University of Colorado Boulder
2021 DOE Collegiate Wind Competition Team

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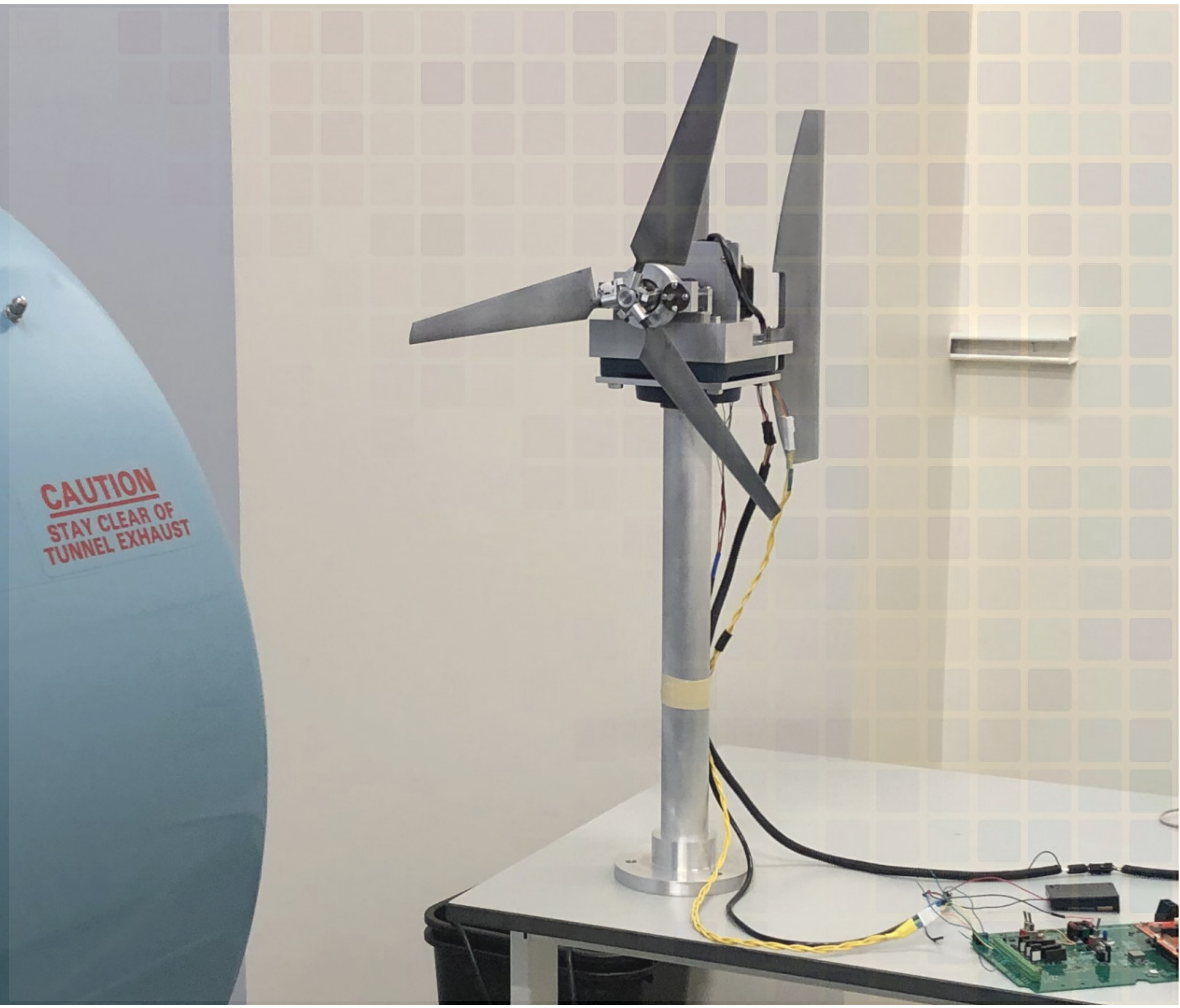


What is the Collegiate Wind Competition?

