GAIA Competition Problem Statement 2023-24

V 1.0 - November 20, 2023

Electricity Access in Rural Peru

This problem statement is pending final review from WindAid, but is being released now to allow competitors to get started. If any specifications change, a new version will be released ASAP and competitors will be notified. Thanks for your patience.

Please direct questions to gaiacompetition@gmail.com.

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1. Problem Context

The seventh United Nations Sustainable Development Goal (UN SDG 7) calls for affordable, reliable, sustainable and modern energy for all by 2030. As of 2023, just over **15% of rural households in Peru lack electricity access**, leaving this segment of the population without power for lighting or device charging [bnamericas].

The fraction of rural Peruvians without electricity access has decreased from 68% in 2004 [World Bank]. The progress in the last two decades has been largely driven by the World Bank's 2005-2017 Rural Electrification Project (REP) and the Peruvian government's 2013-2022 National Rural Electrification Plan (PNER). Both programs directed hundreds of millions of dollars toward rural electricity systems, primarily off-grid solar photovoltaic panels to power indoor lighting. For more information on rural electrification in Peru, including the economic and social benefits of electricity access, lessons learned from prior program implementation, and statistics on electricity end use and generator repair, teams are encouraged to consult the REP Project Performance Assessment Report [World Bank].

The remaining 15% of un-electrified Peru households are the most difficult to reach, and currently get their energy from fuelwood, diesel, or kerosene. Electrifying these households is expected to increase quality of life and economic prosperity. Due to the remoteness of rural areas in Peru and the difficulty of setting up grid transmission lines throughout the diverse geography, **off-grid/microgrid solutions are more appealing than national grid connection** as an electrification strategy for these remaining unelectrified homes. While the Peruvian government has focused on solar photovoltaic and hydro power, strong sources of wind exist in both the coastal and mountainous regions of Peru. This makes Small Wind Turbines (SWTs) an appealing possibility.

SWTs used for rural electrification in developing countries should be manufactured and maintained locally to decrease cost and improve lifetime and user acceptance. These are often referred to as **LMSWTs (locally manufactured small wind turbines)**.

2. WindAid Program

The WindAid Institute is a non-governmental organization (NGO) that installs wind turbines in remote communities around northern Peru not connected to the national grid. They function both as a service organization, installing and maintaining wind turbines in rural communities at no charge, and as an educational organization, running trips for students to gain hands-on experience manufacturing and installing the turbines.

WindAid uses a LMSWT design described in section 3. **GAIA teams are challenged to improve aspects of the WindAid turbine design** (see section 4) and will receive the opportunity to manufacture the best design on a **GAIA-funded WindAid student trip to Peru**.

A total of 8 students from GAIA teams will be selected to attend WindAid's Summer 2024 trip. The trip application process will occur in November-December 2023. GAIA will provide the funds for everything included in the WindAid trip, which includes lodging, meals, local travel within Peru, and wind turbine build materials. Teams will be financially responsible for their flight to and from Peru. The 2024 trip is expected to run for **four weeks in the summer**, with the exact dates to be chosen based on students' academic schedules and WindAid's availability.

A competition in late April will determine which turbine design will be built in Peru. For more information on the scoring and structure of the competition, see the Competition Rules. On the Peru trip, students will build the winning design at the WindAid development and testing facility, and install it at the partner community / rural village. The present document, the Problem Statement, describes the technical requirements for designs.

3. WindAid Turbine Design

Here are some documents from WindAid describing their current turbine design:

1. Blade outline / Blade
2. Generator
3. Installation of the base and turbine
4. Turbine Assembly Drawing
5. Fabrication Process
6. Turbine User's Manual

The table below shows a technical data sheet for the WindAid turbine specification.

Table 1: Technical Data Sheet of the WindAid Turbine

Nominal Mechanical Power	500 W

Nominal Electrical Power	240 W
Nominal Voltage	12 V
Nominal Current	20 A
Rotor Diameter	1.7 m
Swept Area	2.27 m^2
Rotational direction	Anti-clockwise
Cut In Wind Speed	3 m/s
Cut Out Wind Speed	12 m/s
Rotor speed	120 - 600 rpm
Number of blades	2
Hub Height	7 m

This turbine design is paired with either of the following **generator** (alternator) designs. Historically, the WindAid 4.1 Design has been used, and this generator has been installed in many communities. Last year, WindAid partnered with Laplace Laboratories in France to build a generator with higher power. Both designs will be undergoing testing in the coming months to characterize their performance. All generator parts can be sourced from Trujillo, except for the magnets which are from Lima.

