind speeds of 5 m/s. A collection of 10-20 distributed ground turbines collectively serve to reduce the frequency by which successive diesel generators come online, effectively using renewables to shave peak power consumption.

(a)

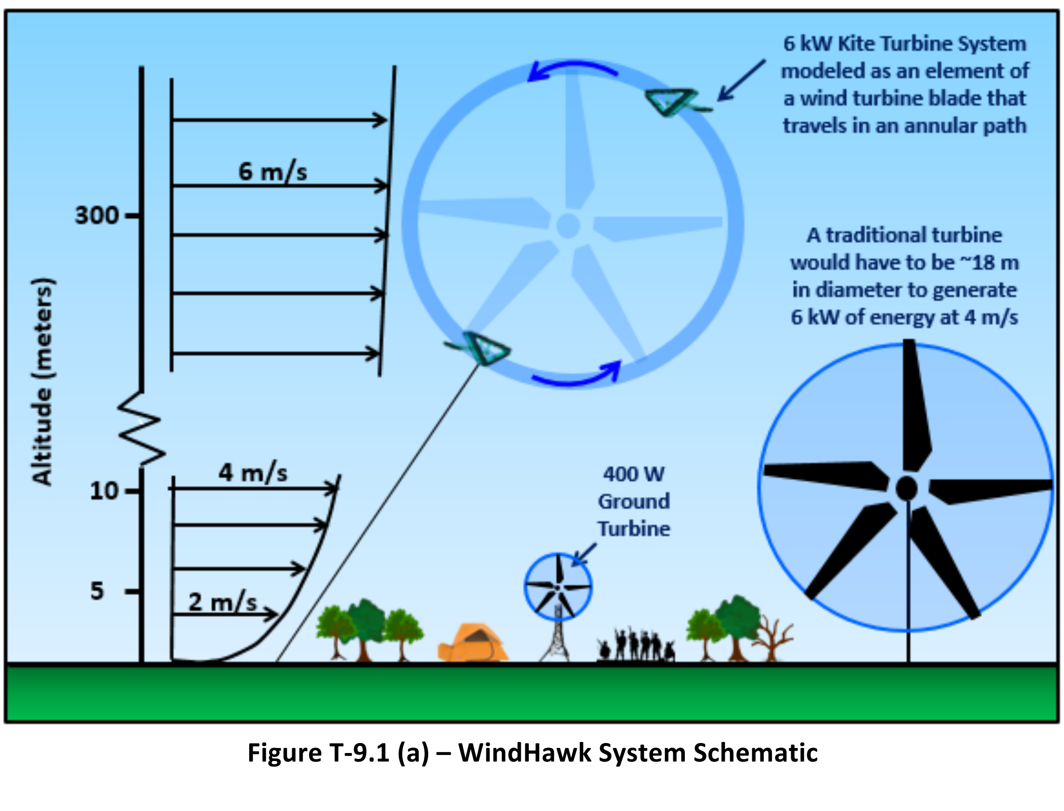


Figure T-9.1 (a) – WindHawk System Schematic

9.1 Summary of the Design Goals

WindHawk Solution's mission is to offer transportable wind energy solutions that meet military standards while improving the Army's operational effectiveness. The wind energy system will not eliminate generator usage, but will drastically reduce fuel consumption by supplementing existing diesel generators. Reliability, durability, and system transportability are key product features to support the army's energy needs anywhere in the world. Engineering drawings for the C-AWS and Ground turbine are shown in Figure T-9.3(a) and Figure T-9.3(b), respectively.

(b)

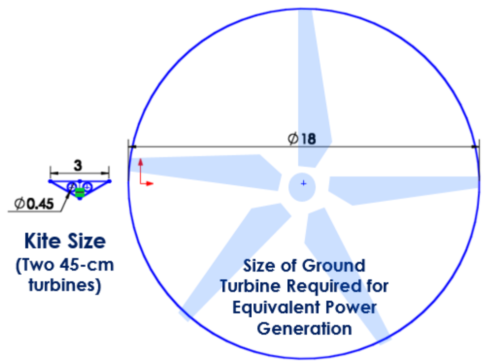


Figure T-9.2(b) – WindHawk System Schematic

- ***Durability***: The system must be able to withstand disparate wind, weather and environmental conditions. Both the C-AWS and terrestrial turbine must be able to autonomously control for wind gusts and other sudden changes in flight conditions.
- ***Reliability***: *WindHawk Solutions* generates renewable wind power with minimal downtime. The system is designed for diesel generator power offset and supplementation while being safe to deploy near personnel. Due to atmospheric boundary layer recovery, wind speeds at higher altitudes are both more consistent and have higher energy density (Figure T-9.2).
- ***Transportability:*** Each of the *WindHawk Solutions'* products are packaged and shipped in a single Tricon® shipping container. The system is designed for a military specified 2-person lift (less than 80 lbs or 36.6 kg)[xvi]. Unpacking, assembly, and deployment of both systems requires minimal training. The package-to-power-production deployment time is less than 30 minutes.

(a) **(b)**

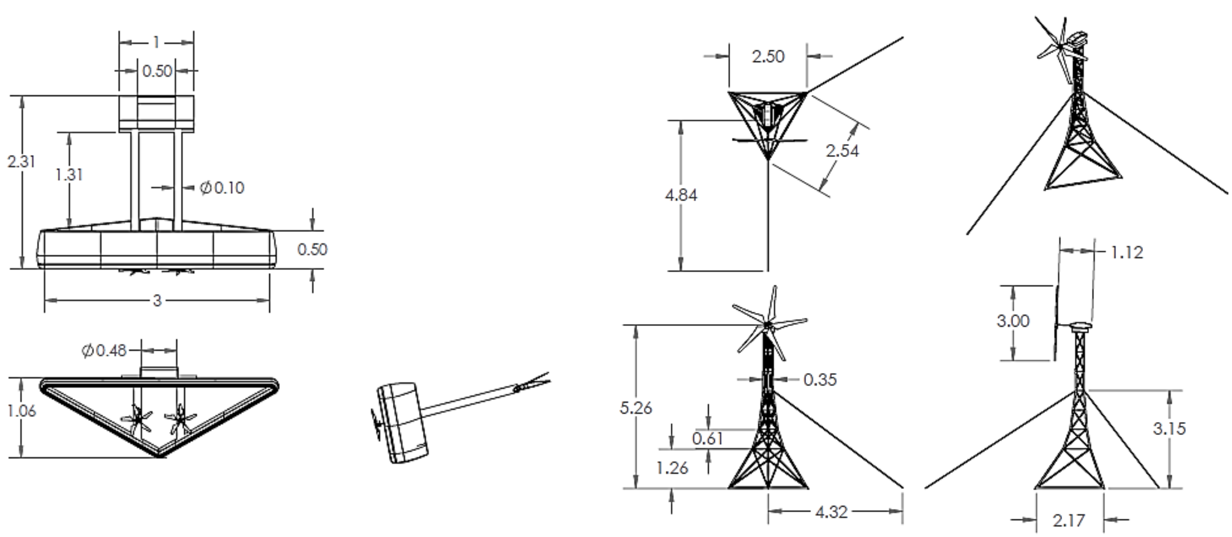


Figure T-9.3 - Engineering Drawings for (a) C-AWS and (b) Ground Turbine

The initiation of the launch sequence deploys the C-AWS using the turbines as a propulsion system. Details of the deployment strategy are discussed in Section 16. The turbines use a pitching mechanism to transition between propeller and turbine mode, regulate power production as well as mitigate loads by reducing blade rotational speeds in higher winds. Each C-AWS turbine is 45 cm in diameter, with five, 18 cm blades. Five blades are used to increase the power to axial force ratio by 0.4 W/N, validated by BEMT. The C-AWS is predicted to generate 26,280 kWh per year.

WindHawk Solutions has formed a partnership with Federal-Fabrics-Fibers (3F) located in Lowell, MA for inflatable airbeam manufacturing. An airbeam is a composite fabric inflatable tube made from Vectran, Kevlar, and polyester. An internal bladder is inflated to 690 kPa, creating a rigid beam. The use of this technology as the primary structural component of the kite design, discussed further in Section 12.2, allows the C-AWS to meet portability and durability criterion at high operational speeds.

The technology used in the C-AWS is leveraged at a higher level of production to produce a second, ground-based, wind system comprising a five-bladed rotor with a similar pitching mechanism and electrical system. The ground turbines are mounted on a lightweight 5 m tall truss-tower. The ground turbine is expected to generate 1,752 kWh per year, assuming a 50% capacity factor.

10.0 Wind Resource Analysis

The inconsistency of wind resources is a challenge facing any wind turbine. The C-AWS must be able to fly and produce power over a wide range of wind speeds. Ideal C-AWS flight speeds are 40-60 m/s, which can be achieved for corresponding ground wind speeds of 3 m/s to 30 m/s. The ground-based turbine is designed for low-wind operation with a target cut-in wind speed near 4 m/s. Due to the atmospheric boundary layer the wind speed increases with altitude (Figure T-10.1). For C-AWS flight altitudes, wind velocity is approximately 1.5 times that of a similarly located ground-based turbine.

U.S. Army deployments can occur anywhere in the world, with each location having varying wind resources. Global wind resource maps show that reasonable energy density wind is available in many locations (Average wind speed at 80 m is 4.59 m/s)[xvii]. Currently, the U.S. Military deployments are heavily concentrated in the Middle East, where average wind speeds range from 4 m/s at 10 m altitude to 6 m/s at 300 m altitude.

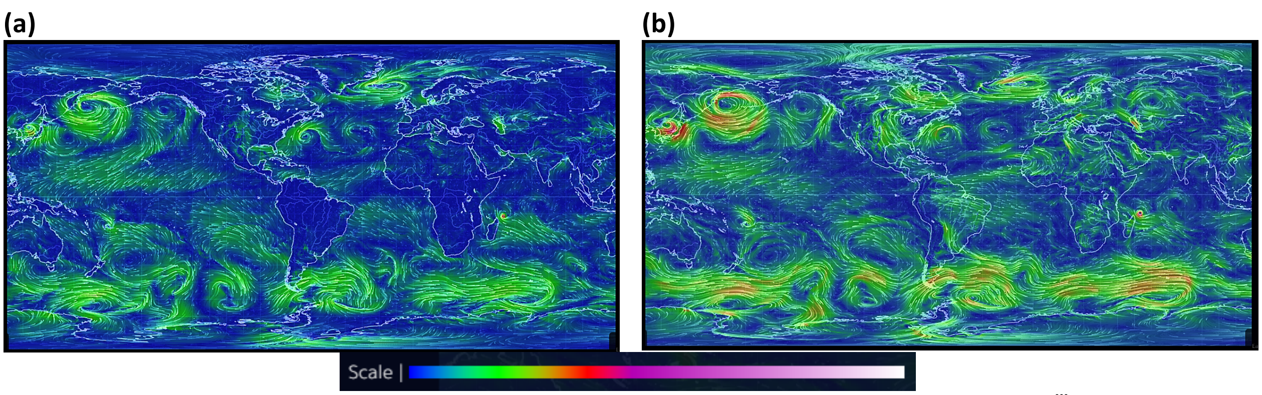


Figure T-10.1 - World Wind Map at (a) Surface and (b) 1000 m altitude[xviii]

11.0 Static Performance Analysis

In this section, static wind power and structural performance analysis is presented for (i) the kite-mounted turbines, (ii) the ground-based wind turbine, and (iii) the inflatable kite.