*"As yet, the **wind** is an **untamed**, and **unharnessed** force; and quite possibly one of the **greatest discoveries** hereafter to be made, will be the taming, and harnessing of the wind."*

-Abraham Lincoln (1844)

The Department of Energy (DOE) anticipates nearly 20-30 percent of the US's energy supply coming from wind energy in the next 10-15 years. The Collegiate Wind Competition (CWC) aims to prepare for this green energy initiative by preparing students across the country to develop **interdisciplinary** skills across the **wind industry**. As CU's first "learn-along" team in the CWC, the team will complete competition challenges, but does not receive funding for the competition or compete for placement. The team aims to use this opportunity to improve opportunities for student and faculty involvement in renewable energy and **pave a path for future success** in the competition.

The CWC is split up into three competitions that represent a different area of the wind industry. The **Turbine Prototype Competition** requires students to build a small wind turbine that can catch wind and complete tasks that reflect key metrics for a successful turbine. The **Project Development Competition** includes developing a wind farm in the western South Dakota region that utilizes adequate wind resources to develop energy while considering community, environmental, and financial factors. The **Connection Creation Competition** aims to get the local community excited about learning and potentially being involved in wind energy while developing networking opportunities with industry professionals.

A Three Part Competition

Turbine Prototype Contest

The team must design and build an effective mechanical, electrical, and aerodynamic wind turbine and load design that is safe and reliable for testing in an on-site wind tunnel. The scale turbine will be evaluated on its start-up wind speed, stability in varying wind conditions, electrical design, and safety measures.