Parameter	WindAid Design 4.1	LAPLACE Design 2022
Magnet direction	Axial Flux	Radial Flux
Number of coils	6	15
Number of magnets	8	10
Wire gauge	11, 12, 14 AWG (depending on the source)	1.1 mm (17 AWG)
Magnet grade	N42	N52
Number of turns per coil	70	140
Magnet size	50 x 25 x 12.5 mm	30 x 60 x 15 mm

Rotor material	14mm thick, 250 mm diameter steel with fiberglass top layer	Polyester resin reinforced with fiberglass and wrapped in carbon fiber
Airgap	12.5 to 13 mm	3.4 mm
Stator material	Fiberglass	Fiberglass
Mold material	Resin	RTV Silicone
Efficiency	50%	80%
Approximate electrical power	200 W	600 W
Cost	710 sol	1144 sol

Note that the Laplace design does not use steel. This decreases its magnetic performance and was done with the intent of eliminating machining for better manufacturability. However, WindAid has said that the use of steel in their current design does not pose a manufacturability problem.

WindAid has also partnered with volunteers from AirBus to redesign the **blades**. The blades all have the same diameter and use a NACA 4415 airfoil, differing only in their chord and twist profile. The AirBus design is less aerodynamically efficient but more structurally efficient. Like the generators, both blade designs will be performance tested in the coming months.

Finally, WindAid's **electrical system** currently consists of a COTS charge controller that is shipped from a supplier in China, a 12V car battery, a 5V linear-regulator based phone charging system, and a screen that shows the battery state of charge to allow families to plan their energy usage. The controller is the only part of the system that is not locally sourced, and it uses an MPPT (maximum power point tracking) algorithm to apply the appropriate torque to the generator to maximize generated power. The electrical system does not currently include any sensors or datalogging functionality, or an inverter to run standard 220VAC appliances. 12V LED lights are the primary load. A previous student project (ReMona remote monitoring project) added sensors, but it has since been abandoned due to the recurring cost of cell service for the IoT connectivity, and the lack of IoT expertise of the WindAid permanent staff. The parameters of the battery are as follows:

Battery capacity	114 Ah
Battery voltage	12 V
Battery mass	24 kg

Extensive additional information is available about all of these systems, including CAD, manufacturing procedures and videos, product manuals, student reports, and cost breakdowns. **Please see the technical resources spreadsheet for an organized list of all documents.**

4. Design Requirements

GAIA teams are tasked to improve the design of the WindAid off-grid small wind energy system to make it more reliable, economical, practical, sustainable, and otherwise impactful. The challenge is as follows:

1. Choose one subsystem of a wind turbine:
    a. **Electronics - required**
    b. **Blades - optional**
    c. **Generator - optional**
2. Redesign the subsystem with any/all of the following objectives in mind, roughly in order of priority:
    a. Lower system cost (capital and operating)
    b. Increase reliability (time between failures) and system lifetime
    c. Improve local manufacturability and local maintainability, including safety
    d. Increase average power output at wind speeds typical of the Peru wind climate
    e. Improve life-cycle environmental sustainability
    f. Any other changes that will allow the system to effectively provide electricity to as many houses as possible in the rural areas of Peru
3. Ensure compatibility with the following functional requirements:
    a. Electricity should be available to support residential household lighting and device charging loads. Example design requirement: electricity should be available for a minimum of 12 hours each day in the evening, night, and early morning hours, and be able to store energy for 1 week in the event of low wind or system failure, under a specified load profile.
    b. The system should function at the sites of WindAid's existing community partnerships (Luz del Sol, Nueva California, and El Chorro, Peru), WindAid's development and testing facility (Trujillo, Peru), and nearby locations in northern Peru. Example design requirement: all turbine components must operate in direct sunlight, rain, and temperatures ranging from 40-90 degrees fahrenheit, with a specified representative hourly wind speed profile.
    c. Materials must be locally sourced in Northern Peru. Materials that cannot be found in rural areas should be sourced from Trujillo. Specialized parts may be sourced from Lima if there is no other option.

To estimate overall system performance and determine interface requirements, teams may assume that **any subsystems not being redesigned will use the default WindAid design**, unless a specific change is necessary. GAIA organizers will coordinate integration between subsystems as needed.

Teams should assess the wind resources, expected demand load, economics, reliability, manufacturability, maintainability, and sustainability of their design **in the context of rural Peruvian communities**, which may require different analyses than what teams are used to for design in developed economies.

4.1 Electronics subsystem details

The biggest challenges with the current electrical system are, with the highest priority first:

- The lack of local sourcing of the controller adds up to $200 in transportation and customs costs, and makes it impossible to repair. Teams should find a locally sourced alternative, which could involve a locally manufactured custom design, or the creative use or modification of locally available products intended for other purposes.
- The weight of the battery makes it difficult to transport. Teams should conduct a tradeoff study to assess the cost, cycle life, and energy capacity implications of moving to a different type of energy storage or a smaller size of the current car batteries.
- The screen is insufficient for alerting families about a low battery level. Teams should add a low battery indicator that is more noticeable, such as a pinging sound, to the charger box.
- The lack of sensors means the turbine performance cannot be monitored and verified. Teams should add sensors and a logging system to detect and record wind speed, turbine speed, current, and voltage.