11.1 C-AWS & Ground based system: Turbine Analysis and Preliminary Design

The C-AWS system generates power using two turbines mounted on a kite. The C-AWS must meet the following design specifications:

- Transportability: System must weigh less than 36.3 kg to meet the two-man lift requirement.
- Reliability: The total C-AWS power goal is 6 kW for ground wind speeds of 6-30 m/s.

- Durability: Blade design should maximize ratio of power production to axial forces.

The ground turbine must meet the following objectives:

- Transportability: A maximum turbine diameter of 3 meters and total system weight of 36.3 kg.
- Reliability: The ground turbine power production goal is 400 W for wind speeds of >4 m/s.
- Durability: The ground turbine must be able to withstand sustained wind speeds of 25 m/s.

During initial C-AWS and ground based turbine sizing, a traditional control volume momentum-energy analysis was performed. For the C-AWS, the turbine axial force (F_{axial}, Equation (1)) must be less than or equal to the kite excess thrust force.

$$F_{Axial} = \left(\frac{1}{2}\rho v^2 A_{Turbine}\right) * C_F \qquad Where: C_F = 4a(1-a) \tag{1}$$

$$P = \left(\frac{1}{2}\rho v^3 A_{Turbine}\right) * C_P \qquad Where: C_P = 4a(1-a)^2 \tag{2}$$

Equations (1) and (2) show that the axial force, F_{axial}, and the power, *P,* are each functions of the axial induction factor, a. Based on the design objectives, the performance of the C-AWS is measured by the ratio of power coefficient to axial force coefficient (Equation (3)).

$$\frac{C_P}{C_F} = \frac{4a(1-a)^2}{4a(1-a)} = 1 - a \tag{3}$$

Equation (3) shows that a larger ratio of C_P to C_F can be achieved by minimizing the axial induction factor, a; however, a value for C_P must be selected for C-AWS power production.

Since the C-AWS is designed without gearboxes, a turbine blade design with high tip speed ratio (TSR) of 5.5 was chosen to achieve rotational speeds of 10,500 RPM. For the C-AWS turbines, the relative velocity of the kite (40-60 m/s) is used for the aerodynamics analysis. Through several iterations, a specific blade profile was designed to generate 3 kW per turbine, which was achieved at 40 m/s. The power analysis was completed by plotting C_P as a function of operational TSR (Lambda) at a variety of blade pitch angles, see Figure T-11.1. A blade pitch angle of 0° produced the largest C_P of 0.4516. The BEMT analysis was then repeated for the ground turbine by using the same blade TSR while scaling the radius of the blades to 1.5 m and adding a 12:1 gearbox. For the ground turbine analysis, wind speeds of 4 – 8 m/s were examined. While the turbine can generate up to 1500 W at wind speeds of 9 m/s and above, the expected power generation for the system is 400 W at average wind speeds. The axial force analysis was completed by plotting C_P, as a function of operational TSR at a variety of blade pitch angles, see Figure T-11.2.

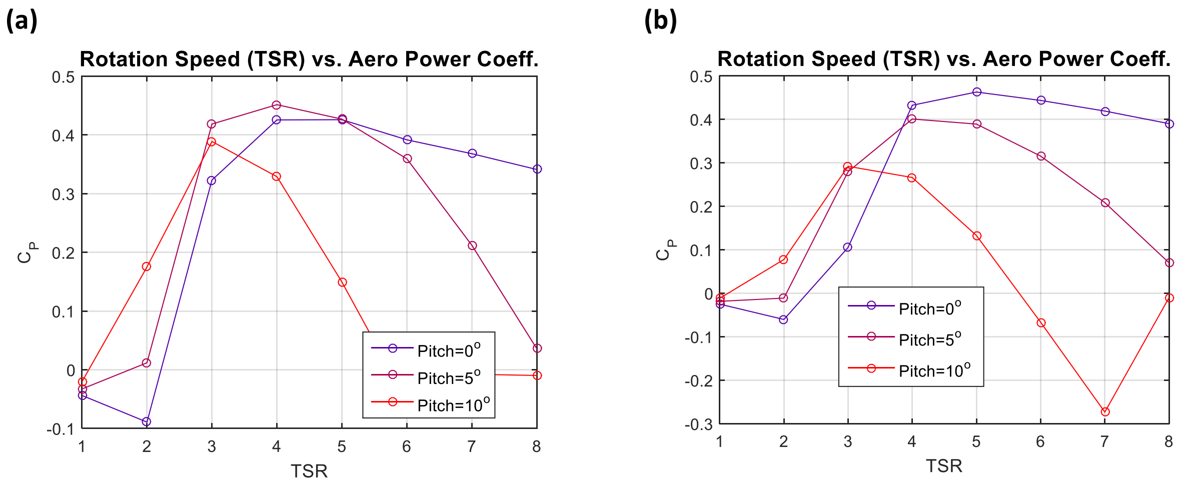


Figure T-11.1- C_P-Lambda Curve Developed Using BEMT Analysis at Varying Blade Pitch Angles for (a) the C-AWS System and (b) the Ground-Based Turbine

The power output curves for both turbine systems, Figure T-11.3, were developed using Equation (2) with C_P values determined from the BEMT Analysis at each pitch angle. For the C-AWS, the blades begin to pitch when the individual turbine power generation reaches 3 kW, regulating power output and protecting the system components. For the ground turbine, the wind speeds are low and therefore the turbine experiences less axial force (200 N). The blades will begin to pitch at velocities above this wind speed to maintain rated power. The axial force curves for each turbine, Figure T-11.4, were developed using Equation (1) with C_F values determined from the BEMT Analysis at each pitch angle.

The power and force balance analysis summarized in Figure T-11.3 and Figure T-11.4, combined with the BEMT analysis, reveal that the C-AWS reaches its optimal power output at a kite-flight velocity of 48 m/s, leading to the conclusion that the performance of the C-AWS is primarily influenced by the ability to control the kite's velocity. This conclusion also defines the specification for operational kite velocity of 40-60 m/s, which will be used as a design objective for the kite system.

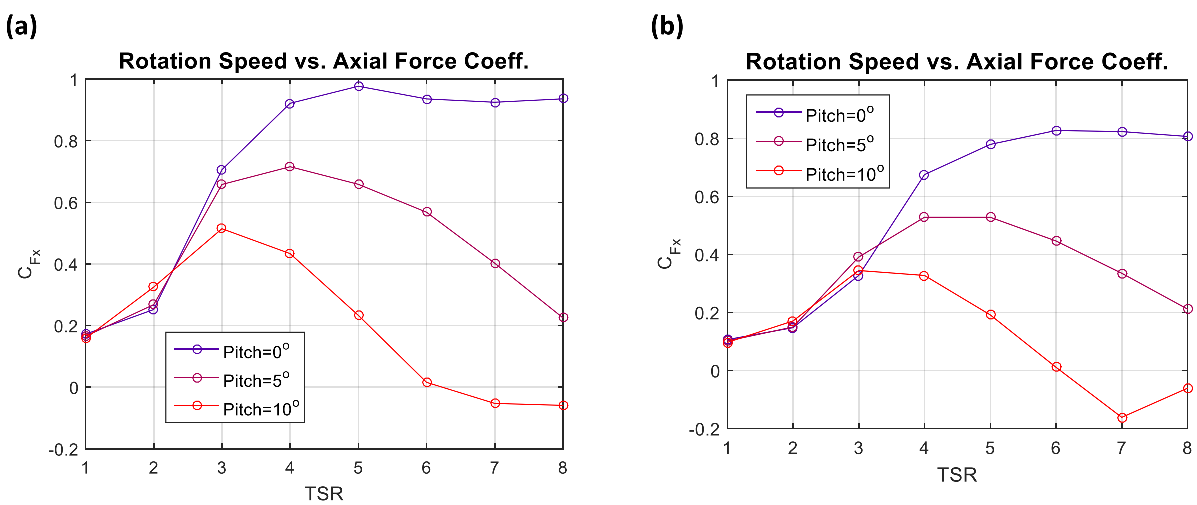


Figure T-11.2- C_F-Lambda Curve Developed Using BEMT Analysis at Varying Blade Pitch Angles for (a) the C-AWS System and (b) the Ground Based Turbine

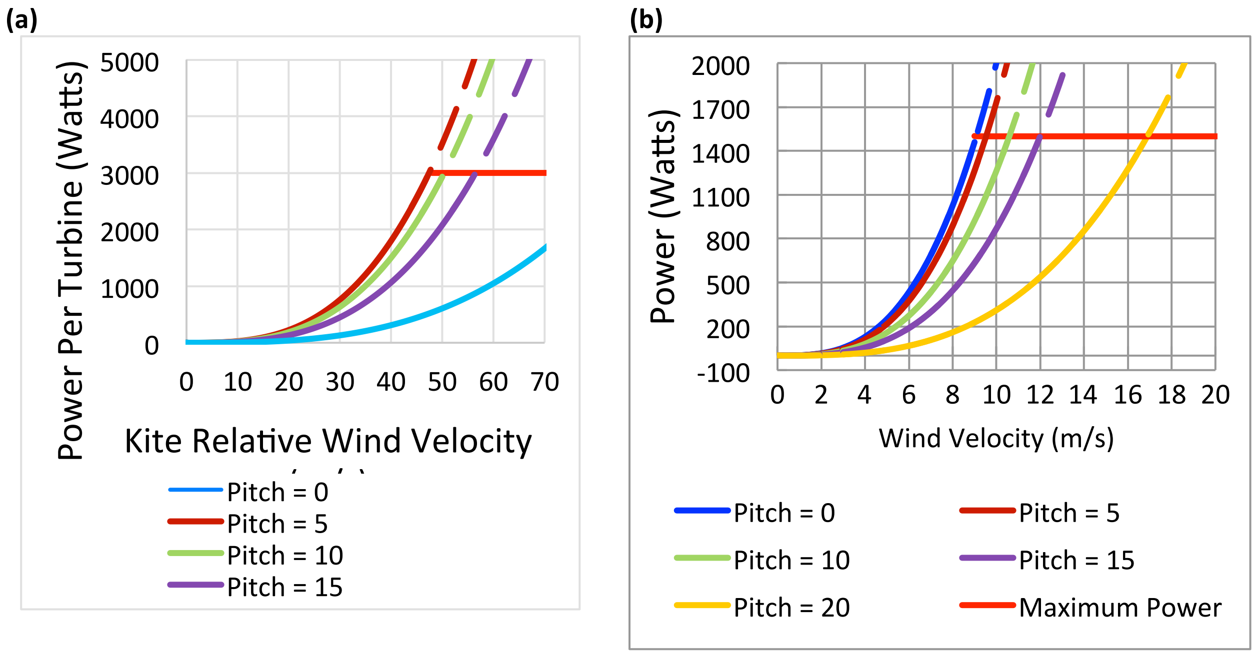


Figure T-11.3 - Power vs. Wind Velocity for (a) the C-AWS System and (b) the Ground-Based Turbine

For both turbine systems, this analysis revealed the power output and axial forces at specific wind speeds. The development of these specifications led to several design outcomes, summarized in Table T-11.1.