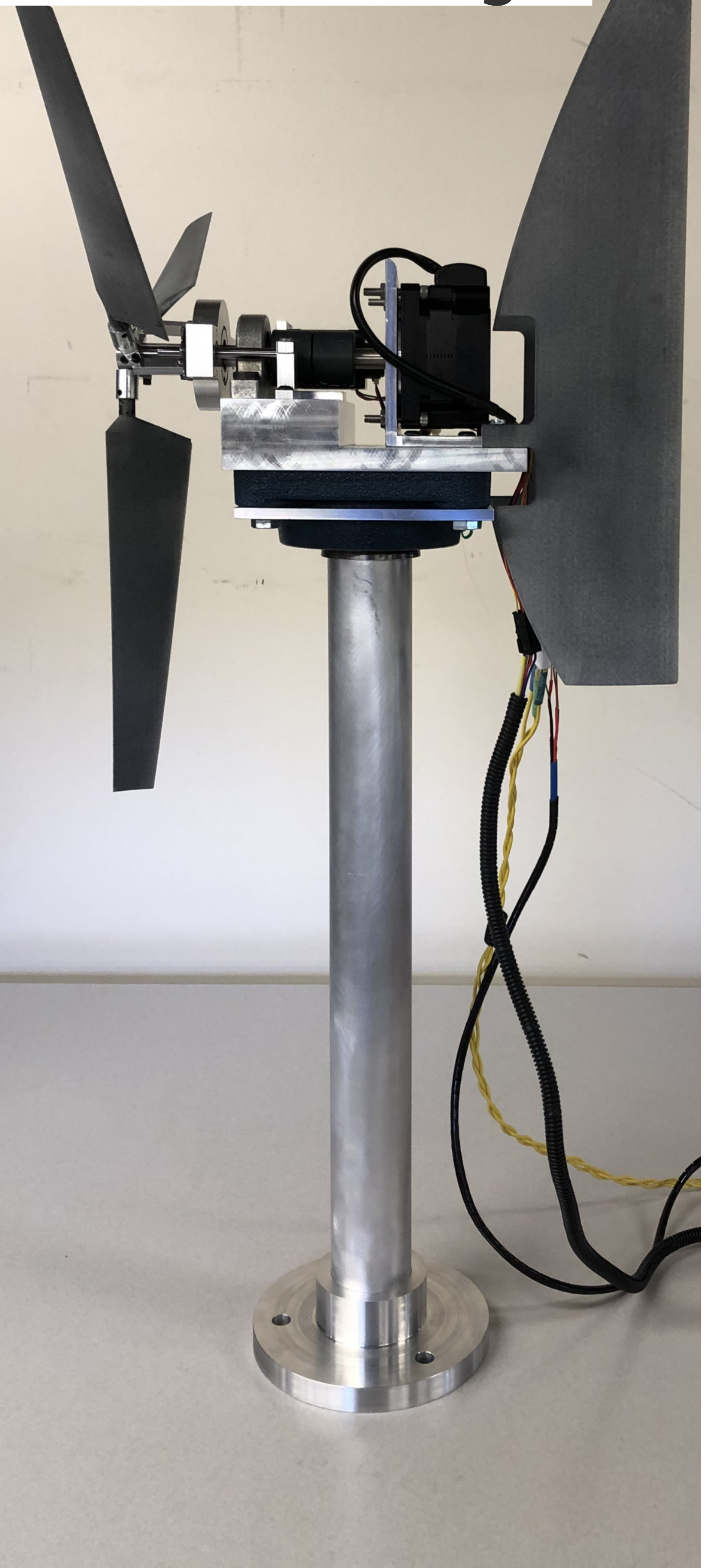
Project Development Contest

The Project Development contest is a year-long effort to analyze key aspects of wind farm siting and development activities. This includes but is not limited to assessment of wind resource data, performance estimates, transmission line access, environmental effects, community concerns, permitting requirements, turbine technology, modeling and optimization, and financial analysis.

Connection Creation Contest

The Connection Creation Contest required teams to connect with industry representatives in the wind energy field to build a professional network and resources for the competition tasks. Furthermore, the contest encouraged teams to inspire the local community to engage with renewable energy through social media, press releases and educational programs with K-12 students to inspire the next generation of renewable energy professionals.

1. Scale Turbine Design



A **scale turbine** was **designed** to fulfill competition performance requirements and **reliably capture the wind** to develop a steady power curve.

Physical design constraints for the competition wind tunnel drove the turbine design. The rotor and non rotor turbine parts had to be contained in a 45 by 45 cm cube and the 15 cm tower could only contain non rotor parts.

Electrical requirements required the output voltage to be direct current (DC) and maintained below 48 volts at all times. Furthermore, the turbine plate had to be connected to earth ground in order to prevent over voltage of the data acquisition systems. The team then identified the following performance goals:

Turbine Performance Goals

- Positive power production and mechanical fidelity in wind speeds of 5-13 m/s
- Electrical system to regulate power production and obtain a steady power curve at wind speeds 5-11 m/s
- Ability to align rotor with wind direction with a stable passive change in yaw angle
- Implementation of an emergency full stop functionality
- Active pitch controller that regulates the load and power of the turbine

Blade Design

The **design of the blades** should optimize the airfoil to produce power within the **5-13m/s range of wind speeds** and be strong enough to withstand the lateral loads from the wind.

The **thrust** and **lift** of the blades given a specific angle of attack will influence the curvature and smoothness of the **power curve**. With this in mind the team used an open source software, **QBlade**, to simulate and optimize the geometry of the blades. An important metric when optimizing the blades is the coefficient of performance, cp. This parameter is the ratio between the power of the turbine and the power of the wind.

Additionally, maximizing this value with different blade geometries and airfoil designs helped the team lower the smallest wind speed needed to generate enough torque to move the generator. For reference. the **theoretical maximum of this parameter is 59%** while our simulated blades were able to achieve a cp of close to **40%**. The design of the blades was iterated through with several different airfoil designs until we ended up using two different airfoils for the tip and the root of the blade.