The following additional design requirements for the controller should be satisfied:

- Input to system: 3 phase AC variable frequency generator coils, with maximum voltage XX V AC (rms, line-to-line) and maximum current XX A AC (rms, line-to-line) - numbers to be updated based on calculations of the generator
- Output of system: 12V DC to charge battery (or less when the battery is at low SOC). Must function at all ranges of battery charge.
- Include a mechanism to dissipate power when the energy storage system is full or otherwise cannot be charged
- Include a mechanism to automatically control the torque that the generator applies to the rotor in order to maximize the power generated
- Include a mechanism to detect when the turbine is operating above the maximum rotational velocity (600 rpm) and perform a shutdown routine to protect electronics from overvoltage
- Include a surge protector and a grounding system for lightning protection
- Be possible to disconnect battery from turbine for maintenance in any wind speed
- Be possible to perform a manual shut down routine for maintenance in low wind speeds
- Safety-critical functionality should be implemented in hardware rather than software
- Any large capacitors that could cause current spikes upon connection must include mechanisms for precharge and discharge
- Include physical isolation and fire safety protections: a dropped screw should not short the system, and wires should not be able to come loose over time

Note: a shutdown routine consists of all moving components braked to a stop and held in place.

4.2 Blades Subsystem Details

Teams will receive the following data from WindAid, for both the WindAid default blades and the new Airbus blades:

- Moment of inertia
- Time-series data of the turbine in real wind conditions lasting several hours
    - Time
    - Wind speed, at specified height
    - Battery current
    - Battery voltage
    - Turbine rotational speed
    - Yaw rotation angle

Teams must analyze the data and produce the following graphs for each blade:
- Electrical power vs wind speed (predicted and experimental)
- Coefficient of power vs wind speed (predicted and experimental)
- Coefficient of power vs tip speed ratio (predicted and experimental)

Teams should then use the data to suggest a blade design, taking into account the aerodynamics, structural stiffness and strength, and manufacturability. A blade design consists of an airfoil selection, a profile of chord and twist angle over the radius, and a material and manufacturing specification. The following additional design requirements for the blades should be satisfied:
- Maximum blade deflection must not result in blade tip hitting tower
- Blades should not yield or fatigue under their own aerodynamic load, with a factor of safety of at least 2
- Produce a thrust load less than or equal to the yield and fatigue strength of the current tower, with a factor of safety of at least 2
- Produce a torque less than or equal to the yield and fatigue strength of the current drivetrain, with a factor of safety of at least 2

4.3 Generator Subsystem Details

Teams will receive the following time-series dynamometer test data from WindAid, for both the default generator and the Laplace generator:
- Time
- Drivetrain torque
- Generator speed
- Battery voltage
- Battery current

Teams must analyze the data and produce the following graphs for each generator:
- Torque speed curve (predicted and experimental)
- Efficiency map as a function of torque and speed

Teams should then use the data to suggest a generator design, taking into account the torque capability, efficiency, cost, and manufacturability. The following additional design requirements for the generator should be satisfied:
- Torque speed curve exceeds the torque-speed operating points of the blades

- Current limit specified to avoid demagnetizing magnets or melting winding wire
- Is compatible with current drivetrain and nacelle, or specifies minor changes if needed
- Is compatible with controller current and voltage rating and shape (sin / trapezoidal)
- Fundamental frequency at maximum speed is less than one tenth of the controller's switching frequency
- Maximizes efficiency at the rotational speed corresponding to the most common wind speed and the optimal tip speed ratio (6.5)
- Protects magnets from corrosion
- Maintains a constant airgap to prevent asymmetries
- Keeps winding wire isolated and not shorting

5. Suggested Timeline

Task	**Start date**	**# weeks**
Kickoff event	11/20/2023	-
Read challenge, decide subsystems	11/20/2023	1
Lit review, brainstorming, planning	11/27/2023	2
Architecture & conceptual design	1/1/2024	2
Detail design (CAD, analysis, sourcing)	1/15/2024	3
Purchase materials for prototype	2/5/2024	1
Manufacture parts for prototype	2/12/2024	2
Assemble prototype	2/26/2024	1
Debug and troubleshoot prototype	3/4/2024	2
Collect test data for prototype	3/18/2024	2
Make improvements as necessary	4/1/2024	3
Work on deliverables	4/1/2024	3
Competition	4/20/2024	-

6. Changelog

Version	Date	Comment
V1.0	11/20/23	Initial release