The design outcomes in Table T-11.1 were verified through wind tunnel testing. The wind tunnel prototype served as a proof of concept for pitch control and blade design. Testing verified that the pitching mechanism shown in Figure T-11.5 can successfully regulate the rotational speed of the turbine as predicted by BEMT. These results are further discussed in Section 6.3. The forces associated with the hub are analyzed in Section 4.3. With preliminary sizing and power output analysis complete, the remaining system design can be executed through the analysis of the kite, airfoils, ground system tower, and electrical components.

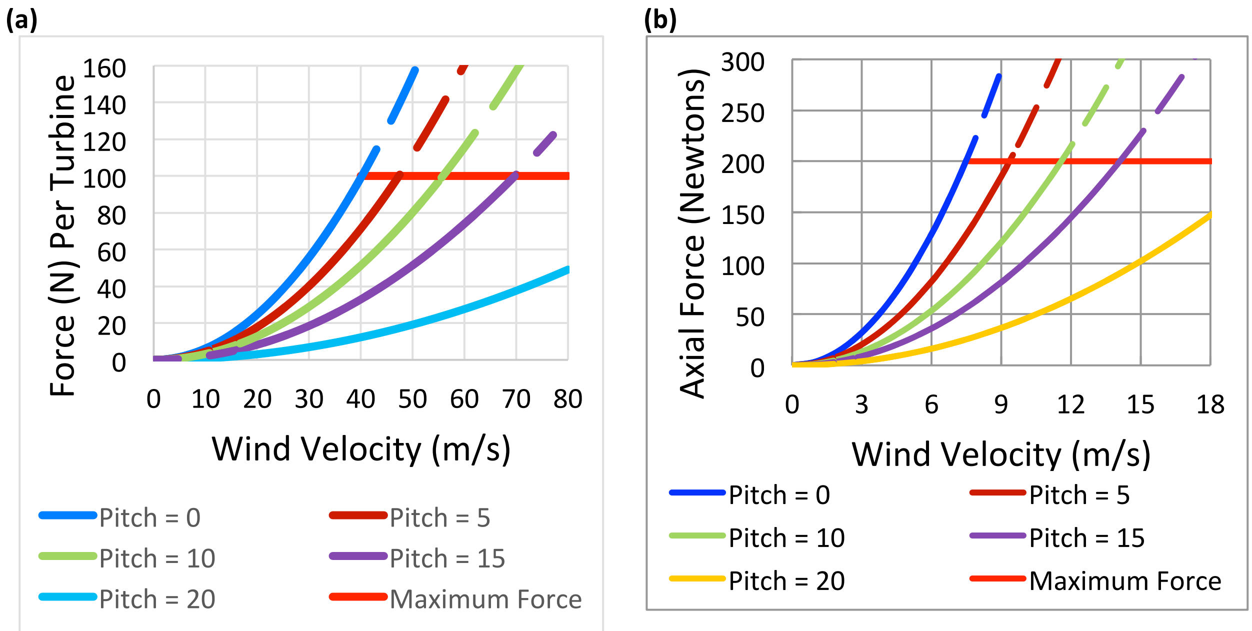


Figure T-11.4 - Axial Force vs. Wind Velocity for (a) the C-AWS System and (b) the Ground Turbine

Table T-11.1 - Design Outcomes Justified by Power and Force Analyses of Turbines, Including BEMT

	C-AWS	**Ground Based Turbine**
Blade Radius	0.18 m (Per Turbine)	1.5 m
Number of Blades	5 (Per Turbine)	5
Rated Power	6 kW (Total)	400 W
Wind Velocity at Rated Power	48 m/s (Relative)	6 m/s
Maximum Expected Axial Force	100 N (Per Turbine)	200 N
Gearbox	1:1	12:1
Generator	100 KV	100 KV
Airfoil Selection	NACA 0012	NACA 0012

11.2 Crosswind-Aerial Wind System (C-AWS): Kite Analysis and Preliminary Design

To support the main design objectives of the system, defined in Section 1.1, the design of the C-AWS kite must reflect portability as well as durability and reliability. Portability of the system is achieved through a maximum weight of 36.3 kg, including the kite, turbines, tether, and ground components. For ease of shipping, a minimal volume is required. Reliability is maintained through the following objectives:

- Ability to produce 6 kW of power in 6 m/s wind.
- Operational kite velocity of 40-60 m/s.
- The kite must be able to produce power in a wide range of wind speeds.
- Preserve the connection to the ground through the tether.

The kite wing design considered two types of kites, hard wing and inflatable kites. Airbeams were selected for this design because of the inflatable wing reduces the kite to a volume of 0.15 m^3 fitting easily into a 1 m^3 box. Airbeams also possess properties of rigid airfoils, which is beneficial because a high lift-to-drag ratio is important for aerodynamic efficiency. The kite was sized to produce adequate lift while maintaining low drag and weight. A crosswind kite is analogous to the tip of a large wind turbine blade in which the power extraction is proportional to the swept area or annular path. Loyd's seminal paper[xix] was used for preliminary kite sizing and power prediction. Initial predictions indicated a wing span of 3 m would be sufficient for our design. Power prediction was verified using an aerodynamics power and force balance analysis. After several iterations, an ideal wing area was found at 4.5 m^2.

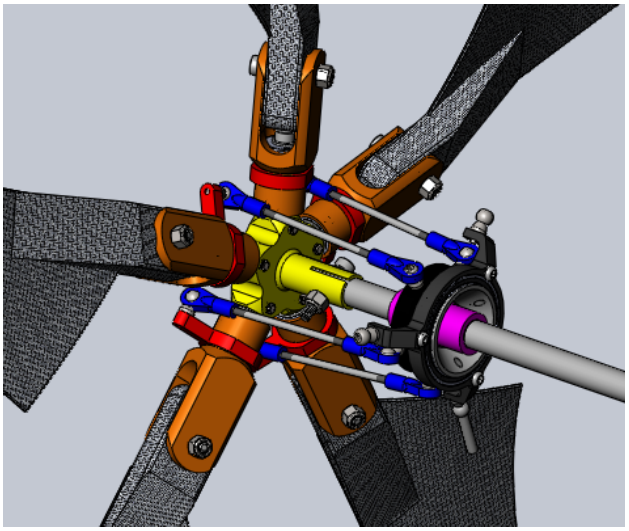


Figure T-11.5 – SolidWorks® Model of Test Stand Pitching Mechanism

The kite system was analyzed using a steady-state aerodynamics force balance analysis shown in **Figure T-11.6**. For simplicity, the kite was initially treated as an aircraft constrained to travel along a straight path. The wind velocity triangles and the resulting aerodynamics forces as well as the free-body diagram of the kite system are shown in **Figure T-11.6**(a) and **Figure T-11.6**(b), respectively.

The steady state aerodynamics analysis considered the kite lift, L and drag, D using Equations (4) and (5), respectively. Where: C_L = Lift Coefficient, ρ = air density $\frac{kg}{m^3}$, v = total relative wind velocity impinging on the kite, and A_{wing} = kite planform area. $C_{D,Total}$ is the total drag coefficient, which is determined by summing all drag components with wing planform reference areas as shown in Equation (6).

$$L = C_L\left(\frac{1}{2}\rho v^2\right)A_{wing} \quad (4) \qquad D = C_{D,Total}\left(\frac{1}{2}\rho v^2\right)A_{wing} \quad (5)$$

$$C_{D,Total} = C_{D,Induced} + C_{D,Profile} + C_{D,Tether} + C_{D,Turbines} \quad (6)$$

For a variety of wind speeds, a static analysis was used to determine the excess force (F_{Excess}) using Equation (7) as a function of kite pitch angle (θ). The excess force predicts the power available ($P_{Available}$) using Equation (8).

$$F_{excess} = L sin\theta - D sin\theta \quad (7) \qquad P_{Available} = F_{Excess} * v \quad (8)$$

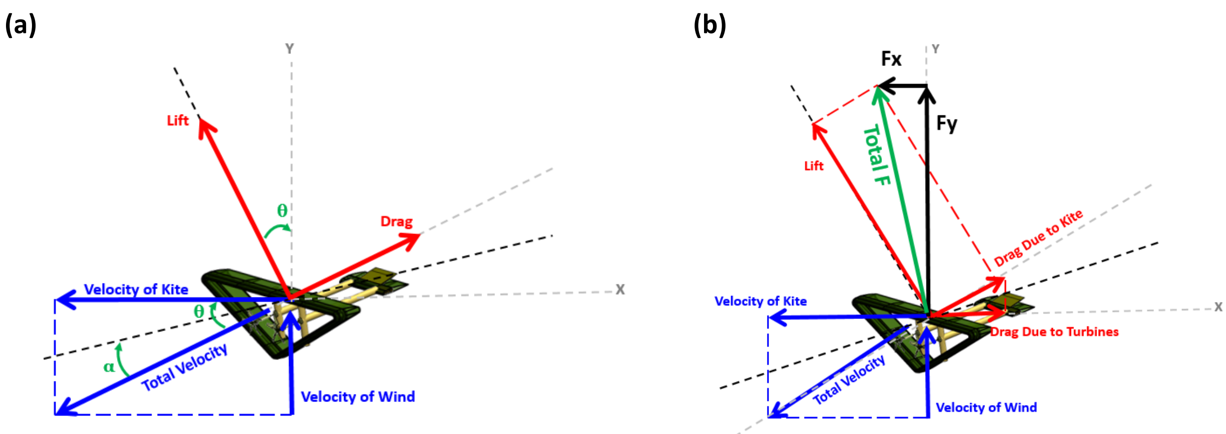


Figure T-11.6 – Preliminary Static Analysis of the Kite System, Including (a) Kite Aerodynamics and Velocity and (b) Kite Free-Body Diagram

The power and force balance analysis was performed using MS Excel to produce the kite power performance curves shown in **Figure T-11.7**. At wind speeds ranging from 5 - 13 m/s, Equations (1) through (4) were used to calculate the kite's total power generation. The dashed lines denote the continued power generation that would occur in a theoretical system. The parameters used in this analysis are listed in Table T-11.2, and were determined and verified through further analysis including XFOIL[19] and OpenVSP[xx].

The power and force balance analysis ultimately supports the claim that kite pitch angle control can be effectively used to modulate the C-AWS velocity and power generation. **Figure T-11.7**(a) shows how the relative velocity of the kite decreases as kite pitch angle decreases for different wind velocities. **Figure T-11.7**(a) shows that the C-AWS produces starts to produce power at ground wind speed of 3 m/s and produces the desired 6 kW of power at wind speeds of 6 m/s and greater.