Pitching System

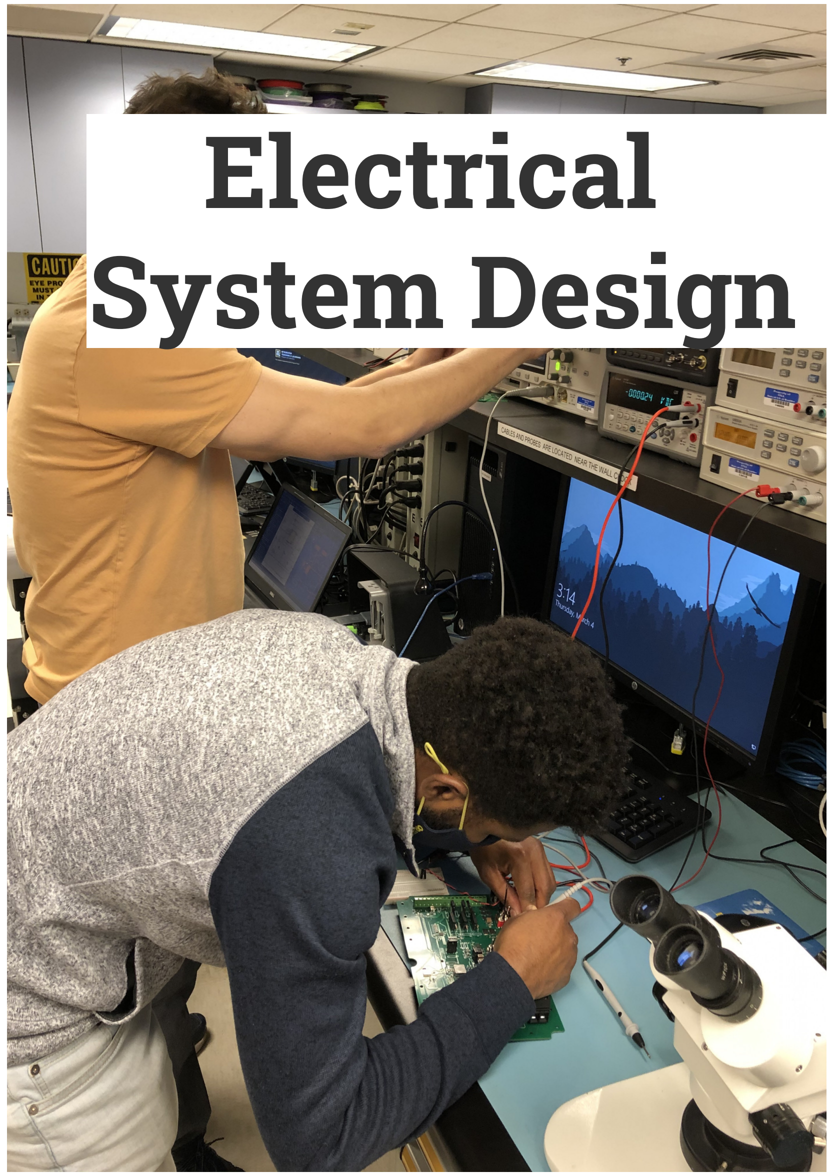
An active pitch system is critical to the performance of the turbine, allowing the autonomous alteration of the **angle of attack of each blade** to control the lift of the blade and resulting rotor speed in different wind conditions, **maximizing power generation**.

The rotor pitches the blades a total of **45 degrees**, which is enough to cover all of the necessary blade pitch angles for optimal performance and emergency stop of the turbine. The system was inspired by a helicopter **rotor swashplate system** in which the rotor converts linear motion produced from a stepper motor into rotational motion delivered to the turbine blades.

The system uses a **thrust bearing** mounted swashplate where push rods connect the swashplate to the blades, as the swashplate is pushed in and out, the rods push the sides of the blades, which changes the **angle of attack** of the blades.

The pitching system is controlled by a PI controller implemented in the turbine electronics to maintain steady power production in all wind conditions.

Electrical System Design



The goal of the electrical system is to convert the **mechanical energy** produced by the turbine's blades into **electrical energy** and **regulate** power production.

The first aspect of the electrical design centered around the generator, the key component for converting mechanical rotational energy to electrical energy. A decision was made early on to purchase an off-the-shelf **Brushless DC (BLDC) motor** because the team had limited resources to design and build a custom generator. Initial calculations determined the range of voltages that the BLDC could output based on the RPMs that we expected from the turbine's blades. This guided the **power electronics** that could be design to process the power produced by the generator.

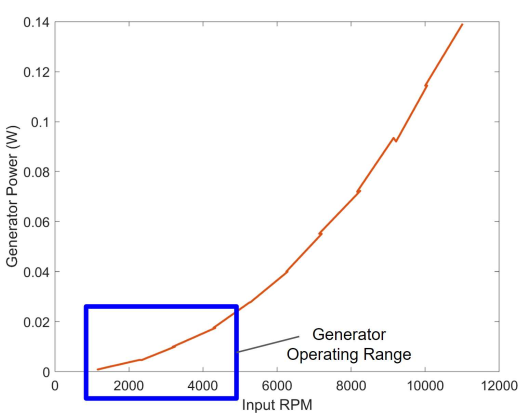
A rectifier circuit was designed to convert the 3-phase output from the BLDC motor to a DC signal. A **Single-Ended Primary-Inductor Converter (SEPIC)**--which has the ability to buck or boost voltages-- was designed to obtain a steady DC voltage of **14V** from a given range of input voltages. Two additional buck converters were designed, one to further reduce the voltage down to 5V to drive the pitching stepper motor and another to reduce it down to 3.3V to power the TI microcontroller unit (MCU). A stepper motor driver circuit was integrated into the PCB to drive the stepper motor, responsible for the pitching mechanism.