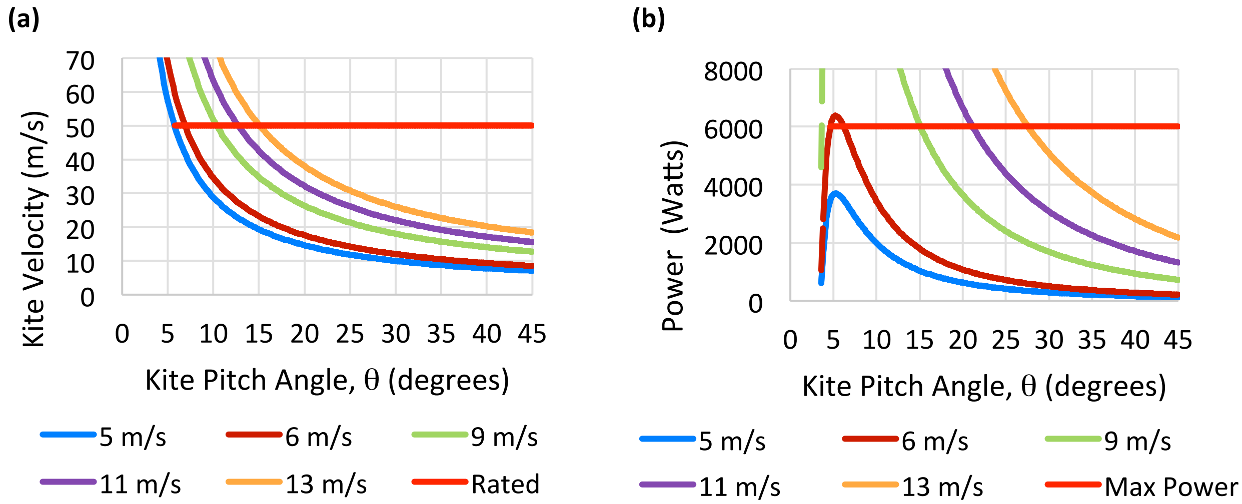


Figure T-11.7 – Kite Performance as a Function of Pitch Angle of Kite, Specifically (a) Kite Velocity and (b) Kite Power Generation

Table T-11.2 - Parameters Used for Aerodynamics Power and Force Balance Analysis of the Kite System

Parameter	Value	Derivation
Total Area of Wing, A_{wing}	4.5 m^2	BEMT Analysis
Air density, ρ	1.225 kg/m^3	Known Property of Air
Kinematic Viscosity of Air, v	0.0000146	Known Property of Air
Area of Tail, A_{tail}	1 m^2	Lloyd
Aspect Ratio, *AR*	6	Determined through historical data
Efficiency, *e*	1.34	Closed wing shape[xxi]
Tether Diameter, D_{tether}	0.003 m	Paragraph 4.2
Tether Length, L_{tether}	300 m	Design altitude of kite, Section 1.2
Coefficient of Power, C_P	0.4516	BEMT Analysis
Coefficient of Lift	0.6	OpenVSP Analysis, Section 5.3
Profile Coefficient of Drag	0.012571	OpenVSP Analysis, Section 5.3
Induced Coefficient of Drag	0.0142527	〚C_L〛 ^2/(π AR e)
Drag Coefficient of Tether	0.1	Lloyd
Total Drag Coefficient	0.1267	Sum of Drag Coefficients
Lift-to-Drag Ratio, *L/D*	22.37	C_L/C_D

The “closed wing” shape is justified by the static performance analysis because:

1. This wing shape has the highest Oswald’s efficiency factor (*e*)[15], see Table T-11.2
2. The direction of the lift vectors on the bottom portion of the kite are directed toward the center, therefore increasing roll stability and enhancing reliability of the system.

The drag due to the tether is a significant contribution to the overall system drag. The cross-sectional shape and the diameter of the tether both affect the drag coefficient. Reducing the cross-sectional area of the tether improves aerodynamics performance but reduces the tether load carrying capability. Tether design is discussed in Section 12.2.

With the initial design complete, the feasibility of the system is proven. Athena Vortex Lattice (AVL) software[xxii] was subsequently used to verify that the kite meets all specified design objectives, further discussed in Section 12.2.

11.3 Airfoil Selection

The kite airfoils were selected based on the following aerodynamics objectives, analyzed using XFOIL[xxiii]. Results are shown in Figure T-11.8:

- A flatter *L/D* curve results in lower power sensitivity to variations in angle of attack
- A high *L/D* results in a kite that produces significant power [Loyd][15]
- A favorable, smooth stall characteristic that does not result in catastrophic loss of lift

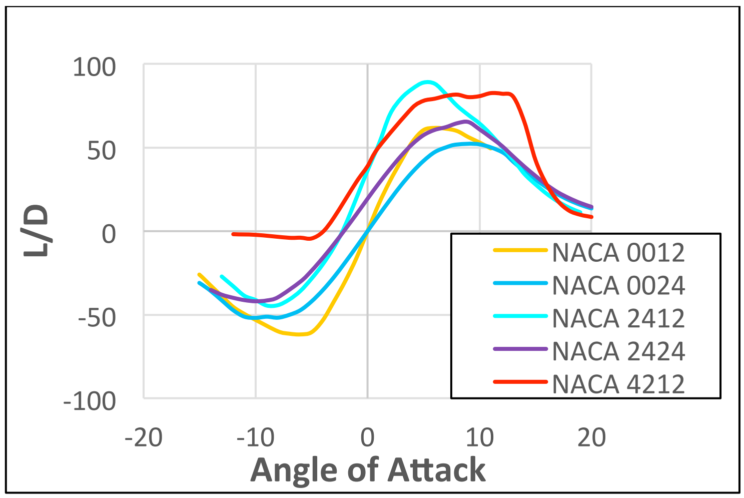


Figure T-11.8- L/D Ratio vs. Angle of Attack Plot Used for Airfoil Selection

The NACA 4212 airfoil was selected for the kite airfoil due to its high and relatively insensitive *L/D*. The NACA 0012 was selected for the turbine blades because it produces the highest *L/D* for a symmetrical airfoil. In addition, the stall angle for NACA 0012 was slightly lower than NACA 4212, aiding the ability to quickly reduce power at high wind speeds.

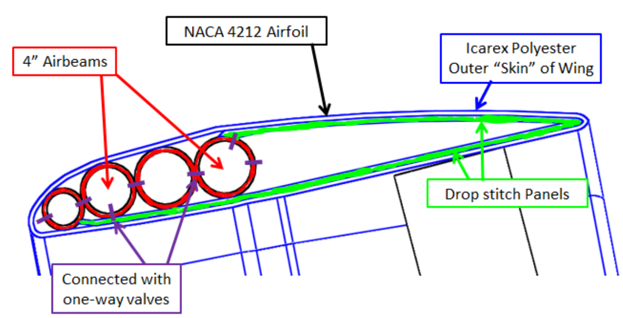


Figure T-11.9 - Kite Wing Structure Using Airbeams – Cross-Sectional Area of Kite Wing

The design objective includes using strategic airfoil selection as well as airbeam technology to increase aerodynamic efficiency, however, the structural nature of airbeams present a challenge for maintaining perfect airfoil shape. This challenge was met by using a unique airbeam configuration, shown in Figure T-11.9. The multiple airbeams within the leading edge of the kite are pressurized into the desired airbeam shape using an outer skin. Following the traditional airbeams are dropstitch panels, which make up the remainder of the airfoil shape at the trailing edge of the wing. By utilizing these two forms of inflatable technologies, the kite to harness their complementary design factors to benefit the final design.

12.0 Weights, Loads and Structural Analysis and Design

The primary goal is to design a system that will support the maximum expected applied loads. It is also important for the system to be as light as possible in order to remain below the 36.3 kg limit. Designing beyond the maximum operating conditions ensures that even in the most extreme environments the C-AWS and ground turbine will remain structurally sound. A safety factor of three was used to meet the quality standard of the military.

12.1 Ground Turbine System Loads Analysis

The ground turbine tower has the following design specifications:

- Maximum weight of 18.1 kg to keep total weight below 36.3 kg
    - Including tower, blades, gearbox, guy wires
- Minimum height of 4.9 m to meet DoD safety clearances[xxiv]
- Material yielding after 800 N of applied axial force in both tension and compression

Three types of towers for the ground turbine were considered: (1) a traditional “multi-segment” tower made of aluminum with hollow cross sections, (2) the same aluminum tower with guy wires to help distribute the forces, and (3) a triangular-prism style steel truss tower with three guy wires (see Figure T-12.1). The truss design was considered after a survey of literature showed several mainstream wind turbine manufacturers (GE and Siemens) are considering truss towers in the field.

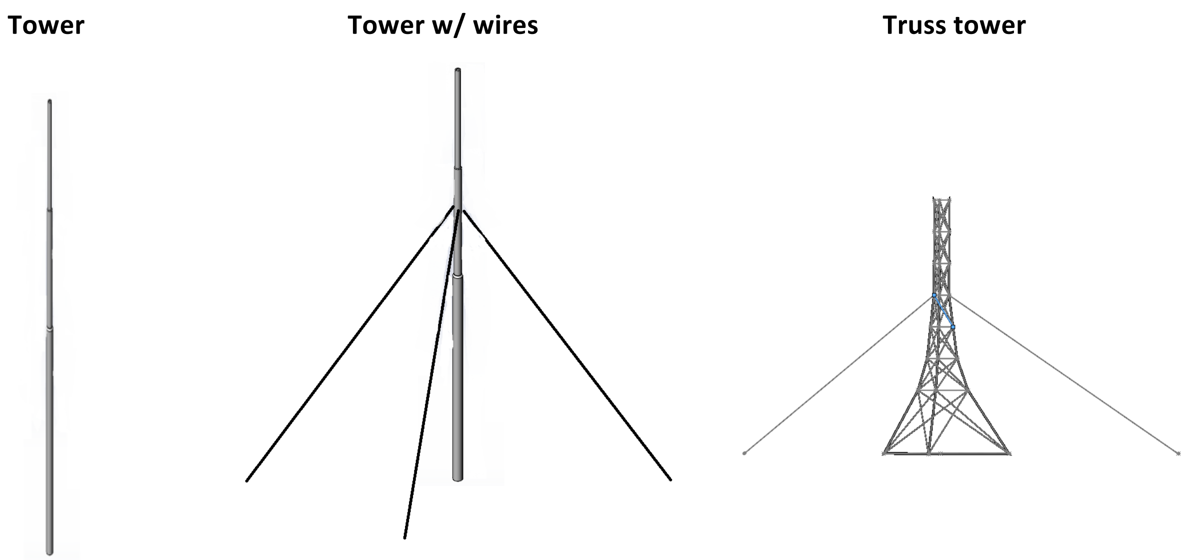


Figure T-12.1 - Ground Turbine Structural Design Possibilities

A basic analysis of the candidate towers indicated that the aluminum tower could not overcome the bending moment due to the applied axial forces. With the addition of guy wires, the bending moment was reduced; however, the tower weight (39 kg) exceeds the design target of 18.1 kg. The truss tower met the design objectives and has a weight of 14 kg. The truss tower is comprised of five members of various cross sectional diameters. The total height of the truss tower is five meters tall.

A load path diagram for both turbines on the ground and C-AWS can be seen below in Figure T-12.2. These show the different components upon which forces are applied. There are more components on the ground turbine making it more susceptible to failure. Highlighting the forces that are transmitted through each component ensures that it will not fail due to forces exceeding the components' allowable load.

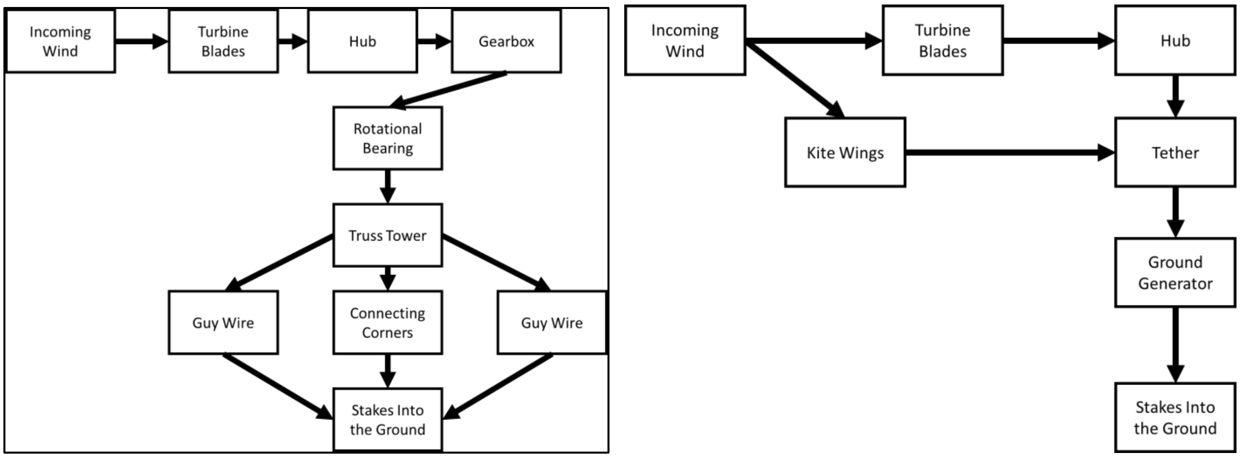


Figure T-12.2 - Load Path Diagrams for Kite Turbine and Ground Turbine

The truss tower is secured to the ground using six tethers (6 m in length) which extend out from the truss at 3.5 m from the base. At each base corner of the truss, there will be a small pad to distribute the load and prevent the truss corner sinking into the terrain. For additional safety, two military standard sand bags are placed on each base corner of the truss. The maximum expected axial force acting on the top of the tower (at a height of 5 m) is 800 N. This produces a torque of 4,000 N-m. A static analysis was performed to determine the critical wind direction, and the truss is designed to withstand maximum rated force at this angle as seen in Figure T-12.3(b). It was calculated that the allowable load of the specialized anchor stakes is 1216 N.

A finite element analysis (FEA) was performed using MATLAB® to examine stresses in each truss member. Extreme load cases were considered for wind angles over a range of 0-120 degrees (due to rotational symmetry). A maximum compression loading occurs at a 30 degree incident wind angle, and maximum tensile loading occurs at an incident wind angle of 90 degrees. FEA was also used to verify that none of the tower members would buckle or yield. Figure T-12.3(a) shows maximum compression, Figure T-12.3(b) shows maximum tension. Figure T-12.3(c) and (d) show the stresses that are in compression and tension. The red dashed line represents the allowable stress before yielding, while the dashed magenta line represents the critical stress where buckling begins. The addition of the guy wires helps to prevent the yielding and buckling of members.

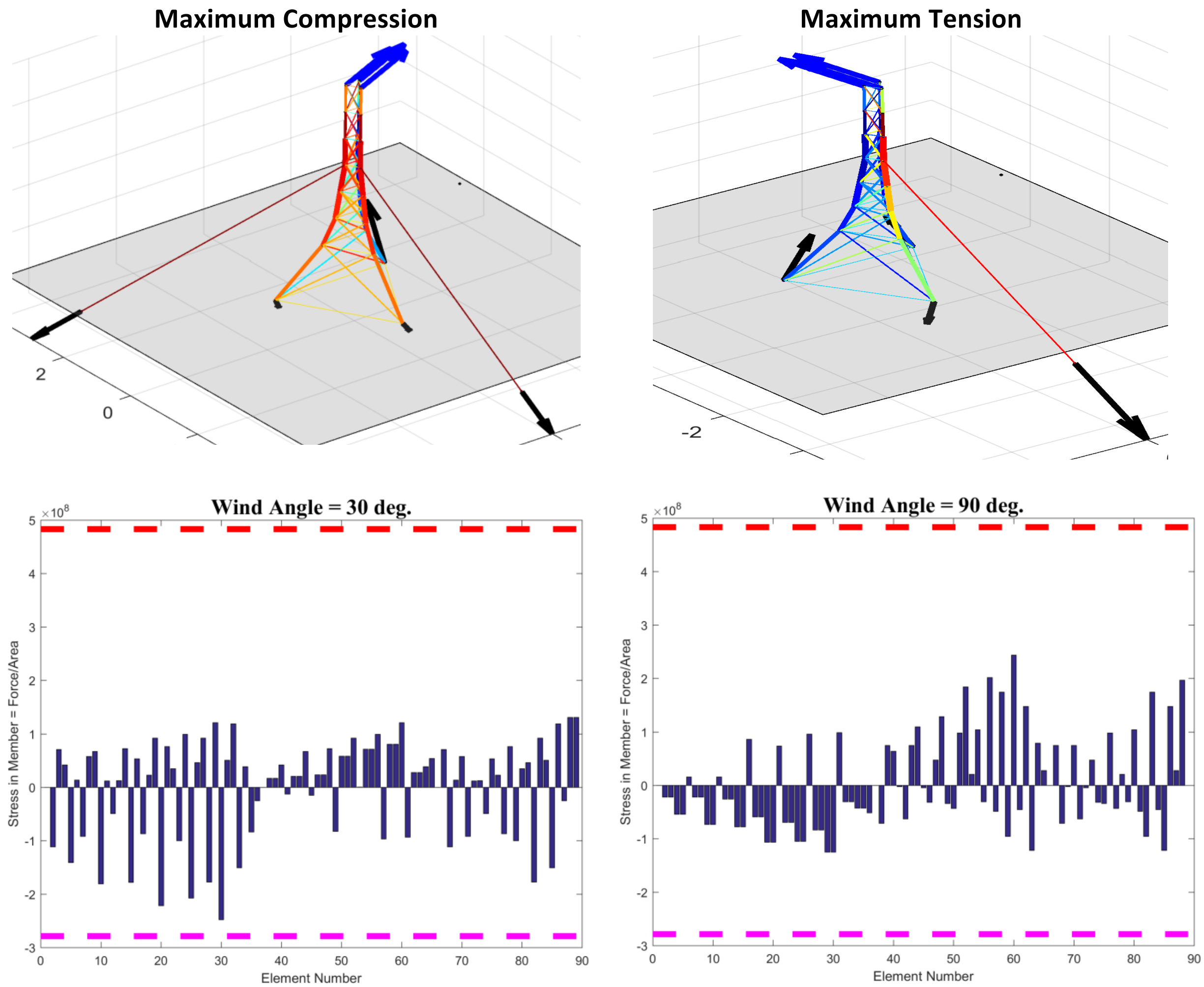


Figure T-12.3 - Maximum Loading Phases for the Ground Turbine

12.2 C-AWS System Loads Analysis

The C-AWS structural system comprises the kite system as well as the tether. This system has the following structural requirements:

- Tether material is able to survive 6000 N of lifting force
- Airbeams support wing root moments and axial force produced by the wing mounted turbines
- Kite must survive worst-case scenario landing
- The C-AWS system, including packaging, turbines, system airbeam structure, and anchoring system is below 36.3 kg

Each wing consists of four airbeams along the leading edge as seen in Figure T-11.9. The lift distribution across the wings is shown in Figure T-12.4. To verify the airbeam design, the top wing was modeled as a beam in three-point bending. The static performance analysis in Section 11.2 revealed the working stress on the wing. At wind speeds of 6 m/s, the kite experiences a lift of about 5500 N, or 1375 N/airbeam. The moment due to pressure, M_p, is calculated using Equation (9), where r is the radius of the beam and P_0 is the inflation pressure.

$$M_p = \frac{\pi}{16}\frac{P_0 r}{2} \tag{9}$$

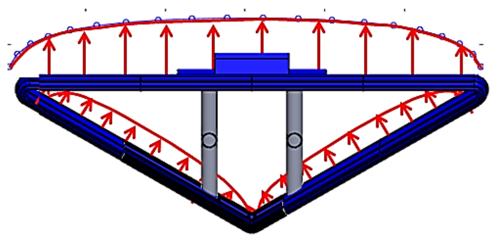


Figure T-12.4 - Lift Distribution Across C-AWS Wing Span

Because airbeams are fabric structures, the mode of failure will be wrinkling, which occurs when the bending stresses equal the stresses due to pressure. The wrinkling moment, M_w, defined as the moment at wrinkling, is calculated using Equation (10).

$$M_w = \frac{\left[\frac{M_p r}{I} + \frac{P_0 r}{2}\right] I}{r} \qquad (10)$$

$P_{wrinkle}$, the load which causes the beam to wrinkle, is found by dividing M_w by one-half of the wing span, 1.5 m. It was found that at 690 kPa, each airbeam is able to withstand up to 2348 N of lift, a total of 9400 N for the wing. The safety factor of 1.7 ensures that the wing can withstand a wide range of wind speeds.

Athena Vortex Lattice (AVL) software was used to verify the stability of the kite's flight. The analysis included pitching, rolling, yaw, and drifting stability. Each mode proved to be stable. An example of rolling mode is shown in Figure T-12.5. The analysis showed that the kite becomes stable in 0.2 s.

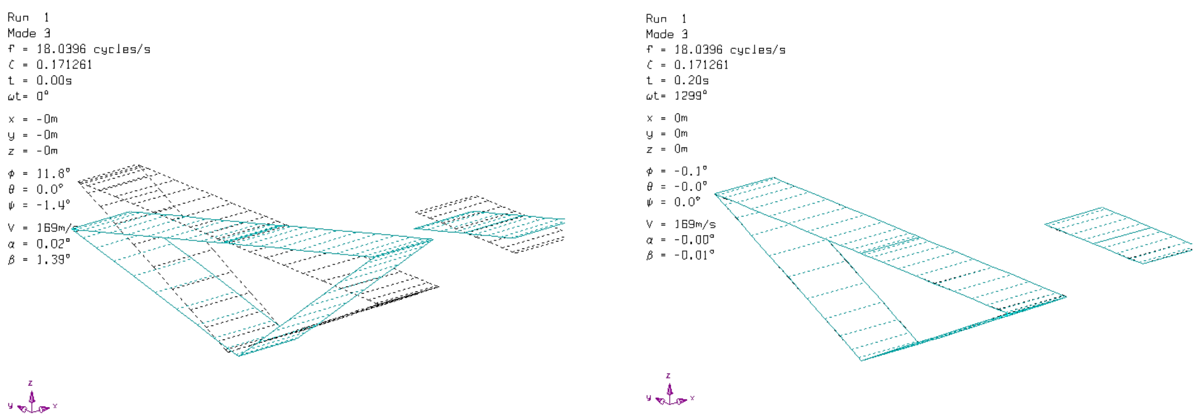


Figure T-12.5 - Rolling Stability Demonstrated in 0.2 seconds using AVL Software Analysis

The kite is secured to the ground by a winched conductive tether that is staked to the ground as described in Section 4.1. Six stakes will hold 6000 N of total force which provides a safety factor of 2.

There are a number of factors that must be considered when selecting a material for the tether such as: material weight, tensile strength, resilience to environmental stress, UV degradation, temperature, vibrations, and abrasion. Keeping all these characteristics in mind, the material selected is Ultra High Molecular Weight Polyethylene (UHMWPE) manufactured by Dyneema. The product is sold in 3, 8, or 12 strand braids; the more strands, the greater the properties but the higher the cost. From C-AWS load analysis, it was determined that there would be 6000 N of force acting on the tether. A UHMWPE tether with a cross-sectional area of 7 mm^2 has a fracture strength of 15 kN[xxv] which provides a safety factor of 2.5. Under cyclic loading, a UHMWPE tether withstood a thousand cycle load test rating of 90%.