As part of the safety requirements, the turbine is required to shut down either on command at the push of a button or when the load is electrically disconnected from the turbine. With this in mind, the team designed a load circuit that would charge a 12V lead-acid battery and also perform the necessary aspects of the shutdown sequence. In order to protect the battery from overcharging, a simple trickle charge circuit was implemented as is commonly done with car batteries. The turbine was required to restart from shutdown with no intervention, so the load circuit was designed to allow current to flow in the opposite direction from the load side to the turbine side. This enables the MCU, stepper motor, and stepper motor driver to be powered so that the pitching mechanism could be engaged to allow the blades to rotate once again from their resting state.

Electrical Testing

The electrical system was tested for **electrical integrity** and **generator integration**

The turbine **generator** is an off-the-shelf motor used in reverse to produce power. To characterize the component as a generator, the team acquired two motors such that one could be driven with a **power supply and motor driver**, and the other could be attached with a shaft coupling and produce power from the motor-provided torque.



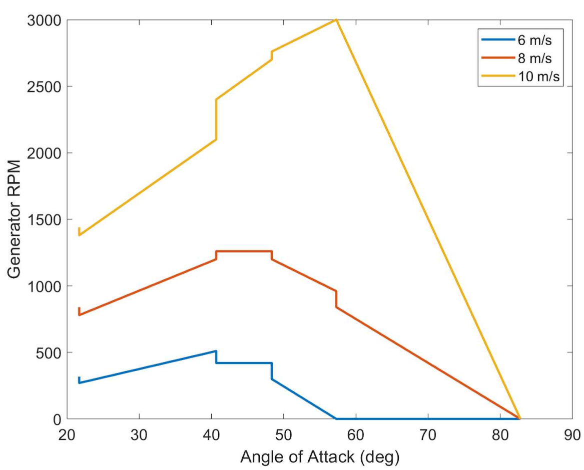
The results from this test are shown in the figure. This test was critical for defining the voltage and power outputs could be expected from the generator over a range of RPMs.

Further tests verified the performance and electrical integrity of the custom **printed circuit board (PCB)** for the turbine electronics. The PCB required placement of over **90 electrical components**, either by hand or with a pick and place machine. After placement was complete, the team used a multimeter to ensure the continuity of each component to ensure that the board was assembled correctly before powering it on for future system tests.

Wind Tunnel Testing

The **fully assembled turbine** was tested for functionality and safety over a key range of wind conditions using the outflow of an Eiffel Configuration Wind tunnel.

Facility limitations due to COVID meant the team couldn't access the competition wind tunnel, instead requiring the creative use of a smaller wind tunnel from the CU aerospace department for turbine performance testing. Although the outflow of the smaller tunnel was more turbulent and less controllable, the team used a handheld anemometer to determine the range and variability of possible wind speeds. The team was limited to test at 5-10 m/s instead of the competition specified <5-13 m/s.



Primary data was collected to model the blade performance and pitch mechanism for the design of the active pitch control system as seen in the above graph.

After subassembly testing verified functionality and critical performance issues were corrected, the tunnel test was the first time the mechanical turbine and the electrical system were integrated together. To test the satisfaction of the competition design goals, key functionality were tested as detailed in the following table:

Requirement	Results
Positive power production and mechanical fidelity in wind speeds of 5-13 m/s	At wind tunnel speeds of 5-10 m/s, turbine produced consistent positive power and showed no signs of mechanical failure
Ability to align rotor with wind direction with a stable passive change in yaw angle	Turbine aligned with airflow with no instability at all wind speeds
Implementation of an emergency full stop functionality	Fully pitched blades and regenerative braking were capable of bringing the turbine to a complete stop in all wind conditions

2. Wind Farm Project Development

The second part of the Collegiate Wind Competition is the Project Development Contest, a year-long effort to investigate key aspects of wind farm siting and project development activities. The team developed the company **Chinook Wind Energy** to develop a **100-MW wind farm** in the western South Dakota area and submit a site plan and cost of energy analysis for the wind farm.

Chinook identified **climate justice** and **community acceptance** as pillars of this wind farm development, recognizing the critical opportunity to support climate justice by providing clean energy to lower income communities in South Dakota. These tenants were supplemented with goals of 20-yr fiscal viability, wind resource potential, environmental impact, and infrastructure requirements to propose a sustainable, responsible wind farm.

The project development was split into three key phases: **Research and Permitting**, to determine relevant federal, state, and local regulations and procedures, **Alternatives Analysis and Site Identification**, to investigate tradeoffs between potential sites and identify promising sites for further analysis, and **Wind Farm Analysis and Optimization,** to accurately asses the energy capture potential, environmental factors, and financial viability of the site.

The Project Development Process

Research and Permitting The wind farm required proper documentation, analysis, and permitting. Permitting is a necessity on the federal, state, and local levels, including but not limited to acquiring a permit satisfying the Endangered Species Act, the National Environmental Protection Act (NEPA), having a plan for storm-water discharge, construction permits from the Public Utility Commission, and the performance of cultural assessments of the area.

Alternatives Analysis and Site Identification The team utilized a tradeoff analysis matrix that assessed sites based on the following key factors weighted for importance:

- **Physical** Wind resource, topography, land cover
- **Infrastructure** Access to power transmission lines, roads
- **Environment** Proximity to water resources, and critical habitats
- **Community** Proximity to towns and households, impact of noise and shadow flicker

An initial assessment of the financial viability of the wind farm was performed with NREL's System Advisory Models (SAM) using a standard turbine, coordinates, and transmission line access as inputs.

Wind Farm Modeling, Analysis and Optimization

GIS tools enabled the **optimization** of wind turbine layout to reflect wind resource, infrastructure, and environmental and community factors.

After performing an alternatives analysis and primary energy capture and financial models, Chinook identified the **Rosebud Indian Reservation** located in Todd county as the preferred site for the 100-MW wind farm project.

The Rosebud site was modeled in **OpenWind**, an industry standard wind farm analysis and optimization tool using exclusively open-source GIS and wind resource data. Key resource, infrastructure and environmental factors were identified and relevant datasets were included in the analysis.

The wind farm layout was co-optimized for the tradeoffs between energy capture and environmental factors such as noise and shadow flicker at surrounding buildings. Limits on wind turbine placement were **driven by environmental factors** including proximity to buildings, water resources, and critical habitats, as well as maximum hill slope and infrastructure accessibility. The wind turbine layout was optimized to minimize wake interactions from surrounding turbines and **maximize energy capture**, resulting in a 12% improvement in net energy capture from primary designs.

Introducing the 100-MW Rosebud Wind Farm

The final proposal for the 100-MW Rosebud Wind Farm is driven by performance modeling, environmental impact assessments, and a robust financial analysis and justification for the project. A virtual power purchase agreement (vPPA) was identified as the ideal financial model for the wind farm. The net present value (NPV) was shown to be sufficient over a 20-year lifespan and General Motors' was selected as the best partner for the PPA and the receiver of the energy produced for their effort to be net zero in carbon emissions.

Rosebud Wind Farm Characteristics

Chinook will be installing 20 Gamesa 4.5MW turbines to produce 451,097 MWh/y. A capacity factor of 51.03% makes us one of the most efficient wind farms in South Dakota.

The wind farm will connect to a 345kV transmission line owned by Lacreek Electric Association. The farm is located within 1 mile of the transmission line, making interconnection easy and keeping costs down.

Chinook and General Motors have an agreed upon a vPPA price of $.055/kWh of production. Chinook plans to start the project before 2022 to secure the production tax credit (PTC) of 0.18 $/kWh for the first 10 years of the project. These factors combine for a 12.64% rate of return by the end of the project.

3. Community Outreach

The Connection Creation Contest aims to **connect** passionate students with faculty, and industry representatives involved in wind energy and encourage teams to **inspire** the local community to engage with **renewable energy**.

Outreach As CU's first CWC competition team, the team aimed to share it's story and opportunities to engage with wind energy with the larger community through social media (@cuwindteam) and news features with the CU Engineering media team and the Colorado Engineering Magazine. These stories documented the competition process in a remote setting and emphasized the resilience, passion, and creativity of the team to blaze a path for CU Wind Energy in the coming years

Professional Development The team built a network of industry professionals within the Research and Development, Wind Project Development, and Turbine Design sectors.