12.3 Airborne and Ground Based Turbines Loads Analysis

The C-AWS and ground-based turbines must meet the following structural requirements:

- Blade structure supports axial loads and resulting root bending moment.

- Blade and hub system have high strength-to-weight ratio.
- Hub is able to withstand high blade centripetal force (C-AWS).
- Gearbox on the ground-based turbine is capable of transforming the low speed shaft rotational power to higher speed shaft power for electrical power generation.

The maximum axial force on the blades is determined in Section 11.1. A cantilever beam bending analysis was performed to guide the turbine blade structural design. For these calculations, the maximum expected per-blade axial force was applied as a point load to the blade tip with a safety factor of 4 applied. The maximum root bending moment is:

- 72 N-m for the C-AWS
- 1200 N-m for the ground-based turbine

Bending stress and blade tip deflection calculations were performed according to:

$$\sigma = \frac{Mc}{I} \quad (11) \qquad \delta = \frac{Pl^3}{3EI} \quad (12)$$

The area moment of inertia of the blade, *I*, was determined using the blade tip dimensions and blade profile. These calculations provided estimates for material thicknesses and confirmed that the blade designs for both systems are structurally sound.

The ground-turbine is a downwind, horizontal axis wind turbine (HAWT). Because a downwind HAWT uses the blades to align the turbine with the incoming wind, the system does not need a passive alignment tail or active yaw mechanism, thereby saving weight.

For all *WindHawk* systems, an active blade-pitching hub is prescribed. For the CWC wind tunnel prototype turbine, this blade pitching mechanism is adapted from an RC helicopter. The mechanism has a 0-to-45 degree pitch angle variation and is actuated by a single, nacelle-mounted servomotor. Connecting rods and ball links actuate blade pitching. Buckling analysis of the connecting rods reveals an allowable compressive load of exceeds the loads for tensile or compressive failure. For the prototype turbine, this hub assembly is robust. Cantilever beam-bending calculations reveal that a slightly modified hub can meet the operational requirements of the C-AWS turbines. The ground turbine, however, will require a hub twice the size to withstand the loads caused by 25 m/s wind speeds.

A thrust bearing supports the axial rotor hub force preventing premature failure of the radial shaft bearings. A thrust bearing capable of withstanding an axial load of 90.3 kN is used for the C-AWS resulting in a five year maintenance cycle. The ground turbine system uses a bearing rated at 45 kN of axial load resulting in a seven year lifecycle. Radial bearings for all other shafts were selected to have lifetimes exceeding the deployment lifetime of each respective system.

The ground turbine hub rotates much slower than the C-AWS. A BEMT analysis of the ground turbine system indicates a 12:1 ratio gearbox will allow the C-AWS generator to be used for the ground turbine system. An off-the-shelf planetary gearbox designed to support a maximum torque of 331 N-m is prescribed for the design.

13.0 Flight Control Systems

The final product for the aerial C-AWS must have control systems that reliably operate in an autonomous manner, control the desired flight trajectory, and dynamically adjust the turbine generation.

C-AWS is deployed by pitching the turbine blades to propeller mode for take-off. The generator is run as a motor to generate thrust. Details of the launch sequence are discussed in Sections 14.1 and 16.3. Once deployed, the C-AWS system flies in a crosswind figure-eight flight path. Sensors used to monitor the flight conditions include altitude, C-AWS velocity, shaft speed, and temperature to ensure safe system operation (see Section 14.1 for further details). The C-AWS is functionally similar to an aircraft and thus the kite motion is controlled by modulating (i) roll, (ii) yaw, and (iii) pitch moments. Figure T-13.1 depicts the control of each moment as well as the benefit. Velocity sensors are used to control the pitch angle of the kite using the elevator. Shaft speed sensors monitor each turbine independently and implement blade pitching for yaw control, power regulation and system safety. In an emergency, such as an abrupt loss of altitude, a parachute is automatically deployed to minimize damage to the kite and surroundings.

Roll is restricted using a y-shaped tether thus eliminating the need for ailerons. Yaw, normally controlled using a rudder, is controlled using turbine drag differential via the blade pitch mechanism. By pitching each turbine independently, drag can be decreased and/or increase, leading to a net moment that will yaw the C-AWS (see Figure T-13.1). Finally, kite pitch angle is controlled using a traditional elevator. Reducing the number of aerodynamic control surfaces by using existing components, the need for additional wiring and programming is reduced.

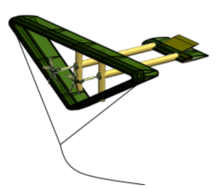
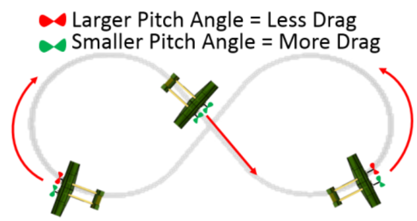
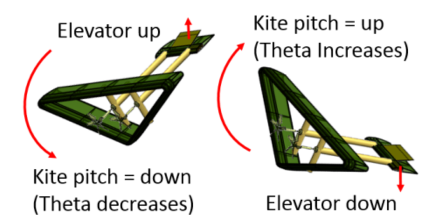
<table>
<tr><th></th><th>Roll Control</th><th>Yaw Control</th><th>Pitch Control</th></tr>
<tr><td>Diagram</td><td></td><td>
</td><td>
</td></tr>
<tr><td>Benefit</td><td>Constrained by y-tether</td><td>Uses existing turbine blade pitch control mechanism</td><td>Only one aerodynamic control surface is necessary</td></tr>
</table>

Figure T-13.1 - Control System for C-AWS Flight Motions

14.0 Electrical Analysis

An electrical systems analysis is performed for the C-AWS and ground-based turbines, and is described in sections 14.1 and 14.2, respectively. After establishing the needs for the C-AWS and ground systems, a wind tunnel prototype turbine is designed to incorporate the union of critical technical aspects and tested in order to validate these technical details for both systems.

14.1 C-AWS Electrical Analysis and Design

The C-AWS is designed with consideration given to the various operational environments. Its operation at high wind speeds requires the electrical components to handle higher voltages and currents. The AC voltage produced by the generator is rectified to DC before being transported to the ground through the conductive tether. The DC voltage is then converted back to AC and phase matched with the micro-grid.

The C-AWS electrical system must be able to provide power to the generators as a lift mechanism in order to reach cruising altitudes; once these altitudes are reached, the C-AWS electrical generation system must function as both power production as well as control of crosswind motion. The motors (i.e., generators) must consume 4 kW for the 36 kg kite to achieve flight. A 0.9 kg battery provides this power and will recharge during normal operation. Two servo motors will be used to independently control each turbine's pitch in order to achieve simultaneous control of crosswind motion and power output.

Many sensors will be used in conjunction with our control systems. A pitot tube with built in barometric and temperature sensors will be used to monitor wind speed and altitude. Hall sensors are used to measure shaft speed to ensure safe operating conditions.

The AC power produced by the generators will be rectified into a DC signal, which is then sent down the conductive aluminum cored tether

14.2 Ground System Electrical Analysis & Design

The ground system is mounted on a truss tower 5 m in height, an altitude at which wind speeds are significantly lower as compared to the C-AWS system. The system, therefore, is optimized for the following design objectives: to harness maximum power at low wind speeds; to maintain safe operation in conditions above the rated speed; and to perform these objectives in an automated fashion with minimal human interaction.

The ground-based system will maximize its power by the choice of an appropriate generator size (i.e., not re-appropriating the aerial generator, which is rated for significantly higher RPM and power), as well as an automated blade pitching system that achieves maximum RPMs at various wind speeds. Safe operating conditions above rated speed will be achieved by using blade pitch to maintain rated RPM or activating the braking system in case of emergency.

The ground system will be equipped with a similar voltage rectification system to the C-AWS, which provides an AC voltage phase matched to the micro-grid.

14.3 Electrical Analysis Wind Tunnel Competition Prototype

The electrical system for the wind tunnel prototype incorporates elements of both the C-AWS and ground-based systems. This electrical system aims to implement key functions, including pitch control, power distribution, and emergency shut-down procedures. The goals of prototype testing are to:

- Minimize the cut-in speed
- Regulate shaft rotational speed above a rated wind speed
- Withstand wind speeds up to 18 m/s
- Successfully shut down within ten seconds of receiving an emergency braking signal
- Minimize voltage drop for low power production conditions
- Requires no connection to an external power source

Generators with low KV ratings were researched to provide maximum voltage at lower RPM. The Turnigy SK3-6354 260 KV and Tiger U8 100 KV motors were chosen as candidates. As seen in Figure T-14.1, the Tiger U8 motor provides consistently higher voltages. This higher voltage allows our electrical components to initialize earlier and reduces power loss through the system.

The pitching mechanism must allow for blade angles of 10-30^{o}, and is achieved by the wind tunnel prototype. Figure T-14.2 shows) voltage output obtained at pitch angles ranging from 10 to 30°. A pitch angle of 10° provides maximum voltage output, while a 30° pitch angle allows for cut-in speeds < 4 m/s.

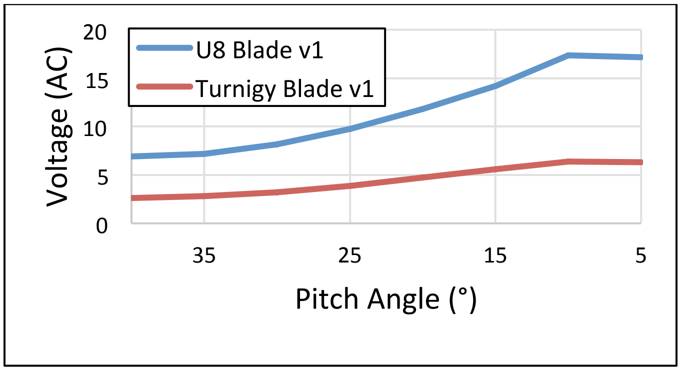


Figure T-14.1 - U8 vs Turnigy at Max Wind Speed

Referencing the schematic in Figure T-14.3, the power through our system can be traced. The generator provides a three-phase AC signal into a three-phase rectifier that produces a smooth DC signal. This DC output is fed into a microcontroller U5 (ATMega328p), which sends a pulse width modulation (PWM) signal into the MOSFET Q1 to control a team-designed boost converter. The output voltage of this converter is in the range of 5-50 V, depending on the input voltage and PWM going to the gate of Q1. A boost-buck converter (Phidgets 3053) then regulates this voltage to 5 V. This 5 V output powers the blade pitching via a servo-motor, the current sensor, and the second microcontroller U1 (Atmega328p). U1 functions as the brains of our turbine to control the pitch of the blades, measure the RPM via a hall sensor U6, and measure the load voltage and current used to calculate our power output. The mechanical latching relay U7 is sent a signal by microcontroller U1, which prevents rectifier power from entering the original microcontroller. When voltage output from the rectifier exceeds 4 V, the U1 microcontroller sends a signal to the mechanical relay U9. The boost converter is then electrically removed from the circuit to prevent excess voltage from damaging the electrical components. Although power from the generator is no longer being fed directly into microcontroller U5, it is still being powered by the switching boost regulator U8.