These connections provided insight into their careers, provided technical mentorship for the competition, and improved student's job prospects in the industry.

K-12 Engagement To educate and inspire the future generation of renewable energy engineers, the CU Wind Team partnered with KidWind, a national wind energy education organization, to present a state-wide virtual turbine design competition and develop a hybrid hands-on lesson plan for 4-6 grade students as an introduction to wind energy and the engineering design process. Over 120 students are designing turbines constructed from household materials for the 2021 competition.

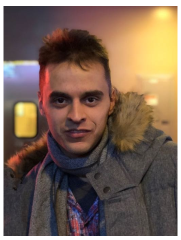
Meet the Team

Abdoul Bah - Logistics Manager

Abdoul Bah is a senior at University of Colorado Boulder where he is finishing his Electrical Engineering degree. As one of only two electrical engineers on the team, Abdoul contributed mostly on the design of the electrical systems, PCB assembly, and testing. Upon graduation, he hopes to start a career in a field related to his Electrical Engineering background and travel the world to help others.

Ioana Dumitru - CAD Engineer

Ioana Dumitru is a senior at University of Colorado Boulder where she is finishing her B.S in Mechanical Engineering. Ioana was responsible for the design and optimization of the turbine blades along with the management of the CAD and manufacturing drawings. In addition, she contributed to research with the wind farm and development of the KidWind outreach. Ioana will be performing research at the Los Alamos National Laboratory upon graduation.

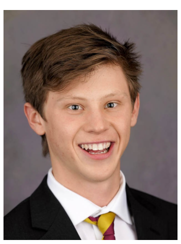


David Imola - Electrical Computer Modeling Engineer

David Imola is a senior at University of Colorado Boulder where he is finishing his Electrical and Computer Engineering degree. As one of only two electrical engineers on the team, David contributed on the electrical systems design, PCB assembly, electrical testing, and control system design. Upon graduation, he will be joining Everactive as an Embedded Linux Developer Intern.

Austin Kim - Project Manager

Austin Kim is a senior at University of Colorado Boulder where he is finishing his Mechanical Engineering degree. Austin is also finishing his Leadership Studies minor and Engineering Management certificate. Austin was responsible for being the main point of contact to project stakeholders and contributed to the wind farm and KidWind lesson plan. Upon graduation, Austin aims to find a career utilizing his mechanical engineering and leadership disciplines.



Charlie McClung - Financial Manager

Charlie McClung is a senior at University of Colorado Boulder where he is finishing his B.S. in Mechanical Engineering and minor in Business Administration. He was responsible for the financial planning and site selection of the wind farm and contributed to the design of the wind turbine. Upon graduation, Charlie will be doing geophysical engineering for Magee Geophysical Services.

James Rizkallah - Test Engineer

James Rizkallah is a senior at University of Colorado Boulder where he is finishing his Mechanical Engineering degree. James contributed to the design of the turbine's tower support system, systems integration, test planning, and wind tunnel coordination. He skis and climbs in his free time and will be working on satellite systems at his internship this summer.

Xander Sugarman - Manufacturing Engineer

Xander Sugarman is a senior at University of Colorado Boulder where he is finishing his Mechanical Engineering degree. Xander was responsible for CAD design, manufacturing drawings and processes, and contributed to testing and assembly. Upon the conclusion of the semester, Xander will be working at SRAM performing suspension testing.

Emily Zuetell - Systems Engineer

Emily Zuetell is a senior at University of Colorado Boulder where she is finishing her B.S in Mechanical Engineering and Applied Math with a minor in Computer Science. Emily was responsible for wind farm analysis and optimization, turbine testing and controls, and KidWind outreach. Upon graduation, Emily will be pursuing a Ph.D. at Carnegie Mellon University in Engineering and Public Policy

Acknowledgements

The team would like to thank our director, Roark Lanning, for his support, guidance, and expertise, throughout the project. The team is also grateful for the Senior Design staff, Dr. Julie Steinbrenner and Dr. Daria Kotys-Schwartz for their guidance and support.

Wind Turbine Prototype

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