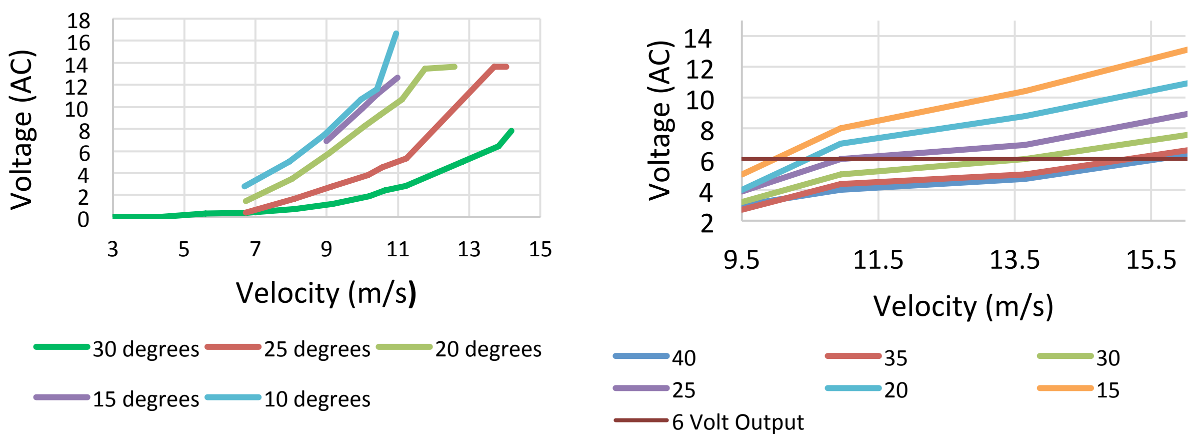


Figure T-14.2 – Voltage vs. Blade Pitch Angle for Wind Tunnel Prototype

The braking system activates when the shutdown button is pressed or the load is disconnected. It must also gently brake in order to protect the mechanical components. The solid state relay (SSR) (Phidgets 3053) controls the active braking by shorting the phases of the motor. During active braking, the blades are first pitched back to 30°, thereby passively slowing the generator while also ensuring the turbine is able to quickly resume rotation. A PWM of increasing duty cycle is sent from microcontroller U5 to the Phidgets SSR, which slows the turbine to below 10% of the rated speed while still providing sufficient electricity to power the electronics.

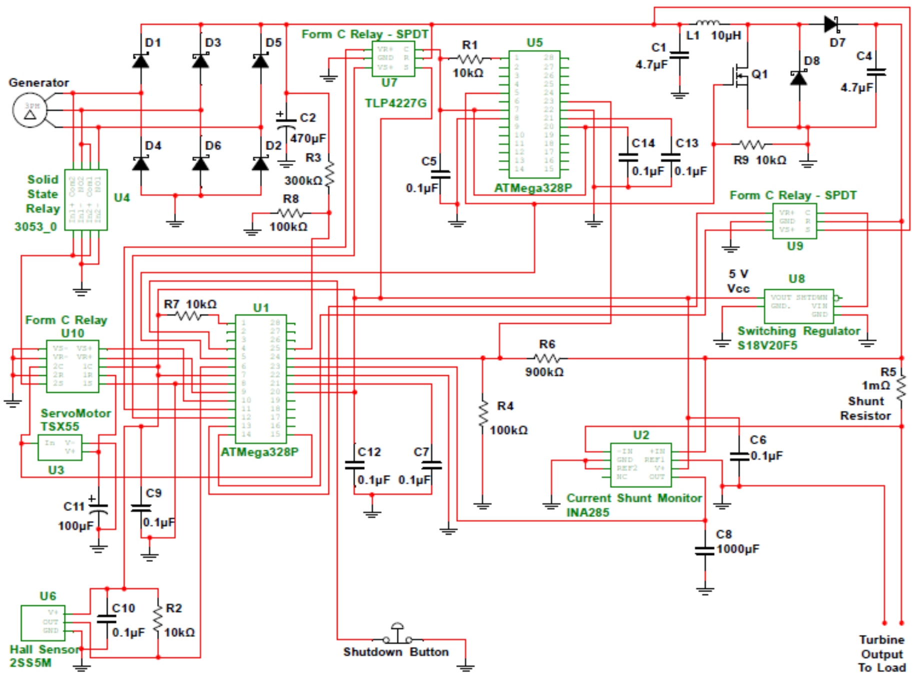


Figure T-14.3 - Wind Turbine Electrical Schematic

The electrical system must be able to measure the output power in order to verify the system is functioning properly. The power production is calculated by the equation

$$P = V * I \tag{13}$$

The microcontroller is capable of reading voltages up to 5 V. The output voltage from the turbine must then be stepped down to accurately measure power generated. Resistors R6 and R4 act as a voltage divider to step down the voltage into the microcontroller. The current is measured using the current monitor U2. After accounting for the voltage divider's effect on input voltage, the power is calculated and output to the load display.

14.4 Operational Modes

Operational modes of the electrical system include initialization under low wind conditions, maximization of power output at any wind speed, regulating power above the rated speed, and safe shut-down with minimal user interaction. These four operational modes or states will be implemented per Figure T-14.4.

The first state, S1, is to initialize the system. In this state, the pitch angle of the rotor blades will be positioned at an optimum angle of 30° to achieve the lowest possible cut-in speed. Turbine electronics will be initialized in this state. The pitching mechanism enables a default pitch angle of 30° for low cut-in without sacrificing maximum power output achieved at 10°.

The second state, S2, is to output the maximum power to the load. During this state of operation, the rotor blades' angle will be continuously updated as dictated by the changing wind speed. This pitch angle modulation ensures that maximum power will be delivered to the load for a given wind speed.

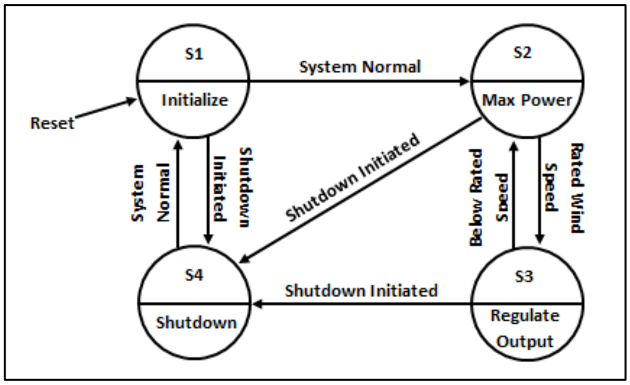


Figure T-14.4 - Control Systems State Diagram

In the third state, S3, the pitching mechanism is used to regulate the shaft speed and output power once the turbine has reached or exceeded its rated speed. The lifespan of the generator is increased by reducing the wear of using a mechanical brake.

The fourth state, S4, is to shut down the turbine and will be used for emergencies or to perform system maintenance. This operational mode is entered if a user pushes the turbine shutdown button, or if the load is electrically disconnected from the output of the turbine. Table T-14.1 lists these four states, their description, and the next possible state.

Table T-14.1 - Wind Turbine State Diagram Table

State	State Name	State Description	Next State	
			State	**Condition**
S1	Initialize	System initialization. Blade pitch is optimum for starting the turbine. Output voltage is boosted to power turbine electronics.	S2	System is normal
			S4	Shutdown initiated or system is not normal
S2	Max Power	System is below rated wind speed. Blade pitch is adjusted for maximum power output.	S3	Rated wind speed reached
			S4	Shutdown initiated
S3	Regulate Power	System is at or above rated wind speed. System will regulate shaft speed and output power.	S2	Wind speed decreased to below rated wind speed
			S4	Shutdown initiated
S4	Shutdown	Manual shutdown initiated, load is disconnected from turbine, wind speed is above safe operational speed, or a system fault exists. Braking system is activated.	S1	System is normal

14.5 Software Outline

The control objectives in the state diagram in Figure T-14.4 must be implemented in software written for a microcontroller. For the prototype, two ATMega328P microcontrollers were selected to provide necessary functionality along with the massive user support network that assisted the team in overcoming challenges associated with implementing of control. Two microcontrollers were needed to provide enough clock/timers to measure the various inputs of our system. The microcontrollers are programmed using an integrated development environment (IDE) named Atmel Studio 7.0, which is powered by Microsoft® Visual Studio.

The turbine control software interprets shaft speed, voltage at the output of the rectifier, and at the output turbine as input data. It also reads the current at the output and the status of the shutdown button to determine the appropriate operational mode. In order to guide the software development, the software flow chart shown in Figure **T-14.5** was created.

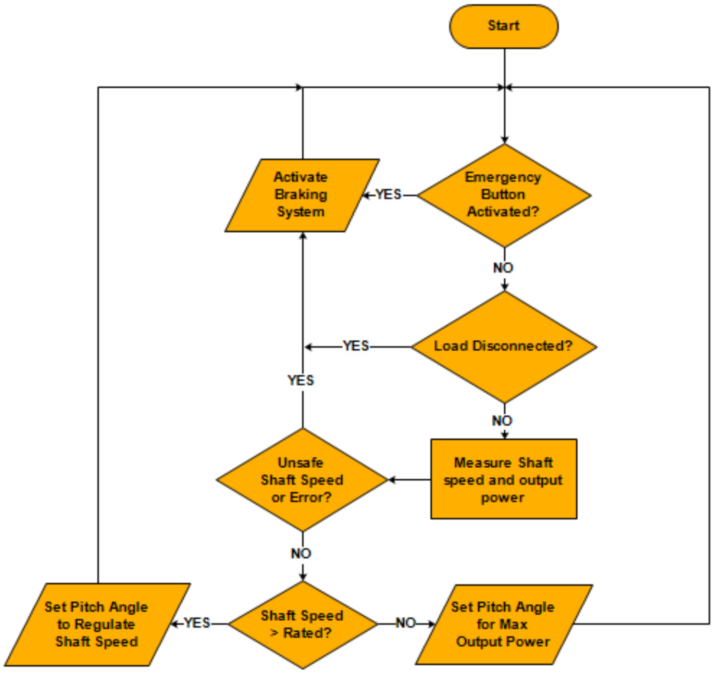


Figure T-14.5 - Software Flow Chart to Implement Control Systems State Diagram

The program first needs to determine if a system shutdown has been indicated. This need is accomplished by attaching the shutdown button to an input to the microcontroller, which then monitors the input for a change of state. Next, the system needs to determine if the load is disconnected; this need is achieved by measuring the current through a shunt resistor at the output of the turbine. If the flow of current stops, an open circuit exists between the turbine and the load, which means the load no longer connected to the output. If the current rapidly increases, then short circuit exists between the output of the turbine and its ground, which also means the load is no longer connected to the output. Once it is determined that the system is not in shutdown mode, pitch optimization is implemented based on the measured shaft speed. The shaft speed is measured to determine if the system has reached rated wind speed. If it has not reached rated speed, the pitch angle is set for max output power. If the shaft speed is above rated speed, the pitch is set to regulate shaft speed down to its rated value. The system then checks for shutdown conditions again and proceeds in a continuous loop.

15.0 Manufacturing Strategy and Facility Design

The primary technical objectives associated with the manufacture of the C-AWS and ground-based turbine systems are to ensure high manufacturing quality that meets customer standards, and to optimize the manufacturing efficiency to maintain a cost-effective process to support a viable business model. The manufacturing floor plan will consist of an efficient input-to-output layout, in which the raw materials and sub-components entering one side of the plant will flow through processes toward the final product exiting on the opposite side of the plant for shipment to the customer. Each intermediate station holds raw materials, machinery, and components required to produce subassemblies for each product. The majority of components such as the kite, gearbox, generator, and electrical components are purchased from suppliers while parts with a specialized design, such as the blades and truss tower, are fabricated in-house to ensure the quality of products produced meets MIL spec standards.

The proposed manufacturing layout of both the kite and ground turbines in shown in Figure T-15.1. The goal of this chart is to aid in the organization of the manufacturing process as materials and products flow through the facility. Some parts will need a sub-assembly line to manufacture the part first before going into the nacelle. Utilizing these processes, a 3600 square foot facility with 14 manufacturing employees yields two C-AWS units and six ground turbine units per day.

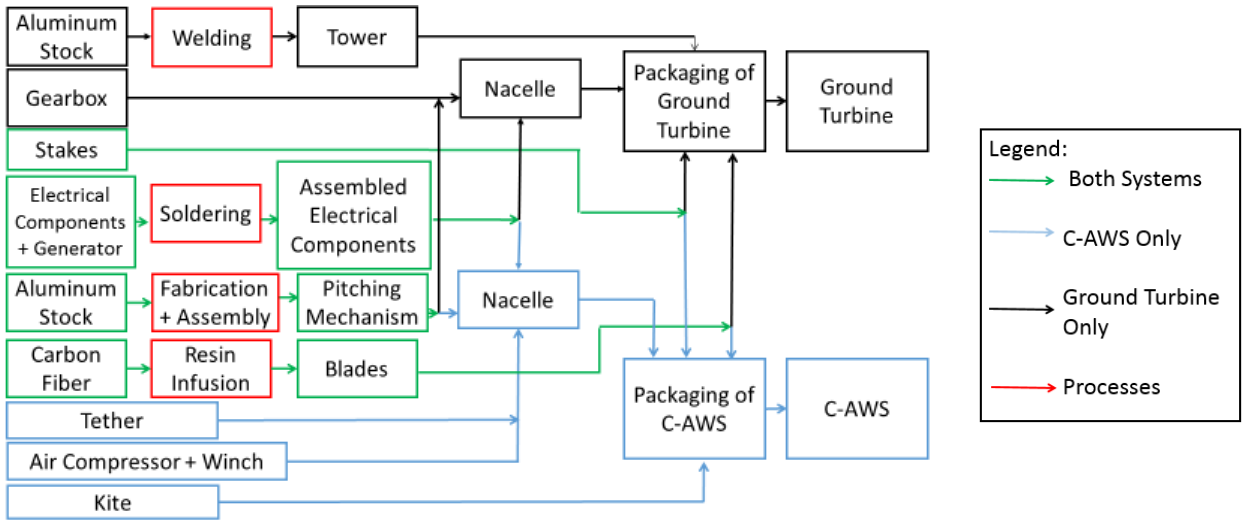


Figure T-15.1 - Flow Chart for Manufacturing Facility

16.0 Deployment Strategy

Deployment of *WindHawk Solutions*'s systems includes: system transportation, system siting, wind resource assessment (previously discussed), installation, maintenance, and reliability in operation.

16.1 Military Transportation of the WindHawk Solutions System

The U.S. military efficiently transports large amounts of equipment around the world. WindHawk Solutions will provide a package that is compatible with existing military shipping protocols. Both the ground-turbine and the C-AWS systems are designed specifically to pack into military standard Tricon® containers. The internal dimensions of a Tricon® 1 container are listed in Table T-16.1.

Table T-16.1 – Tricon Container Dimensions - Interior[1]

Type	Interior Length	Interior Width	Interior Height
Tricon1	2.299 m	1.882 m	2.262 m

The C-AWS is packed in two 1 m x 0.94 m x 1 m Pelican® containers. The layout for the C-AWS is specified in Figure T-16.1. Four C-AWS will fit to one Tricon® 1. For the C-AWS, the inflatable kite is packaged in a separate Pelican® container and the supporting materials (control system, generator, etc.) are packaged in a second similar container.

For the ground-based system Figure T-16.2. The truss tower is packaged in one Pelican® box, while the nacelle and other sub-systems are packaged in a second Pelican® box. This packing allows two ground-based turbines to be shipped in a single Tricon® 1, and each disassembled turbine satisfies a two-person lift. The Tricon® 1 container will have ~ 5.5 m^3 available for shipping other items with the turbines.

16.2 Siting the *WindHawk Solutions* Ground and Kite Systems

Traditional small-scale wind turbines are installed such that they are above any object in a 200 foot or 61 meter radius. Following this guideline, the ground systems will be installed around the perimeter of the base. The C-AWS will be installed 500 m away from the base so that in the case of a failure it is impossible for the kite to fall within a base. Ground conditions must be such that a stake can be driven in and hold the force on the guy wires.

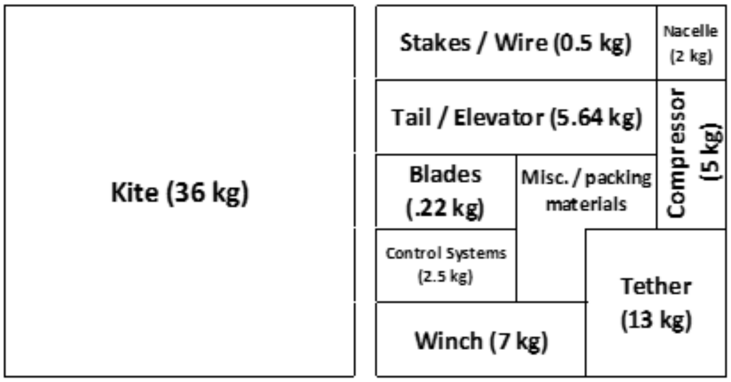


Figure T-16.1 - C-AWS Pelican® Package Layout

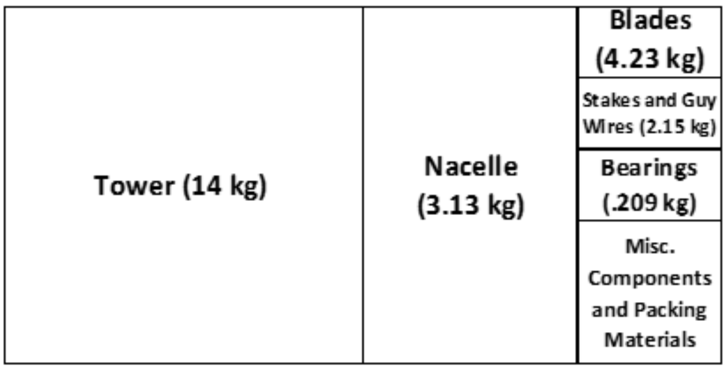


Figure T-16.2 - Ground Turbine Pelican® Package Layout

16.3 Deploying the WindHawk Solutions: C-AWS

The C-AWS is removed from the Pelican® case, the winch assembly is staked to the ground, and the kite is inflated. One stake can hold 1,216 N, so with an upwards force for 3000 N, six stakes will provide a safety factor of 2.4. The kite is carried out about 10 meters and the launch sequence is initiated. The turbines will then turn on in thrust mode and the winch will pull the tether in to create tension. As the kite catches wind it will continue to lift into the sky and pull the tether out with it.

When the kite reaches an altitude where it encounters steady wind velocities (between 200 and 300 m), it begins to fly as specified in Section 13.0. In the event of a failure during any stage of operation, a small emergency parachute will be released to reduce the kite speed and safely return the kite system to the ground.

When the kite needs to be taken out of service, it will first orient itself so that it faces upwind to depower the crossing kite. The winch will reel the tether in and pull the kite towards the ground. As the kite approaches the ground and the wind cannot support it, the turbines blades will be pitched to propeller mode to provide thrust as needed to lands the kite softly.

16.4 Deploying the WindHawk Solutions: Ground Turbine

The ground turbine is removed from the Pelican® case and the truss tower is erected and secured by the guy wires and stakes. Before the last truss section is placed on top, the nacelle and blades are mounted to it. Finally, the last truss section is hoisted to the top with the guy wires. The ground system is then connected to the micro-grid and is ready to produce power.

17.0 Maintenance Strategy

Maintenance is a concern for wind turbines operating in austere environments. The *WindHawk* systems are designed around core components which are easily interchanged. If a component in a nacelle fails, the entire nacelle can be removed and replaced with spare parts minimizing system downtime. On-site maintenance and repair is limited to simple components and sub-assemblies. Keyed assemblies will minimize the training required for service and repair. Captive hardware, latches, and snap fits will also reduce the risk of part misplacement and minimize the number of tools required to service the system. Selected subassemblies, such as the swashplate and blade grip internals will not be field serviceable. This will enable permanent securing of select small hardware through the use of soldering, welding and adhesives. This permanently secured hardware will reduce the number of components to be inspected as well as downtime required to perform inspections.

The kite airbeam pressure will need to be monitored and adjusted every two weeks or after. These re-inflation service intervals will be ideal opportunities to perform system checks. Pitch control, generator performance, and kite control surfaces will need to be inspected before each flight for proper function. The nacelle will be swapped and parts repaired if any of the aforementioned systems fail inspection, the turbine shaft does not rotate, or bearings begin to show wear.

17.1 Reliability and Risk Management

The system is of considerable weight and travels at velocities that could injure those within its operating perimeter. Any number of small component failures could result in the compromise of the system's air-worthiness and result in the loss of kite control. The system modestly increases risks to soldiers who are near the turbines; however, this risk is offset by the already known risks of driving a tanker truck through contested territory in conflict zones. To minimize the risks from the turbine system failure, hardware must remain torqued, bearings must meet required loads and RPM's, and electrical systems must have fail-safes. Under the following scenarios, the system will perform an emergency shut-down procedure and deploy an emergency parachute to slow its descent:

- Complete turbine failure
- Control surface failure
- Tether failure, whether electrical or mechanical
- Kite below minimum floor altitude
- Excessive time spent in free fall signifying a possible control systems failure

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2.1 A-1: 3F Letter of Support

Federal-Fabrics-Fibers

45 West Adams Street, Lowell MA 01851
Phone (978)441-3037 | Fax (978)441-3862

April 25nd 2016

Dear Mr. Christian Bain:

I would like to express my support for the utilization of our Airbeam technology in the UMass Lowell WindHawk Solutions design submission for the Department of Energy-sponsored 2016 Collegiate Wind Competition.

Since 1991, Federal-Fabrics-Fibers, Inc. (3F) has been at the global forefront of advanced textile applications. Our patented 2&3D Shaped Woven technology (AirBeam) can be seen in a wide variety of military, federal, and commercial applications around the world. 3F is constantly exploring the capabilities of our Airbeam technology and developing new and innovative solutions for mobile structure applications that require rapid deployment.

3F hosted the WindHawk team for an extensive tour of our facility, followed by an information session with our Technical Director, Fred Geurts. We have also provided the team with a sample of our Airbeam technology for testing and research documents for reference. We are excited to have the opportunity to work with WindHawk Solutions and assist in the development of their Aerial Wind System, and we believe our technology is an excellent fit for their needs.

We look forward to continuing our collaboration with WindHawk Solutions as your team moves forward in your development process.

Sincerely,

Fred W. Geurts, Ph. D.
Technical Director,
Federal-Fabrics-Fibers, Inc.,

www.FederalFabrics.com